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Modeling of assembly system complexity in manufacturing

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Modeling of Assembly System Complexity in Manufacturing

by
Samin Shokri

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Chapter 6	*Shokri, S. and ElMaraghy, W., "Modeling of Assembly System Complexity in Manufacturing".*	*Submitted to CATS2008 [2nd CIRP Conference on Assembly Technologies and Systems*
Chapter 7	*Shokri, S. and ElMaraghy, W., "Reduced Combinatorial Complexity: A new Approach to Assess the Assembly Complexity".*	*Submitted to CATS2008 [2nd CIRP Conference on Assembly Technologies and Systems*

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ABSTRACT

Global competition, increased products variety, shorter time-to-market, and higher quality impose an increased complexity to the manufacturing systems. Assembly is a stage in the production system that has a significant portion of the total cost as well as a high impact on the final product quality. Therefore, recognition and management of complexity in assembly will result in cost efficiency in manufacturing systems.

This thesis aims at modeling the assembly complexity in physical and functional domains. A matrix-based model is proposed to capture the effect of product and process-related elements on complexity in the physical domain. A novel notion, i.e. Reduced Combinatorial Complexity (RCC) is introduced, which deploys the entropy theory to measure complexity in the functional domain.

The proposed models have been applied on different case studies. The results show that applying the Design For Assembly (DFA) method on products will result in reduction of the assembly complexity. In addition, RCC confirms that dividing assembly into subassemblies will lead to significant reduction in complexity. Furthermore, it can be used as a tool to compare different subassemblies and their effect on reducing the assembly total complexity.

DEDICATION

To my parents and Ehsan for their support and patience.

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LIST OF ABBREVIATIONS

AD	Axiomatic Design
APD	Assembly Process Design
ATP	Assembly Technology Planning
BAPP	Basic Assembly Process Planning
CI	Commonality Index
D&C	Divide and Conquer
DAC	Design for Assembly Cost-Effectiveness
DFA	Design For Assembly
DFM	Design For Manufacture
DI	Differentiation Index
DP	Design Parameter
FR	Functional Requirement
HTA	Hierarchical Task Analysis
LHS	Left Hand Side
MHS	Material Handling Systems
NRCC	Normalized Reduced Combinatorial Complexity
PR	Precedence Relations
PSP	Product Structure Planning
RCC	Reduced Combinatorial Complexity
RHS	Right Hand Side
RMS	Reconfigurable Manufacturing Systems
SI	Setup Index

Chapter 1

Thesis Overview

This chapter gives a brief description of complexity in manufacturing systems and its sources, assembly complexity and the importance of measuring complexity in assembly. Followed by motivation of this study, the objectives and approach of the research is described.

1.1. Introduction

Today's competitive environment leads the manufacturing systems to respond rapidly to the changing market demands, with the focus on higher quality and lower price. Therefore, industrial entities face increased challenges in their manufacturing and assembly systems in different production aspects. Nowadays, customers are expanded and their miscellaneous requirements result in more variety and diversity in products. On the other hand, products become more complex and complicated in order to convey the functions required by customers. In addition to diversity, products should be offered with high quality and at the same time with low price. All these factors impose complexity to all the stages of production process such as design, selection of manufacturing technologies and suppliers, assembly and distribution. Therefore, appropriate design of the production processes, products, and supply chain will reduce the total manufacturing complexity and the incurred costs.

The field of complexity is becoming increasingly important in science and engineering [Suh, 2005]. The complexity of production systems is the critical cause of many management problems in industrial companies [Wiendahl, 1994]. Manufacturing systems look for new answers to deal with the growing complexity in their systems. There are several approaches to describe complexity in manufacturing systems and to define metrics to measure complexity. Most of the studies have focused on defining the product complexity and introducing ways to reduce it. Additionally, the effect of product variety on the complexity has been studied.

1.2. Motivation of the Study

Manufacturing assembly has a significant influence on the final product cost. In addition, it has a high impact on the final product quality. Assembly, as an important stage in production system, faces growing complexity because of different types of products, large number of components, different assembly sequences, and human involvement in the assembly tasks. In fact, new and complex products with higher variation and number of parts are generated to satisfy the varying demands of customers. As an example, between 1975 and 1990, the amount of part numbers went up by approximately 400% [Wiendahl, 1994]. These factors introduce an increasing complexity to the assembly system. Therefore, appropriate design of assembly sequences, subassemblies, and components will reduce the complexity of assembly and the total manufacturing cost.

Measuring assembly complexity can be used as a tool to identify stages in assembly that affect the total complexity the most. In addition, it has been proven that there is a close relationship between the assembly complexity and the defect rate: The higher the assembly complexity, the more defect rate in manual assembly. Assembly complexity has been studied from different views. For instance, Goldwasser and Motwani [1999] developed complexity measures for two-handed assembly sequences. Richardson at al. [2004, 2006] and Ben-Arieh [1993, 1994] tried to reduce assembly difficulty by considering the product-related factors, such as part count and fastening types. Rodriguez-Toro et al. [2002, 2003, 2004] address the product-related complexity in an assembly-oriented environment, mentioning that the total assembly complexity is a function of component and assembly. In the component level, we deal with manufacturing and process complexity while in the assembly level, the main elements are the structural, and sequence factors. Martin and Ishii [1997] and Prasad [1998] discussed the effect of variety on assembly complexity. As mentioned above, most of the studies have considered the effect of product-related elements on assembly complexity.

This thesis proposes a complexity approach on assembly systems that deals with the product- and process-related factors affecting the assembly complexity. It is important to measure complexity at different stages of assembly to examine the effect of each component or subassembly on the total complexity of the assembly. This insight will assist the manufacturing industry in the proper product design in order to reduce the total manufacturing cost, time, and complexity.

1.3. Objectives and Approach

The objective of this research is to develop a model that represents the assembly complexity in both physical and functional domains.

The purpose of this thesis is to demonstrate that:

- The complexity of assembly, due to product and process-related elements, will be reduced by reducing the part count.
- The result of measuring assembly complexity is compatible with the results of DFA analysis.
- Dividing assembly into subassemblies will reduce the assembly complexity.
- Assembly complexity metric is a tool to select the assembly sequences with lower complexity.

In order to achieve the thesis objectives, a number of models including a matrix-based model are proposed for measuring the assembly complexity. In this model, the assembly tasks, i.e. handling, alignment and insertion, are analyzed according to their required effort amount to be accomplished. In addition, the effect of part selection is considered on the assembly complexity. In this model, we benefit from DFA method guidelines in measuring the product-related complexity section. The number of parts and their diversity are the other factors that affect complexity in this model.

Furthermore, a new approach is introduced to measure the complexity in functional domain, called Reduced Combinatorial Complexity (RCC). This approach is formulated using the Shannon's information theory in achieving success in selection, orientation, and insertion tasks in assembly. Incorporating the proposed model in different assembly sequences and subassemblies indicates the amount that each assembly sequence reduced the complexity. It further determines the appropriate step to introduce subassemblies.

Chapter 2

Literature Review: Assembly Systems

This chapter reviews some of the basic and significant concepts in the assembly area. The first part describes the assembly system, the importance of assembly and different types of it. In the second section, the importance of assembly sequence analysis and some significant works in this area is studied. Also, it is mentioned that the assembly complexity measure can be a criterion in selection of an assembly sequence. Finally, the Design For Assembly (DFA) method is described.

2.1. Assembly in Manufacturing

Assembly is an important process in manufacturing as it brings together all the upstream processes of design, engineering, manufacturing and logistics to create an object that perform a function. [Whitney, 2004]

The products are assembled through the assembly process in which the functional requirements are identified and the parts and subassemblies are designed to meet the recognized requirements. In addition to the definition of each part, the relation between the parts must be identified as well. The parts can perform the required task and work together if they are assembled.

Since it is not feasible or cost effective to produce a product as a single piece, each product is breakdown to parts or subassemblies. The other factor that results in assemblies is that the product should perform several functions, which is not feasible by one-piece product. Typical assemblies consist of many parts, each with a few important geometric features, all of which must work together in order to create the product's several functions [Whitney, 2004].

Assembly has a high effect on top-level business decisions. For instance, an appropriate assembly sequence allows adding different parts at the last steps of assembly. Therefore, a company is able to present higher variety of products, with lower cost. Another instance is that appropriate design of subassemblies allows a company to outsource their production or increase the possibility of customized products.

Assembling a mechanical product normally can be expressed as a long chain of activities and actors. Figure 2.1 illustrates the main processes of assembly.

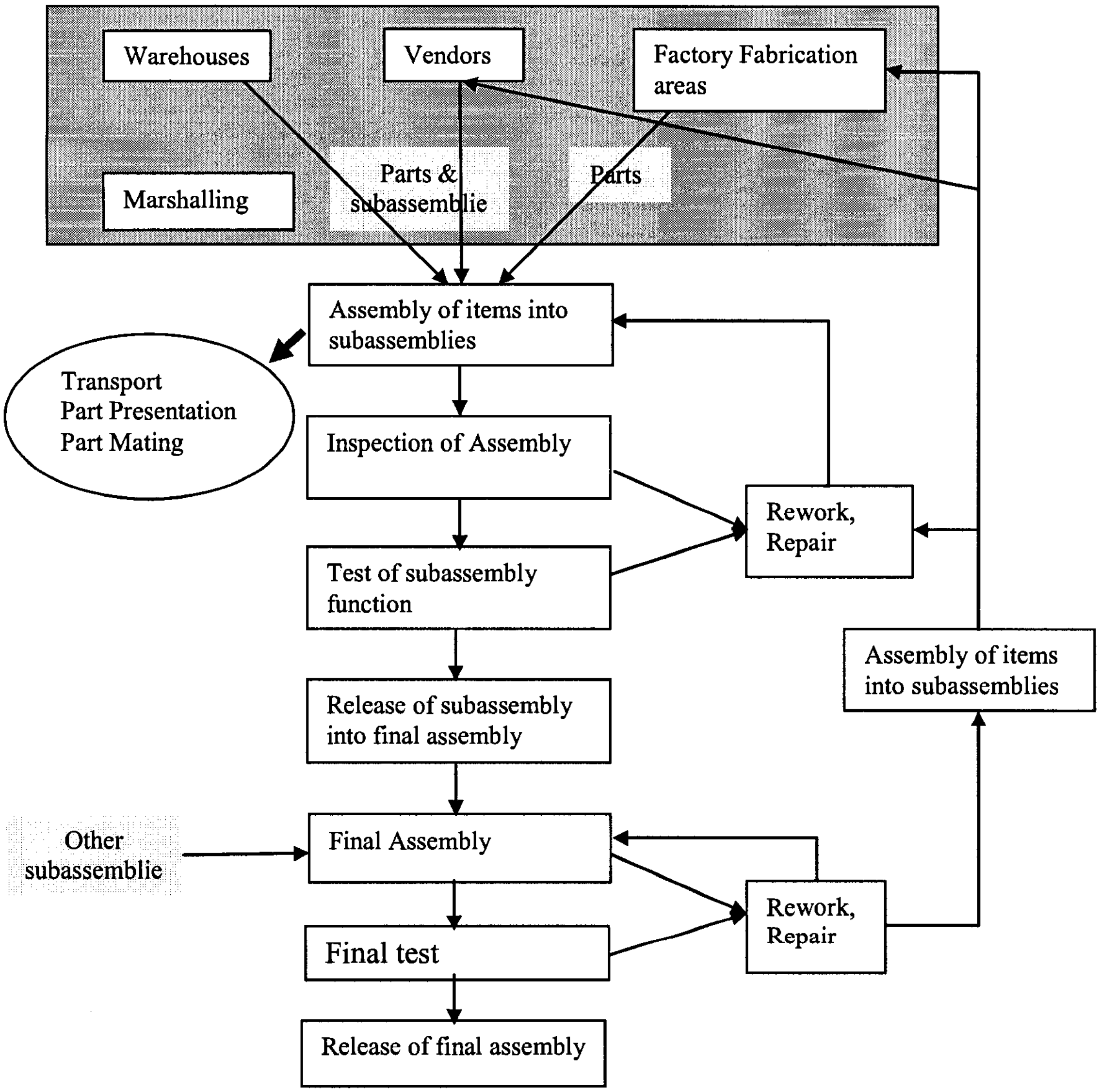


Figure 2.1: The main processes of assembly [Whitney, 2004]

Boothroyd addresses Henry Ford's principles of assembly as follows:

"First, place the tools and then the men in the sequence of the operations so that each part shall travel the least distance whilst in the process of finishing. Second, use work slides or some other form of carrier so that when a workman completes his operation he drops the part always in the same place which must always be the most convenient place to his hand and if possible have gravity carry the part to the next workman. Third, use sliding assembly lines by which parts to be assembled are delivered at convenient intervals, spaced to make it easier to work on them." [Boothroyd, 2002]

Generally, assembly can be performed manually, automatically or in a hybrid manner. In the manual assembly, an operator is responsible for assembling the component and can adapt to changing condition in the assembly, such as part variation, and mislocation. In this case, the quality of final product can be deteriorated because of the operator error or fatigue.

In the case of high production, simple assembly tasks can be performed automatically with special-purpose machines. These automated machines are connected to each other by some type of transfer systems for part conveyance. Each assembly task is performed at one station with a machine equipped with dedicated jigs and fixtures. The problem is that part variation, misalignment and mixed products should be recognized by using sensors, which is not always economic or efficient. The improper product alignment can result in jamming, incomplete operation, and machine downtime. However, automation can be justified when the production volume is high, product life cycle is long, and assembly tasks are simple [Crowson, 2006].

Since assembly as a significant stage in manufacturing system, appropriate design of assembly processes, subassemblies, and parts will reduce the total manufacturing cost.

2.2. Assembly Sequence Analysis

Determination of the product's assembly sequence is an important part of the process planning activity in assembly. This consists of identifying the feasible orders of assembling the components together to construct the product and then determining the best feasible sequence according to different criteria.

As assembly sequence highly affects the other aspects of product design and production, it should be done at early stages of product design for the following reasons: One of them is related to the construction of parts, i.e. some assembly sequences do not provide enough space for tools to reach the fastening points. The other issue is related to the quality of the product. The selected assembly sequence should provide opportunity to test the function of a subassembly, or the assembly sequence should be chosen in a way that the fragile parts are not assembled at the early stages of assembly, as there is the probability of failure. The other reason is related to the assembly process. Some sequences may not allow a part to be jigged or gripped from an accurately made surface, making assembly success doubtful [Whitney, 2004]. In addition, the assembly sequences that need more reorientations and part flipovers are not reasonable. Finally, the assembly sequence should provide the product variations at lower cost. This means that the introduction of product differentiations should be delayed to the last steps of assembly.

There are algorithms and heuristic methods that define how to find the assembly sequence. Unlike the algorithms, heuristic methods are fast but may result in sequences that are not correct, or they may miss some feasible sequences, i.e. the ones that can be finished and no parts will be left over.

One of the algorithms is proposed by Bourjault [1987]. He deployed the liaison diagram and used the sequence of liaisons to generate assembly sequences. Liaison diagram is a graph in which each vertex and each liaison represent one component and a physical connection between two components, respectively. An example of liaison diagram is illustrated in Figure 2.2.

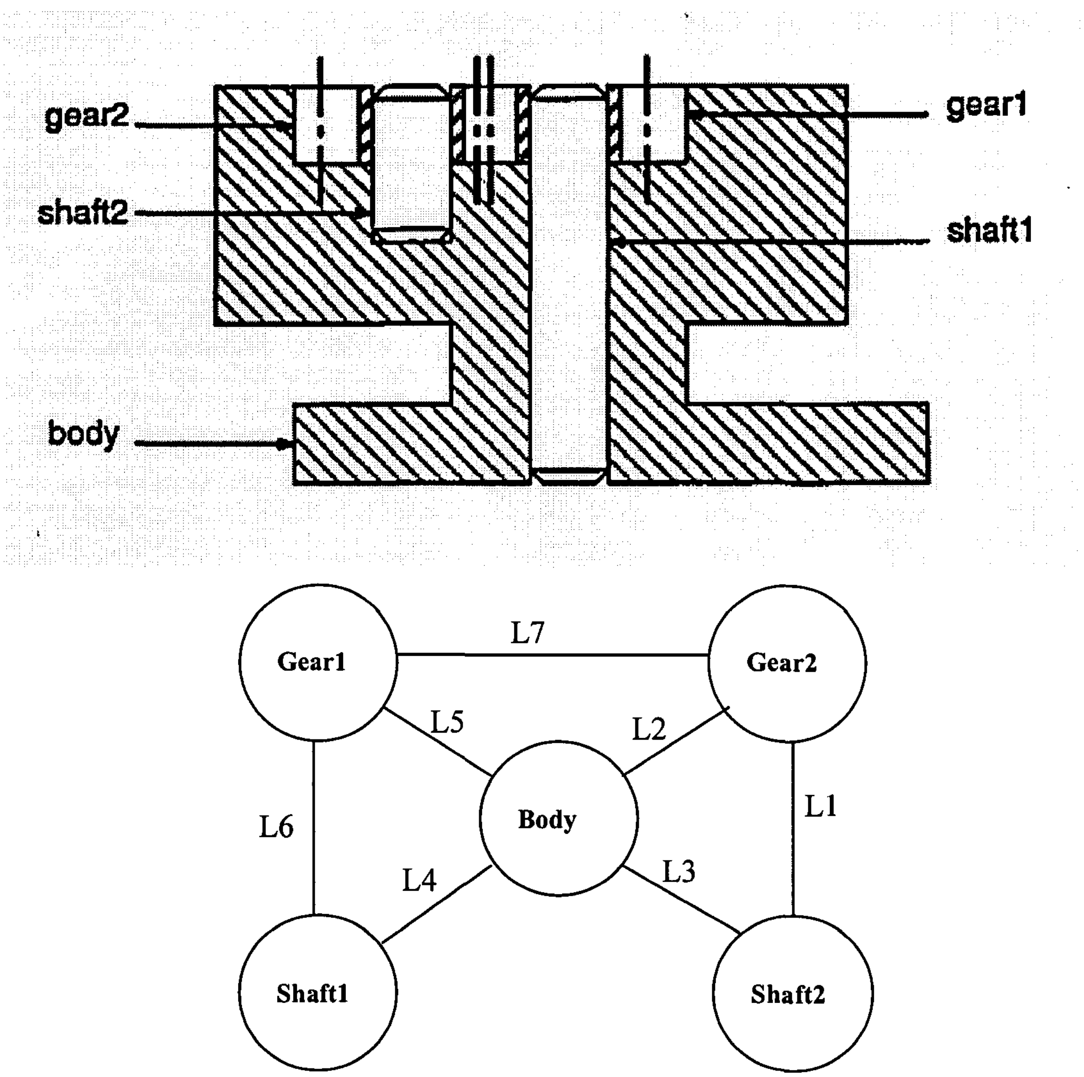


Figure 2.2: An oil pump assembly and liaison diagram [Laperriere, 1992]

Once the liaison diagram is generated, each liaison is tested through a set of questions to see if it can be accomplished at a given stage of assembly.

The questions are:

1. Can L_i be established if L_j and L_k have already been established?
2. Can L_i be established if L_j and L_k have not been previously established?

The answers to these questions are "yes" or "no". The results generate a list of precedence constraints in binary relations of the liaisons, representing by R and S:

> $R = \{(L_i, L_j) \mid (L_i, L_j) \in L \times L \wedge L_i$ cannot be established if L_j is already established$\}$
>
> $S = \{(L_i, L_j) \mid (L_i, L_j) \in L \times L \wedge L_i$ cannot be established if L_j has not been established$\}$

where, L denotes the set of all liaisons of a product. The precedence relations indicate the required liaisons to establish each particular liaison. Finally, all the liaisons are combined with each other to generate feasible assembly sequences.

The other work, which was built on Bourjault's method, was done by Whitney and De Fazio [Whitney, 2004]. They improved Bourjault's method in such a way that it can handle larger problems and can easily link to CAD. Actually, they improve the questions generated by Bourjault to the following:

1. What liaison(s) must be established before L_i can be established?
2. What liaison(s) must be left undone so that L_i can be established?

For Liaison L_i, typical answers for both questions are as below:

> $A1_i$: $(L_j \vee (L_k \wedge L_m)) \rightarrow L_i$
>
> $A2_i$: $L_j \rightarrow (L_r \vee (L_s \wedge L_t))$
>
> Where $\rightarrow$ means "must precede" and L_j, L_k, L_m, L_r, L_s, and L_t are other liaisons in the product [Laperriere, 1992].

Instead of answering "yes" or "no" for every pair of liaison, their answers consist of Boolean phrase of liaisons. The answers give a set of Precedence Relations (PR), which is divided into a Left Hand Side (LHS) and Right Hand Side (RHS) sets. LHS represents liaisons that must be established before establishing liaisons in RHS. In this case, for each PR, there is at most one liaison in RHS.

In their study, a binary vector represents the state of assembly at each assembly point. The assembly state is shown in a ranked-based algorithm. In rank 0, it is assumed that the product is completely disassembled. The completely disassembled and assembled liaisons are shown by 0 and 1, respectively. Then, the parts that can be assembled are recognized at each rank according to the values of Boolean phrase. Each rank includes different possibilities of part assembly, which is continued in the next ranks until all the parts are assembled. Figure 2.3 illustrates the ball-point pen assembly and its graph of connections. In figure 2.4 the feasible sequences generated by this method for a ball-point pen is illustrated.

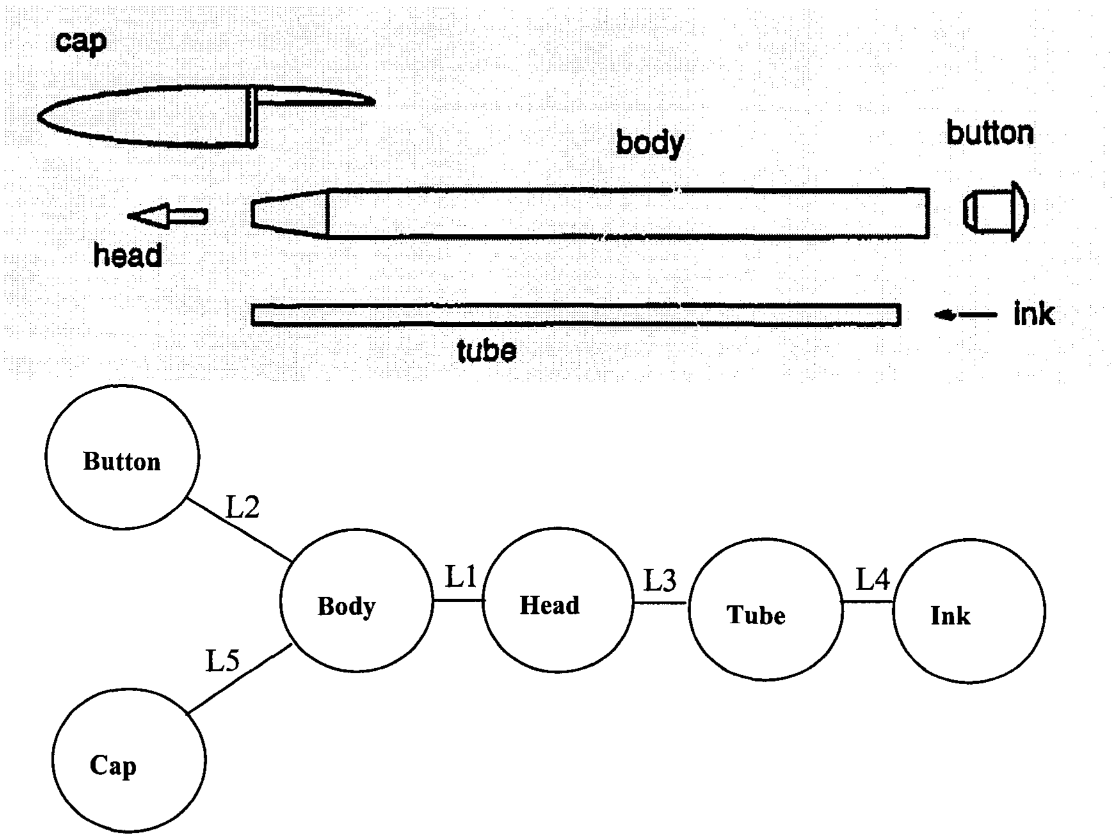


Figure 2.3: Graph of connections for the ball-point pen [Laperriere, 1992]

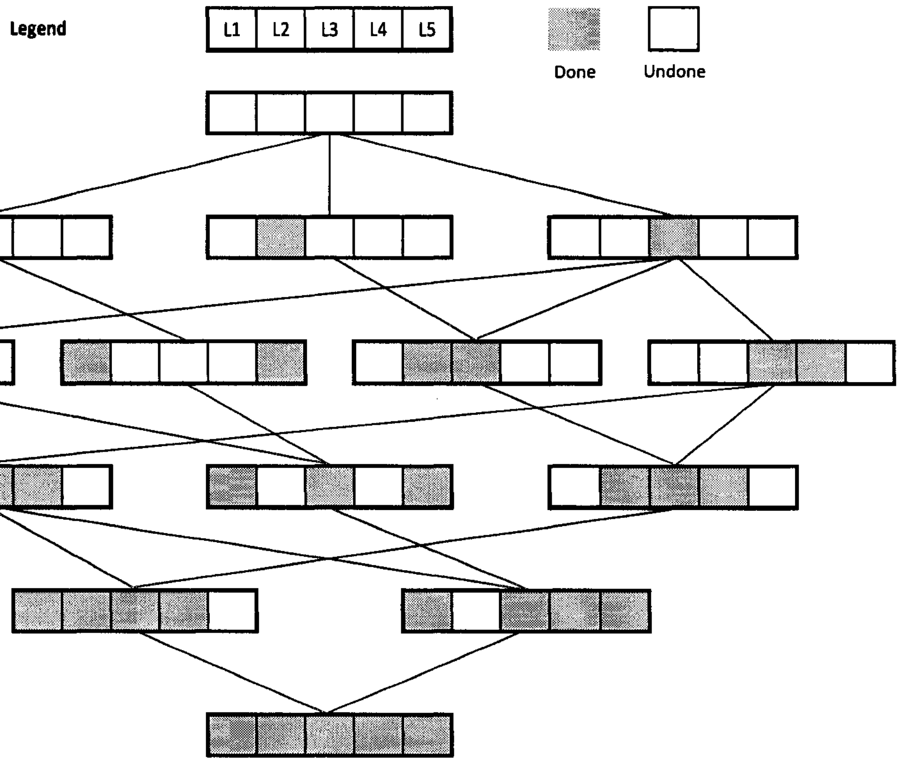


Figure 2.4: Directed graph of assembly sequence for the ball-point pen [Laperriere, 1992]

The next work is done by Homem De Mello and Sanderson. In their proposed method, a graph called AND/OR tree is generated that contains the precedence relations. AND/OR tree is generated based on decomposition of the assembly. Generation of all possible disassembly sequences starts by obtaining the graph of connection from the given relational model of the assembly. Next, all the cut sets of the graph are generated, representing all the possible ways of splitting the graph [Laperriere, 1992]. This gives all the possibilities of subassemblies in the assembly. The same approach is continued until the single parts are left. In fact, the decomposition approach result in generating AND/OR tree.

All the process planning approaches consist of two phases: generating all feasible sequences, and choosing the best sequence according to different criteria. The criteria can be time, cost, number of reorientation, number of fixtures, or the necessity of a linear sequence. In addition, different assembly sequences may result in assemblies with varying qualities.

Selection of each assembly sequence highly affects the assembly process-related issues such as required tools and fixtures, how to insert the parts and handle the parts during insertion, whether they need any support during insertion, as well as the assembly difficulty. Hence, assembly sequence is a factor that influences assembly complexity. Different assembly sequences have different complexity amount, and complexity measure can be one of the criteria of choosing an assembly sequence.

2.3. Design For Assembly (DFA)

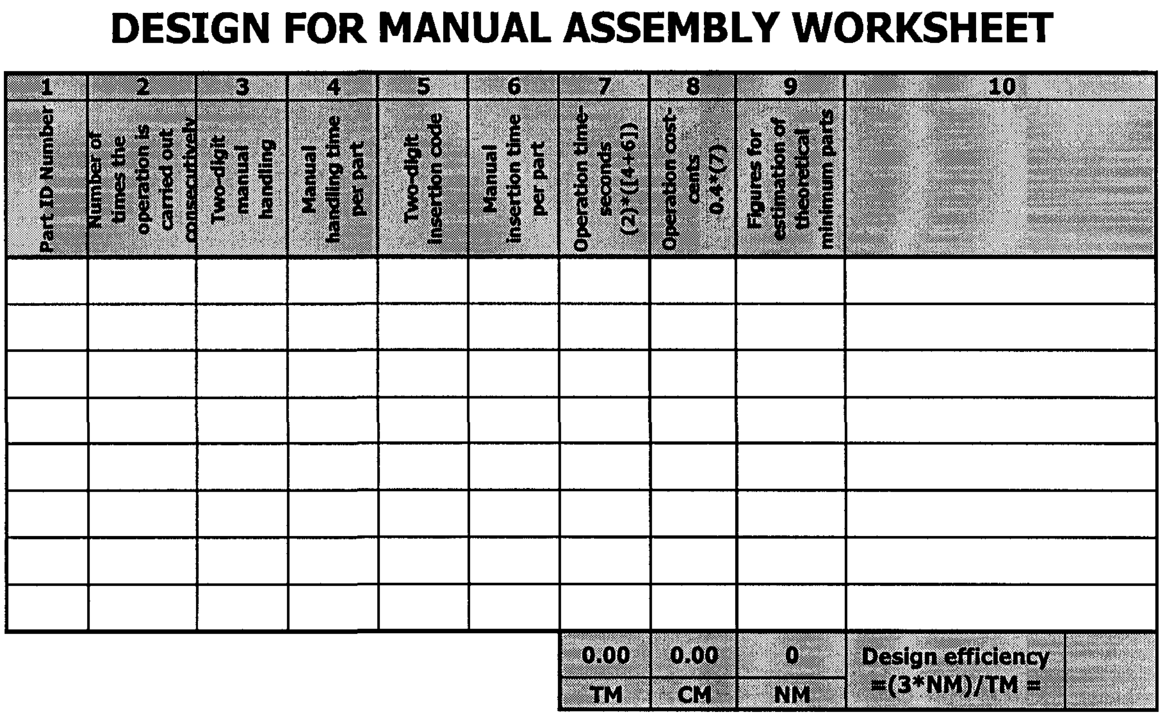
DFA was first systematized in the 1960s by Boothroyd et al. The basis of this approach is "classification and coding", a common technique in Europe in the domain of group technology [Whitney, 2004].

Later on, different methods were generated as the name of DFx, each of them including procedures, guidelines, and metrics to improve the product in the context of "x".

Since the changes applied at the early steps of design process result in more cost efficiency in the total product development, it is suggested that DFx methods are better to be applied early in the design process.

In the DFA method, part feeding, orienting, handling and inserting are identified as the most important tasks. The classification in DFA method is according to the part shape, size, weight, ratio of length to diameter, and symmetry. The parts are classified according to these metrics and then a score and time estimate is nominated for them, with higher scores representing less time needed to accomplish assembling the part. On the other hand, parts with lower score are considered more difficult to assemble or to have more chances of assembly error.

Once the data are extracted from the DFA table, they should be entered into the DFA worksheet. This worksheet provides guidelines to calculate the assembly's total time, efficiency, and cost. A sample of DFA sheet is illustrated in figure 2.5.



DESIGN FOR MANUAL ASSEMBLY WORKSHEET

1	2	3	4	5	6	7	8	9	10
Part ID Number	Number of times the operation is carried out consecutively	Two-digit manual handling	Manual handling time per part	Two-digit insertion code	Manual insertion time per part	Operation time-seconds (2)*([4+6])	Operation cost-cents 0.4*(7)	Figures for estimation of theoretical minimum parts	
						0.00 TM	0.00 CM	0 NM	Design efficiency =(3*NM)/TM =

Figure 2.5: DFA worksheet for manual assembly [Boothroyd et al., 2002]

DFA aims at increasing assembly efficiency and reducing assembly time and cost by eliminating unnecessary parts. In fact, by reducing the part count, a great saving occurs in both assembly and manufacturing of the parts. Boothroyd developed criteria to nominate the parts to be eliminated. The idea is to subject each part to three criteria that might justify its inclusion in the product, and eliminate any part that fails the criteria. These three criteria are as follows [Whitney, 2004]:

1. During operation of the product, does the part move relative to all other parts already assembled? (Small motions that could be accommodated by flex hinges integral to the parts are not counted.)
2. Should the part be of a different material or be isolated from all other parts already assembled?
3. Must the part be separate from all other parts already assembled because otherwise the assembly or disassembly of other separate parts would be impossible?

Therefore, the parts with “yes” to all of the three questions are not appropriate candidates to be eliminated and should stay in the part structure.

As expressed earlier, DFA aims at simplifying the product in order to reduce the assembly difficulty. Simpler products have fewer parts, resulting in fewer assembly operations, workstations, factory space, and workers.

In spite of being a well-systemized method to simplify assembly, DFA method has a number of drawbacks. First, implementing DFA requires the selection of a nominal assembly sequence since the previous assembled parts affect the difficulty of assembling each remaining part. The other issue is that, reducing the part count and merging them together generally will result in complicated parts to produce. Therefore, it is better to apply the DFA method along with the Design For Manufacture (DFM) method.

Chapter 3

Literature Review: Complexity

This chapter introduces different definitions for complexity in various fields of study. Then, it reviews the main approaches for complexity: Shannon's Entropy theory and Axiomatic Design (AD). In the entropy approach, the amount of information is measured to reflect the complexity. The more the information amount, the more complex the system becomes. In the axiomatic design section, the design axioms are described and then the complexity definition based on axiomatic design and different types of complexity are explained.

3.1. Complexity Background

To discuss complexity and complexity measures, it is necessary to exactly define complexity. However, there is no unique definition for complexity that can be used for all the fields of study, such as biology, information theory, computer science, and manufacturing systems. According to the Merriam-Webster dictionary, "complex" is defined as "composed of two or more parts; hard to separate, analyze, or solve". In addition, Oxford dictionary defines the word "complex" as "consisting of many different and connected parts; not easy to understand; complicated". The common part in both definitions is that a complex system is composed of numerous but related parts, which is difficult to understand. Therefore, the words complex and complexity should be defined according to the field of study. Table 3.1 shows some of the definitions used in the areas of computer science, biology, manufacturing science, physics, information theory, large technological systems, etc.

All the different views agreed on that the complex system is consists of numerous and inter-related parts which is difficult to understand. Therefore, it can be inferred that the manufacturing assembly is a complex system as it is composed of different components that are related to each other by number of fastenings.

Field of Study	**Definition**
Computer Science	The complexity of an object (pattern, string, machine, algorithm, ...) is the difficulty of the most important associated with this object.
Biology	A complex system has a multitude of partial simple descriptions but we cannot construct from them a single "largest" description that is also simple. In this sense, the reductionistic paradigm fails for complex systems.
Manufacturing Science	A manufacturing system may make thousands of part types (not just parts) during a year. There may be hundreds of machines. At each moment, the managers are faced with hundreds of decisions, such as: which part should be loaded onto each machine next? The consequences of each decision are hard to predict.
Physics	A complex system is a complicated system, composed of many parts, whose properties cannot be understood.
Information Theory	The complexity of a system is closely related to the content of the information that the system contains.
Large Technological System	A system is complex when it is built up of a plurality of interacting elements, of a variety of kinds, in such a way that in the holistic result no evidence can be traced of the characteristics of the single elements.

Table 3.1: Various views to complexity or a complex system [Kim, 1999]

3.2. Different Approaches to Complexity

There are two main approaches found in the literature that describe system complexity and complexity measures. The first approach is based on Shannon's [1949] information theory/entropy. The second approach uses the information content in Axiomatic Design as a measure of complexity [Suh, 1999].

3.2.1. Information Theory/ Entropy Approach

Shannon [1949] first used the information theory/entropy concept in communication, to measure how much information is produced in a process. In his work, information is a measure of uncertainty. He employed probability to show the uncertainty of the information source.

Consider a set of "n" possible events with the probabilities of occurrence p_1, p_2 ... and p_n. Suppose we randomly choose one event, for example event j, with the probability of p_j. Before the selection, we find that there is an amount of uncertainty about the outcome; however, we gain the same amount of information after the selection. Therefore, the information measure equals to equation. 3.1:

$$H(p_1, p_2, \dots, p_n) = -\sum_{i=1}^{n} p_i \log p_i \qquad (3.1)$$

Where H is the entropy amount, and p_i is the probability of event i

When the probability of the occurrence of an event is low, we are uncertain about its happening. Analyzing equation 3.1 shows that lower probabilities result in more information amount.

3.2.2. Axiomatic Design Approach

The complexity definition based on Axiomatic Design was proposed by Suh [1999]. In this approach, the information content is used to measure the complexity. Suh defines complexity as a measure of uncertainty in achieving the Functional Requirements (FR) of the design. Actually, in the Axiomatic Design approach, the information theory/entropy is used to measure the information content in achieving design goals.

3.2.2.1. Definition of Complexity in Axiomatic Design Approach

There are four domains in the design world: customer domain, functional domain, physical domain, and process domain. According to the Axiomatic Design principles, the design process is mapping between domains. Figure 3.1 shows the different domains in the design world and the mapping between them. For instance, a product design is mapping from the functional domain to the physical domain.

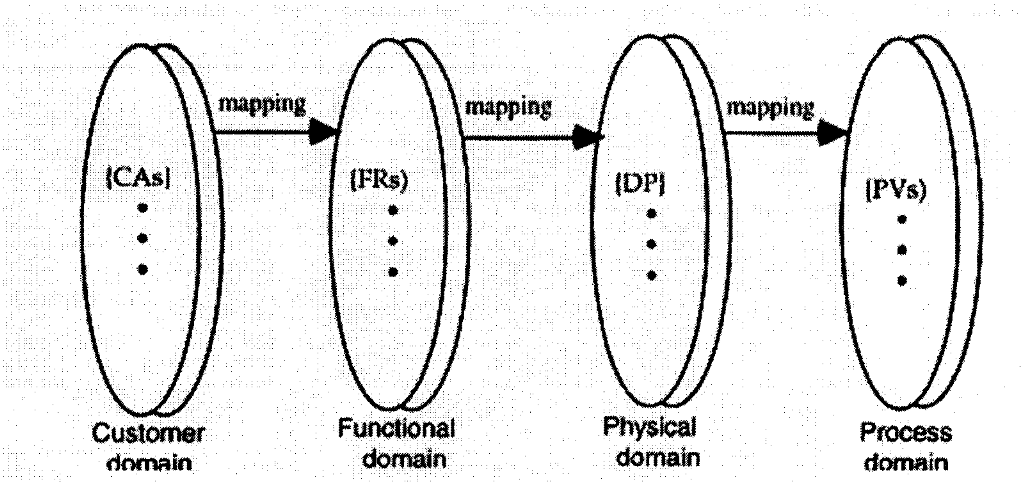


Figure 3.1: Domains in the design world [Suh, 1999]

In a product design, the design task is to achieve the goal, the set of Functional Requirements (FRs), by mapping FRs from functional domain to Design Parameters (DPs) in the physical domain [Suh, 1999]. Therefore, the selection of DPs determines the probability (and uncertainty) of satisfying the FRs.

Complexity can be defined in the physical domain and functional domain. In the physical domain, complexity is defined as the inherent characteristic of physical components, like algorithms, products, processes, and manufacturing systems. As a result, it is inferred that the more parts a physical object has, the more complex it is. On the other hand, the complexity in the functional domain is defined as a measure of uncertainty in achieving a set of tasks defined by FRs in the functional domain [Suh, 2005].

In the axiomatic design, complexity is defined in the functional domain. Here, complexity is related to the information content, which is the logarithmic function of the probability of satisfying the specified FRs. In calculating the information content, the same notion introduced by Shannon [1949] is deployed. Equation 3.2 shows the information content in axiomatic design.

$$I = \sum_{i=1}^{n} -p_i \log_2 p_i \qquad (3.2)$$

where p_i is the probability of achieving FR_i ,and n is the total number of FRs.

3.2.2.2. Classification of Complexity in Axiomatic Design Approach

In axiomatic design, complexity can be dependent or independent of time, considering whether the system range varies as a function of time or not. As a result, complexity is classified into time-dependent and time-independent complexity. Each class of complexity is further divided to two different types. Time-independent complexity is divided to time-independent real complexity and time-independent imaginary complexity. On the other hand, time-dependent complexity is classified into time-dependent combinatorial complexity and time-dependent periodic complexity. Figure 3.2 illustrates the classification of complexity in Axiomatic Design.

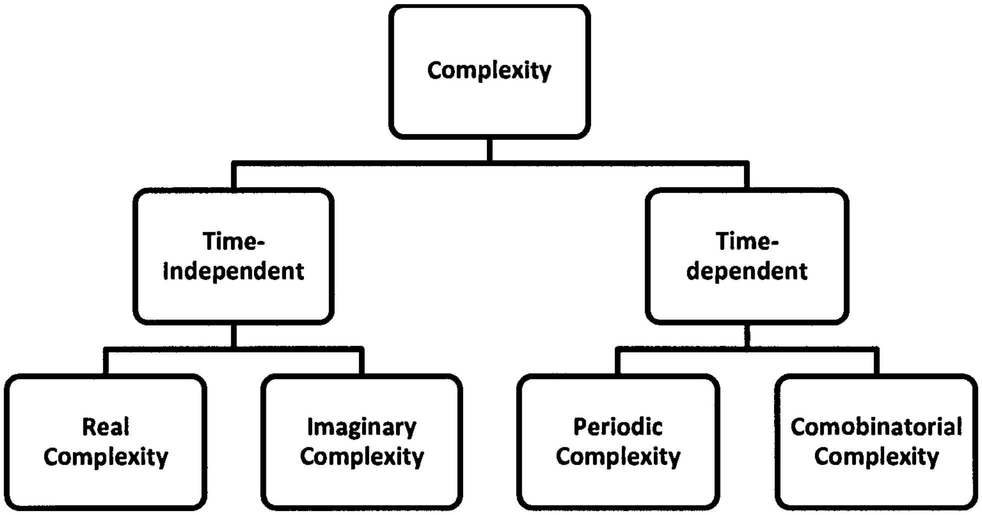


Figure 3.2: Classification of complexity [ElMaraghy et al., 2005]

In the time-independent complexity, time has no effect on the system range. Real complexity is a result of not satisfying FRs at all times. In other words, real complexity is a consequence of the system range not being inside the design range [Suh, 2005]. It is defined as a measure of uncertainty when the probability of achieving the FR is less than 1.0 [Suh, 2005].

Imaginary complexity is not real uncertainty, but arises because of the designer's lack of knowledge and understanding of a specific design itself. The imaginary complexity arises when the design has many FRs and it is a decoupled design. A decoupled design has a triangular design matrix. In this kind of design, the independence axiom is satisfied if we rearrange the DPs in the appropriate order.

In the time-dependent complexity, the system range changes as a function of time. Time-dependent combinatorial complexity is defined as a complexity that increases as a function of time due to a continued expansion in the number of possible combinations with time, which may eventually lead to a chaotic state or a system failure [Suh, 2005]. In the combinatorial complexity, the decisions of the past highly affect the system's future complexity in an unexpected manner.

Time-dependent periodic complexity is defined as a complexity that only exists in a finite time period, resulting in a finite and limited number of probable combinations. In this kind of complexity, the uncertainties from the previous period are irrelevant to those of the next period.

To decrease the time-dependent complexity, we may change the time-dependent combinatorial complexity to time-dependent periodic complexity by introducing the notion of functional periodicity, in which the system FRs are reinitialized. In other words, the concept of introducing the functional periodicity is to change a coupled design into a decoupled one followed by controlling the function that leads the system into a chaotic state.

Chapter 4

Literature Review: Complexity Metrics

In this chapter, different complexity metrics are introduced. Most of the studies deploy Shannon's [1949] information theory to describe the system complexity. Some of them use the Axiomatic Design approach [Suh, 1999]. The other group uses heuristic methods to express product, process, or system complexity.

4.1. Information Theory/ Entropy/ Axiomatic Design

In this section, a brief summary of the previous works that used entropy or axiomatic design will be explained. Some of them applied the exact definition of entropy or axiomatic design in their metrics, while the rest used a combination of these theories along with the other definitions of complexity.

Frizelle and Woodcock [1995] proposed a method based on the entropy approach to measure the complexity both in the structural and operational nature. In this method, complexity measurement involves analyzing the product in its manufacturing process and the effect of machines on its production. Frizelle and Woodcock [1995] mentioned that there are two fundamental types of complexity: structural (static) complexity and operational (dynamic) complexity. Static complexity is a time-independent complexity and is because of the impact of product structure on the resources that will produce [Frizelle and Woodcock, 1995]. On the other hand, the dynamic complexity is a time-dependent complexity that deals with the operational behavior of the system, form direct observations of the system. The static complexity introduced by Frizelle and Woodcock is expressed in equation 4.1.

$$H_{\text{Static}}(S) = -\sum_{i=1}^{M}\sum_{j=1}^{N_j} p_{ij} \log_2 p_{ij} \qquad (4.1)$$

where M is the number of resources in S,

N_j is the number of possible states at resource j,

and p_{ij} is probability of resource j being in state i.

Frizelle and Woodcock suggested that the static complexity can be reduced by simplifying product and processes.

The other work that emphasizes on the structural and functional complexity of a design process is by Braha and Maimon [1998]. They introduced the notion of operators and operands to describe a design. To define the structural complexity, they measure the "design size" and "designing effort". In the functional level, they employed the information content to measure complexity.

In measuring the design size, Braha and Maimon considered the total and unique number of operators and operands. Therefore, they measure the size and diversity of information. According to their paper, the design effort is a measure of mental activity to reduce a design problem [Braha and Maimon, 1998]. In their measure, effort is related to the reciprocal of information content.

Kuzgunkaya and ElMaraghy, [2006] introduced a new metric to measure the inherent structural complexity of manufacturing systems based on the complexity of its components: machines, buffers, and Material Handling Systems (MHS). This paper incorporates the quantity of information using the entropy approach as well as the diversity of information. In addition, in their model, they benefit from the manufacturing systems complexity code developed by ElMaraghy [2006].

As it is expressed in equation 4.2, the total complexity of Reconfigurable Manufacturing System (RMS) is a function of:

- Number, type, and state of machines
- Number, type, and the state of buffers
- Number, type, and state of the MHS and its components [Kuzgunkaya and ElMaraghy, 2006]

$$H_{RMS} = w_1 H_M + w_2 H_{Buffer} + w_3 H_{MHS} \quad (4.2)$$

where H_M represents the complexity of machines,

H_{Buffer} is the complexity of buffer,

H_{MHS} represents the complexity of MHS,

and w_i is the relative weight of each element.

In order to measure the machines' complexity, they consider the availability and reliability of the modules installed in the machine as well as the base part. For the buffer, the affecting factors are the state of the buffer, i.e. whether it is empty or not, and the product variant in the system. Finally, for the complexity of MHS, the reliability of the MHS and the number of transformers in the MHS are considered important factors.

Their proposed metric exploits the entropy approach to measure the system structural complexity, and can be used as a comparative tool to select the least complex configuration at the early deign stages.

4.2. Heuristic Complexity Metrics

In the following section, we will describe a brief summary of the previous works using heuristic approaches to create the complexity metrics.

ElMaraghy and Urbanic [2003, 2004] develop metrics that measure the three kinds of complexity in manufacturing systems: product, process, and operational complexity. They consider the effect of the human operator and his perception of the task's complexity in their metric development.

Their model is based on the three elements of complexity: the absolute quantity of information, the diversity of information and the information content. Note that here the information content is different from the one introduced by Suh [1999]: Here, the information content is the measure of relative effort to achieve the required results. They generate a matrix-based model that considers the effect of product, environment, process, and operator on the complexity.

As "absolute quantity of information" may contain redundancy, the information entropy measure is used as a compression factor to define the "information quantity" element. Equation 4.3 illustrates the quantity of information:

$$H = \log_2(N + 1) \tag{4.3}$$

where N is the total quantity of information [ElMaraghy and Urbanic, 2003].

The diversity of information is illustrated in equation 4.4. The diversity of information is defined as the ratio of distinct information to total information.

$$D_R = \frac{n}{N} \tag{4.4}$$

where n is the quantity of distinct information,
and N is the quantity of information [ElMaraghy and Urbanic, 2003].

The quantity and diversity of information in all the three kinds of complexity, i.e. product, process, and operational complexity, are measured from equations 4.3 and 4.4. A matrix-based methodology is used in order to define the information content.

As mentioned before, the product complexity is a function of quantity of information, $H_{product}$, diversity of information, $D_{R, product}$, and the relative effort, $C_{j, product}$. The relative effort is dependent on the effort amount needed to produce the final product; it is independent of the process type and the volume. Figure 4.1 shows the elements that affect the product complexity.

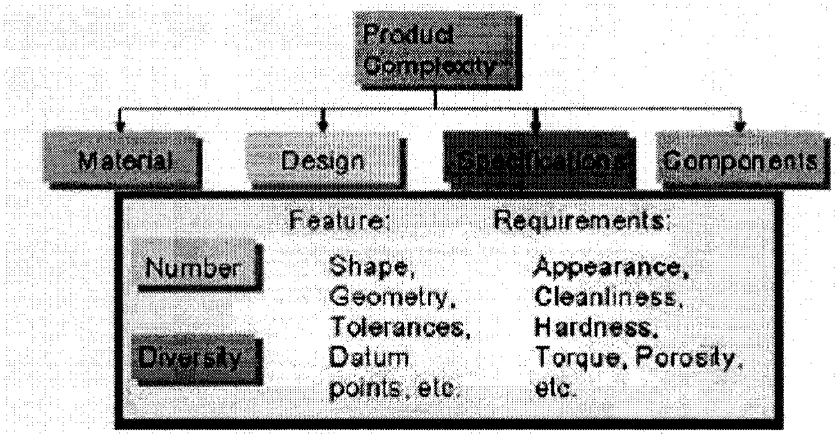


Figure 4.1: Product complexity elements [ElMaraghy and Urbanic, 2003]

For each feature in the product, the effect of physical characteristics such as shape, geometry, tolerances, etc., as well as the specification checks is analyzed. Therefore, a multi-tier ranking system is used where low, medium, and high effort levels correspond to factor levels 0, 0.5, and 1 respectively [ElMaraghy and Urbanic, 2003]. Equation 4.5 represents the product complexity index, $CI_{product}$.

$$CI_{product} = (D_{Rproduct} + C_{j,\,product}) * H_{product} \qquad (4.5)$$

For the process complexity, the same approach in product complexity is exploited. Figure 4.2 shows the process complexity elements.

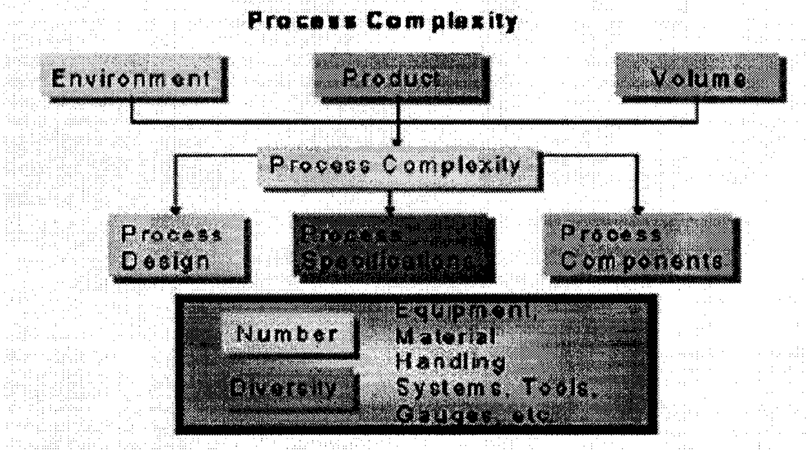


Figure 4.2: Process complexity elements [ElMaraghy and Urbanic, 2003]

Since the manufacturing systems constituents highly affect the process complexity, to define process complexity, the main constituents of the manufacturing process should be identified. An example of machining is used in ElMaraghy and Urbanic's work. The main elements of machining process are in-process features and steps, types of tools, tool holders, spindles, fixtures or set-ups, product orientations, type of machines, and type of gauges [ElMaraghy and Urbanic, 2003].

For each constituent, the process complexity index, pc_x, is defined by equation 4.6.

$$pc_x = (D_{R\ \text{process, x}} + C_{\text{process, x}}) * H_{\text{process, x}} \qquad (4.6)$$

After defining the individual process complexity indices, the process complexity is expressed by equation 4.7.

$$PI_{\text{process}} = \sum pc_x + CI_{\text{product}} \qquad (4.7)$$

They measured the complexity at the operational level, which directly affects the system usability, and is interconnected to the product quality and the process output. [ElMaraghy and Urbanic, 2004]

The product, process, and operational complexity are interrelated to each other. Figure 4.3 illustrates the elements affecting the operational complexity and their inter-relation. The operational complexity is a function of product, process related tasks, and production logistics. [ElMaraghy and Urbanic, 2004]

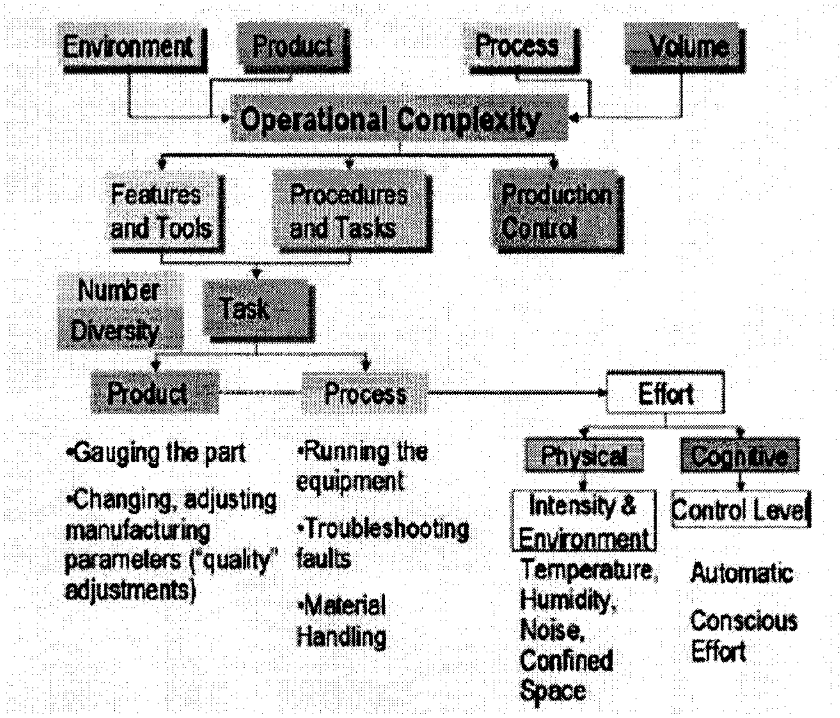


Figure 4.3: Manufacturing complexity cascade [ElMaraghy and Urbanic, 2004]

The relative operational complexity coefficient c_o is related to the product-related and process-related tasks. For each product- and process-related task, the physical and cognitive elements that affect the effort level is determined and ranked according to a multi-tier ranking system. When the product-related and process-related complexity coefficients are defined, the operational complexity index is expressed by equation 4.8.

$$OI = (D_{Rop,product} + C_{o,\,product}) * H_{op,\,product} + (D_{Rop,\,process} + C_{o,\,process}) * H_{op,\,process} \tag{4.8}$$

This heuristic method employs the entropy theory to define complexity metrics in order to measure the complexity of manufacturing systems from the product and process views taking into account the human effect on them. One issue that is not considered in this method is the relative effort of manufacturing of each feature on the production of other features.

According to the literature, the complexity of manufacturing systems, products, processes, and operations is related to the information to be processed in the system.

Increasing size and variety of the system leads to more information; therefore, the system faces an increased complexity.

In their paper, ElMaraghy et al. [2005] introduced a new complexity coding system to classify and code the manufacturing systems components, which are machines, buffers, and MHS. This coding system aims at structural configuration of the manufacturing system and employs the amount and variety of information to measure the complexity. The digits in the code represent the type and general information of each equipment, its controls, programming, and operations. It classifies the different types in each category and assigns a number to each of them. The larger code value indicates more component diversity, requiring more information in order to operate the system. Equation 4.9 represents the complexity index I for individual equipment's subcomponent. As mentioned, the complexity index for individual equipment is related to the amount and diversity of information.

$$I_x = D_R * H \tag{4.9}$$

where $D_R = \frac{n}{N}$ is the diversity of information,

and $H = \log_2(N+1)$ is the quantity of information.

In the second part of this paper, they employ another approach to determine the complexity of machines, buffer, and MHS. Here, they use the availability of each equipment in order to represent the success of the system in achieving the design requirements.

Later on, they apply the proposed methods on three different manufacturing systems: (1) a serial line utilizing dedicated milling machines, (2) a dedicated broaching operations, and (3) a parallel system utilizing four axis CNC machines. Both complexity approaches verify that the dedicated milling machine has the highest structural complexity.

Next, ElMaraghy [2006] proposed a new coding system to classify manufacturing system according to its structure. This code can be captured the structural, time-independent real complexity. The coding system provides a string of digits for machines, buffers, and transporters of the system, where the value of this string is based on the degree of structural, control, programming, and operational complexity of the manufacturing system equipments. Figure 4.4 illustrates the manufacturing systems' characteristics and components.

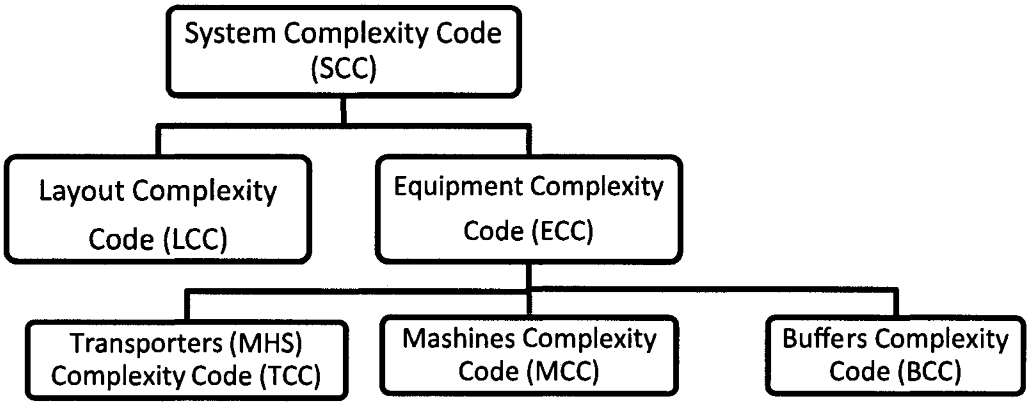


Figure 4.4: Manufacturing systems characteristics and components [ElMaraghy, 2006]

In each category, the coding system assigns digits for their type and general structure, controls, programming, and operations.

In addition to structural complexity of the manufacturing system components, she provides a coding system to capture the layout and the connectivity between the components' complexity.

In fact, this code is a classification code that considers the manufacturing systems equipments, and can be used to compare different manufacturing systems at the design stage according to machines, buffer, and MHS.

In another study, Kim [1999] addresses the manufacturing systems complexity with regard to the increase in product variety. In addition, he claims that the effect of product variety on complexity in the lean manufacturing system is less than in mass production system.

To prove his hypothesis, Kim developed heuristic metrics to measure the system complexity based on the system theory perspective. His proposed metrics are:

- Relationship between system components
    - Number of flow path
    - Number of crossings in the flow paths
    - Total travel distance of a part
    - Number of combinations of products and matching machines

- Elementary system components
    - Number of elementary system components
    - Inventory level

Some information about the effect of each component on the structure of manufacturing system can be gained by using the above-mentioned variables. A drawback of this method is that the importance of each metric is not mentioned.

A number of studies have tried to measure the design effort and time. Bashir and Thomson [2001] mentioned that the product complexity, technical difficulty, experience, and skill of team members, team structure, and use of design-assisted tools influence the effort of design projects. According to Bashir and Thomson [1999], product complexity is a function of the number of functions and the depth of functional tree. The effort of their multivariable model is a function of product complexity and severity of requirements. According to the result, the product complexity has a high impact on the variation of effort.

A summary of the papers mentioned in this chapter is shown in table 4.1.

Author	System Level				Complexity Aspect				
	Product	Process	Operational	System	Entropy	Size	Variety	Coupling/ Relationship	Effort
Frizelle and Woodcock [1995]				*	*				
Kuzgunkaya and ElMaraghy, H.A. [2006]				*	*	*	*		
ElMaraghy and Urbanic [2003, 2004]	*	*	*			*	*		*
ElMaraghy et al. [2005]				*	*	*	*		
ElMaraghy [2006]				*	*	*	*		
Kim [1999]				*		*		*	
Braha and Maimon [1998]	*				*				
Bashir and Thoson [1999, 2001]	*					*			*

Table 4.1: Summary of main papers in the manufacturing complexity

Chapter 5

Literature Review: Complexity Metrics for Manufacturing Assembly

In this chapter, different metrics to measure the assembly complexity are introduced. Some of the studies consider only the effect of product on the assembly complexity, while other studies focus on the assembly process-related complexity.

A typical product can be assembled in different sequences, from which a sequence can be selected as the most appropriate one. There are different ways to evaluate assembly sequences. In his papers, Ben-Arieh [1993, 1994] proposed the assembly operation difficulty as a tool to assess the assembly sequences. In this method, the main parameters that affect the assembly operation's difficulty are identified and assigned fuzzy triangular values, and then weighted. Thereafter, the sequence receives an aggregate value for its difficulty.

In this paper, the main parameters that affect the assembly difficulty are related to the part's geometry and to the mating operation. The geometry-based parameters are the shape of components, required force to assemble components, mating direction, alignment of components, stability of the resultant part and the amount of support required for the assembly operation [Ben-Arieh, 1993, 1994]

The other parameter that affects the assembly operation's difficulty is the mating operation. Different mating operations have different levels of difficulty. For example, welding operations are more difficult to perform compared to simple snapping. The mating operations are divided into six categories: Position contact, Snap contact, Spring contact, Gear contact, Clamp fit and Belt contact.

The factors mentioned by Ben-Arieh can be used to define the amount of effort to perform the assembly task.

In addition, Richardson et al. [2004, 2006] identify the tasks that affect the assembly complexity. They introduced seven tasks based on Hierarchical Task Analysis (HTA) that have impact on cognition in the assembly. These tasks, which are related to the physical characteristics of the assembly object, are selection, symmetrical planes, fastening points, fastenings, components, component groups, and novel assemblies. Assembly steps are another factor that are not related to the physical characteristic of the assembly object, but influence the assembly difficulty. Compared to the DFA method, the identified tasks consider the cognitive aspect of the assembly rather than the physical aspect.

Goldwasser and Motwani [1999] developed complexity measures for two-handed assembly sequences. They introduced a framework to optimize several complexity measures that are related to the assembly cost. The complexity measures that result in lower assembly cost are:

- Fewer number of directions
- Fewest reorientations
- Fewest number of non-linear steps
- Minimum depth of an assembly sequence, and
- Fewest numbers of removed parts

In their method, they just considered the general factors in the assembly-sequence planning. In fact, factors such as the effect of assembly sequence on tools, fixtures, and the stability of part after insertion are not considered.

Rodriguez-Toro et al. [2002] aim at presenting a method to optimize balance between manufacturing capabilities and assembly operations in a product design. They believe that the design processes supported by CAD tools focus on the components of the product rather than the product itself. As a result, companies face redesign and rework in their assembly process.

According to Rodriguez-Toro et al. [2002, 2003], a large portion of the product cost are determined at the design stage and much of this cost incurred during assembly [Rodriguez-Toro et al., 2002]. Therefore, it is important to take into account the assembly considerations at the product designs stage in order to reduce the subsequent problems.

Design For Assembly (DFA) method is a significant tool that helps reduce the part count, while improving the product quality and reducing a number of assembly problems. However, DFA focuses on the shape analysis of each component. In this method, some parts are eliminated or integrated to reduce the assembly difficulty and optimize the assembly time and efficiency. As a result, components that are more complex are created and in some cases, insertion processes that are more complex are required. Therefore, in order to evaluate the product with respect to all these considerations, it is necessary to take into account the complexity in different stages of manufacturing and assembly.

In order to find the optimum balance for a product design, between manufacturing capabilities and assembly operations, they considered the notion of complexity in two levels [Rodriguez-Toro et al., 2002]. Figure 5.1 shows the layout of these two levels.

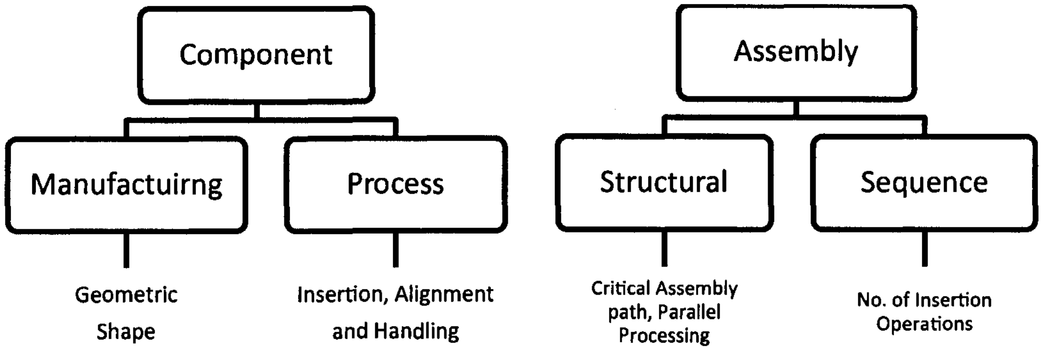


Figure 5.1: Different complexity factors considered at a particular level [Rodriguez-Toro et al., 2002]

Then, the major factors that affected each kind of complexity were presented. The manufacturing complexity, C_m, is a function of part geometry, material, tooling, process, and batch size. The process complexity, C_p, is a function of component geometry, and should address the difficulty of handling, alignment, and insertion operations of each individual component.

In the assembly complexity level, the structural complexity, C_{st}, deals with the configuration of a product in terms of its product structure. In fact, the structural breakdown can have a significant impact on the ease of assembly, but more particularly on the critical assembly path [Rodriguez-Toro et al., 2002]. Structural complexity is a function of number of components, levels in hierarchy, subassemblies, branches, etc. Finally, sequence complexity, C_s, is directly related to the number of assembly operations.

The total design complexity is considered as a combination of the different types of complexity. Equation 5.1 shows the total complexity.

$$C_t = \frac{w_1 C_m + w_2 C_p + w_3 C_{st} + w_4 C_s}{w_1 + w_2 + w_3 + w_4} \tag{5.1}$$

In addition, they mention the relation between component complexity, cost and part count. Figure 5.2 illustrates the influence of part count and component complexity on cost.

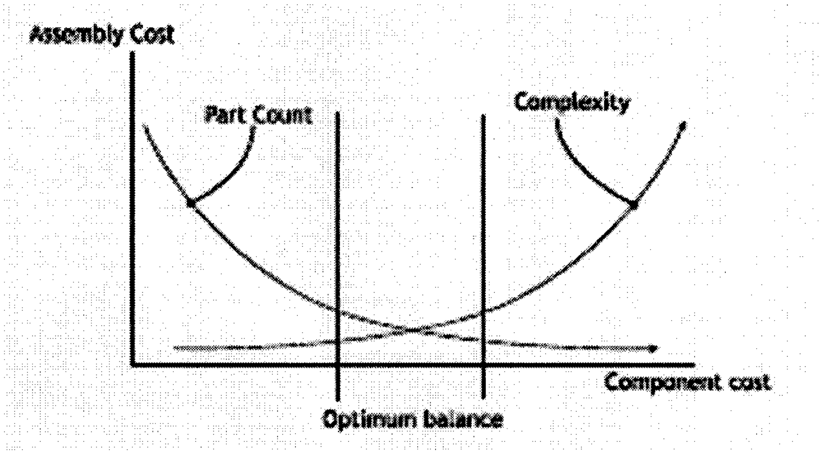


Figure 5.2: Influence of component complexity and part count on cost [Rodriguez-Toro et al., 2002]

According to the figure, reducing part count may result in parts that are more complex thus increasing the manufacturing cost. On the other hand, the assembly operation complexity will be reduced because of the fewer number of parts. From the complexity view, the higher the complexity, the more manufacturing and assembly cost.

Later on, they analyzed the proposed complexity at different levels from the structural and dynamic views. The new classification is shown in figure 5.3.

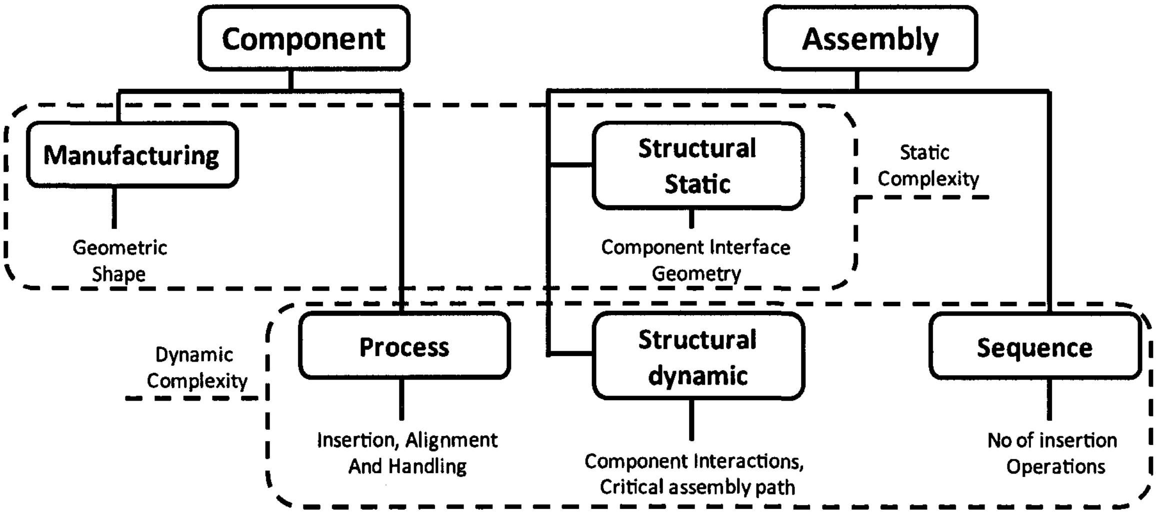


Figure 5.3: Complexity taxonomy for proactive DFA [Rodriguez-Toro et al., 2004]

In this study, Rodriguez-Toro et al. mentioned the sequence complexity mainly addresses the prediction of the most convenient path [Rodriguez-Toto et al., 2004]. In the structural complexity, they considered the interaction between components, tolerances, geometry of interfaces, and kinematic constraints to develop the assigned weightings.

In some studies, the complexity of assembly is measured by the time required to perform the assembly. Braha and Maimon [1998] suggested that the structural complexity of assembly can be measured by the information associated with the assembly interfaces. The higher the number of features in the assembly interfaces, the more assembly time. They consider the parts as operands and the interfaces as operators. Therefore, in their proposed metric both the number of assembly operations and the number of parts are included.

One of the main issues in defining the assembly complexity is the effect of product varieties on the complexity of manufacturing and assembly. Fujimoto et al. [2003] address the product and process-based complexity while using Assembly Process Design (APD) for entire product. APD is a collection of a series of activities that include Product Structure Planning (PSP), Basic Assembly Process Planning (BAPP), and Assembly Technology Planning (ATP). To define complexity at each stage, the notion of information entropy is used.

In the PSP stage, the product specifications and customer requirements are translated to the functional requirements. The exact and detailed information about the physical properties, such as components geometry, their features, and specific manufacturing information is not available. The available information are the number of varieties, parts, and the assembly sequence. To describe the complexity at this stage, the information entropy was used. Equation 5.2 illustrates the complexity at the PSP stage.

$$C = -\sum_i w_i \sum_j c_{ij} \log_2 c_{ij} \qquad (5.2)$$

where C is the complexity,

c_{ij} is the probability of how much variety j satisfies function i,

and w_{ij} is the relative importance of having variety j in the i^{th} function. [Fujimoto et al., 2003]

In the BAPP stage, in addition to the information gained in the PSP stage, the information such as component geometry and mating features are defined. In this stage, the complexity is due to the varieties flowing through the station and the varieties added in the station. In this stage, the approaches that can be taken into account to reduce the complexity are:

- Reduce the differences in number of parts,
- Limit the direction of change,
- Delay the product differentiation

In the ATP stage, detailed design with precise dimensions, surface finish, fits, tolerances, process planning for manufacturing the components and the assembly design are performed [Fujimoto et al., 2003]. In this stage, the impact of variety is on the uncertainty dealing with conveying the base part, material supply, gripping, and positioning. Similar to BAPP, the complexity is because of the varieties flowing through the station and the varieties added in the station. In this stage, the approaches that can be taken into account to reduce the complexity are:

- Localize standardization of the part
- Process restructuring – postponement of operation
- Introduce new technologies.

In another study, Martin and Ishii [1997] develop a method to increase variety while decreasing the variety cost. Their proposed indices capture the amount of variety within a design. These indices are Commonality Index, Differentiation Index and Setup Index.

Commonality Index (CI) measures the amount of using standard parts in a design. A higher amount of CI is desirable, as it indicates that the different varieties within the product family are being achieved with fewer unique parts [Martin and Ishii, 1997]. Equation 5.3 illustrates the Commonality Index.

$$\mathrm{CI}=\frac{u-\max p_j}{\sum_{j=1}^{Vn} p_j-\max p_j}\ ,\ 0<\mathrm{CI}\leq 1 \tag{5.3}$$

where u is the number of unique parts,

p_j is the number of parts in model j ,and

Vn is the final number of offered varieties.

Differentiation Index (DI) deals with differentiation in the design flow. By using DI, the work in process and assembly complexity can be decreased. Equation 5.4 illustrates the Commonality Index.

$$DI=\frac{\sum_{i=1}^{n} d_i v_i a_i}{nd1\ vn\ \sum_{i=1}^{n} a_i} \quad , 0< DI\leq 1 \tag{5.4}$$

where v_i is the number of different products existing at process i,

n is the number of processes,

Vn is the final number of offered varieties,

d_i is the average throughput time form process i to sale,

d1 is the average throughput time form beginning of production to sale, and a_i is the value added at process i [Martin and Ishii, 1997]

As it can be inferred from the equation, the lowest amount of DI is desirable.

Setup Index (SI) indirectly measures the effect of the switchover cost on the overall cost of the product. The setup index is illustrated by equation 5.5.

$$SI=\frac{\sum_{i=1}^{n} vi\ ci}{\sum_{j=1}^{vn} C_j} \quad , 0< SI\leq 1 \tag{5.5}$$

where vi is the number of different products existing at process i,

ci is the cost of set-up at process i,

and C_i is the total cost (material, labor and overhead) of jth product [Martin and Ishii., 1997]

A similar work to Martin and Ishii. [1997] is presented by Prasad [1998]. First of all, he mentioned five sources of complexity in a system producing different varieties, which are:

- Inherent product complexity
- Process complexity
- Team cooperation and communication complexity
- Computer and network complexity, and
- A maze of specifications including international regulations and safety [Prasad, 1998]

To reduce the product and process complexity, he proposed to apply the breakdown structure, in a way that any inherent concurrency can be eliminated. As a result, tasks can be run in parallel. The problem in this method is that higher number of tasks in decomposition results in more communication and cooperation between performing tasks. The optimum level is the one that maintains a balance between product and process complexity on one side and communication complexity on the other side.

It has been shown that complexity in the assembly operation has a strong correlation with the occurrence of defects [Shibata et al., 2003]. Here, metrics for complexity are provided using assembly time estimation and ease-of-assembly rating.

The first metric is a process-based factor that uses a "time standard" defined for a set of assembly tasks. Here, the main idea is to find the difference between the time of each assembly job element and the minimum assembly time at that station, which does not contribute to defect. Then, the relation between process-based complexity factor and defect rate is shown in a logarithmic format. The higher the complexity factor, the higher the defect rate.

The second metric is a design-based factor that uses the DFA method to evaluate the assembly. This tool helps the designer to find the sources of defect that are not captured by the process-based complexity factor. This complexity factor is based on the evaluation score from the Design for Assembly Cost-Effectiveness (DAC) method, which was developed by Sony Corp. in Japan [Shibata et al., 2003]. In this method, the ease-of-assembly is calculated based on three factors: (1) part characteristics: the difficulty of handling and orienting a part; (2) assembly characteristics: the difficulty of assembling a part; (3) base part assembly characteristics: the difficulty of assembling a part due to the features of the base part. Then, the total ease-of-assembly is calculated for all of the parts. The design-based complexity factor is the reciprocal of the total ease-of-assembly.

Considering the design-based and process-based complexity factors together gives an insight to predict the assembly defects and further provides a guideline to improve the original design.

A summary of the papers mentioned in this chapter is shown in table 5.1.

Author	Complexity FactorSystem			Complexity Aspect				
	Component	Fastenings	Process	Entropy	Size	Variety	Coupling/ Relationship	Effort/ Difficulty
Ben-Arieh [1993, 1994]	*	*						*
Richardson [2004]	*	*						*
Goldwasser [1999]			*					
Rodriguez-Toro et al. [2002, 2003, 2004]	*		*					
Braha and Maimon [1998]	*		*					
Fujimoto et al. [2004]	*		*	*				
Martin et al. [1997]	*		*		*	*		
Prasad [1998]	*		*		*		*	
Shibata et al. [2003]	*		*					*

Table 5.1: Summary of main papers in the assembly complexity

Chapter 6

Proposed Model: Complexity Metric for Manufacturing Assembly

In this chapter, the factors that affect the assembly complexity are described and analyzed. Then, a matrix-based model is developed to measure the assembly complexity based on the identified factors. In this model, the concepts introduced by ElMaraghy and Urbanic [2003, 2004], and the Designers' Sandpit project are used. The former presents heuristic metrics to measure product, process, and operational complexity for the manufacturing systems. The later presents an introduction to the concept of product complexity in support of assembly-oriented design, in which complexity is divided into two levels: component and assembly level. Finally, the model is applied on some case studies and the results are compared according to DFA analysis.

6.1. Problem Statement

Complexity of assembly systems results in increase in assembly difficulty and therefore highly affects the assembly cost and time. According to the DFA methods, the assembly time and cost is a function of part count. A higher part count indicates that more time is needed to perform the assembly, resulting in a more costly assembly.

It is generally believed that by decreasing the number of parts, we face complicated parts that need complicated manufacturing processes, resulting in an increase in manufacturing complexity and cost of each part. On the other hand, it results in lower assembly cost and complexity, as we have fewer part counts.

Conversely, an increase in part count results in less complex manufacturing and lower cost in parts manufacturing, while increasing the assembly complexity and cost.

DFA aims at simplifying the assembly by reducing the part number. Therefore, we anticipate that the complexity of assembly should be decreased by applying DFA on different case studies. In this chapter, the assembly and manufacturing complexity metrics will be applied on a case study to examine the effect of DFA method on the complexity of product assembly and manufacturing. However, the focus of this research is to model the assembly complexity metric and evaluate the result by DFA results. Figure 6.1 illustrates the impact of changes in part count on assembly complexity and assembly cost.

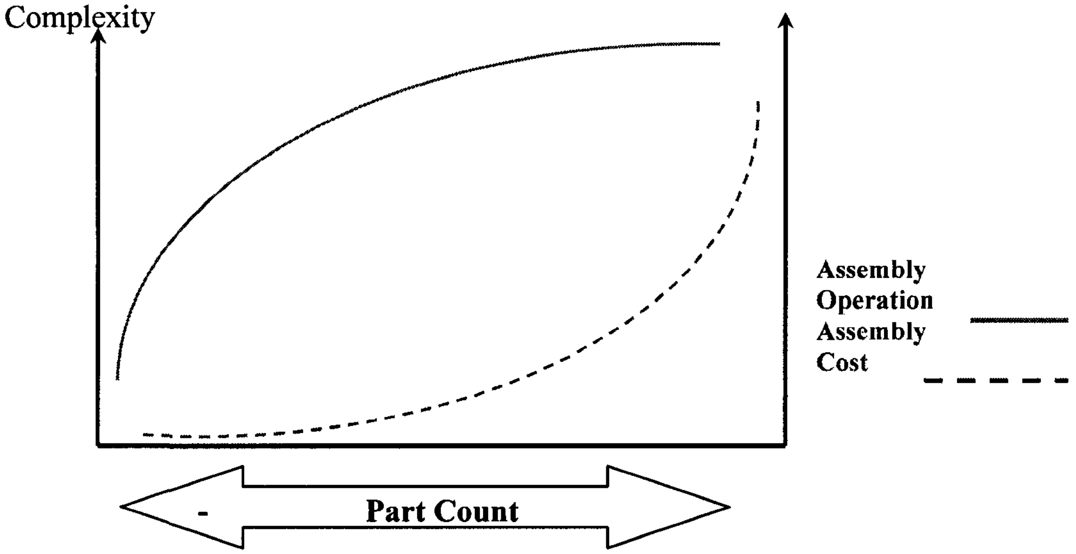


Figure 6.1: Complexity and cost analysis according to part number

Figure 6.2 and 6.3 illustrate the IDEF0 for the first and second layer of measuring assembly complexity. Assembly complexity is a function of product and process-related factors.

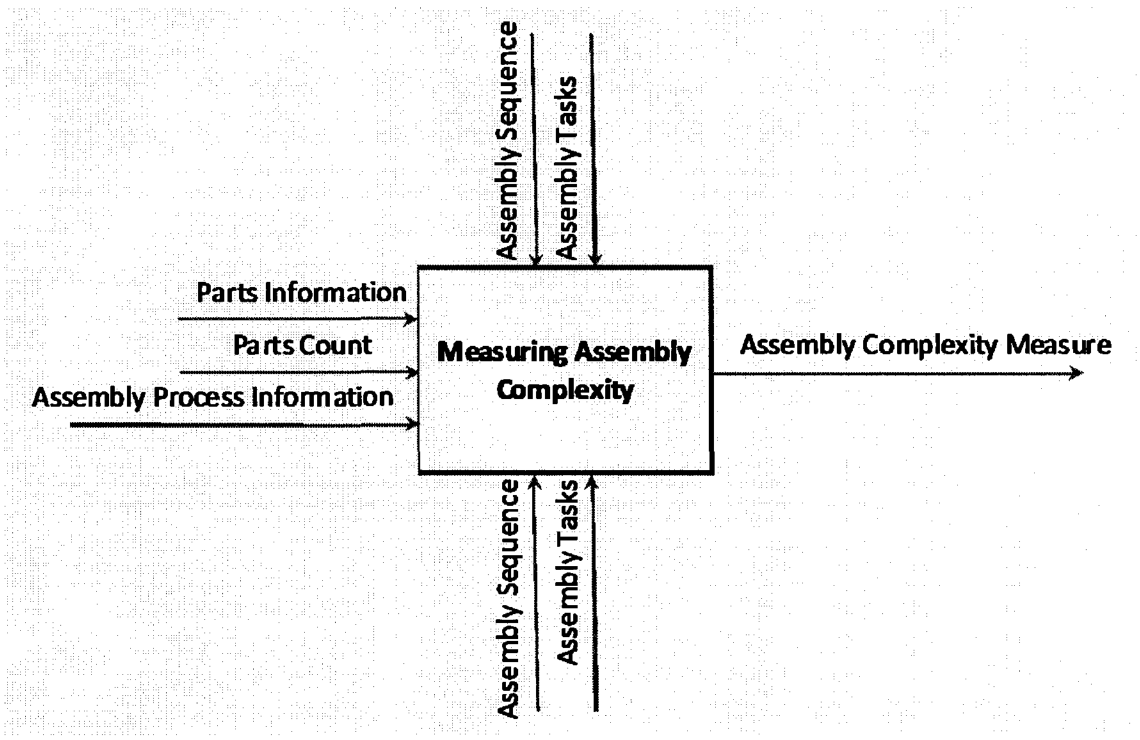


Figure 6.2: IDEF0- First layer, measuring assembly complexity (Physical domain)

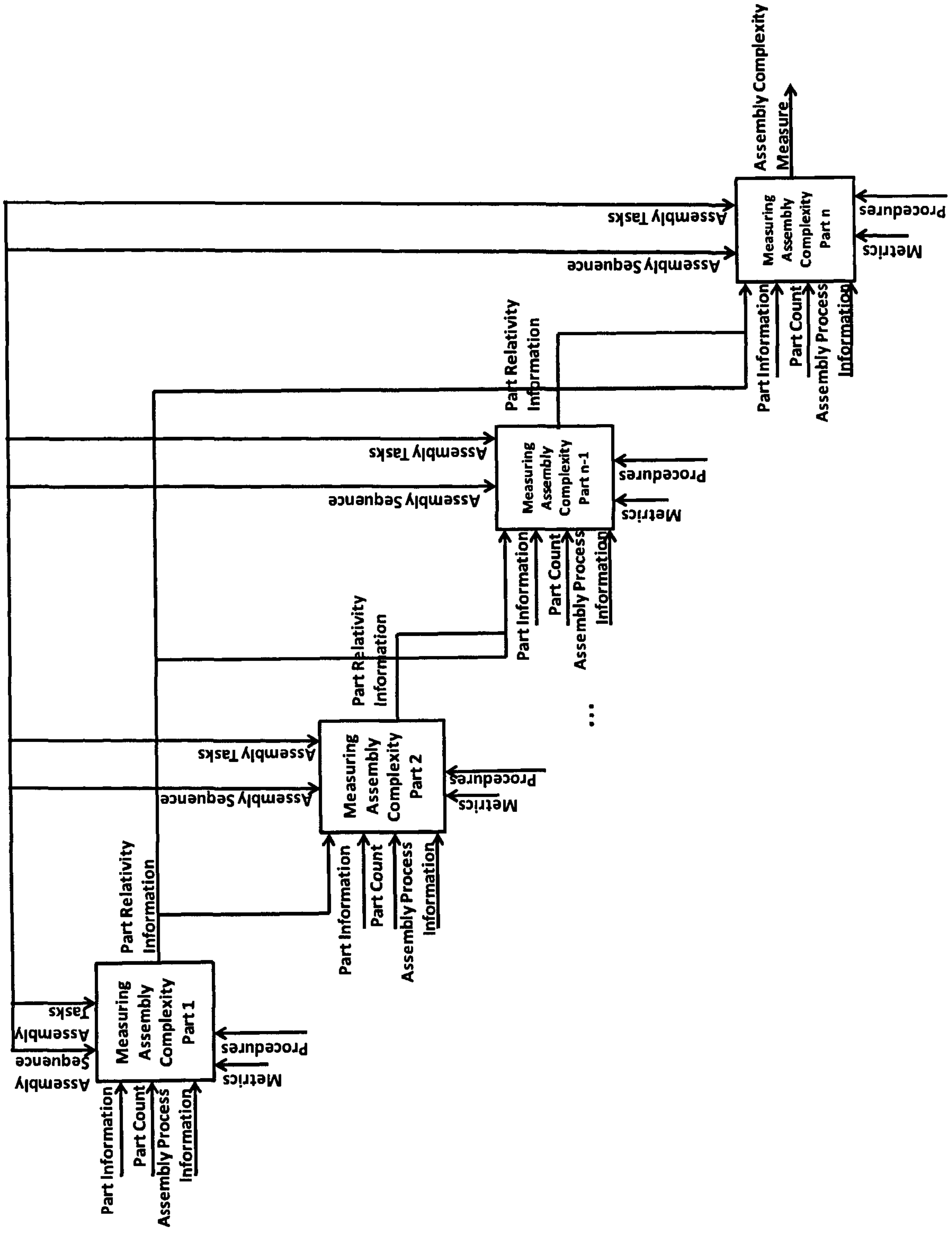


Figure 6.3: IDEF0- Second Layer, measuring assembly complexity (Physical domain)

6.2. Assembly Complexity

Manufacturing complexity is divided into three types: component complexity, process complexity, and operational complexity. Components are important factors affecting the complexity of the other two types. In addition, components are one of the main factors affecting the assembly complexity. The following diagram, figure 6.4, shows the assembly complexity pyramid.

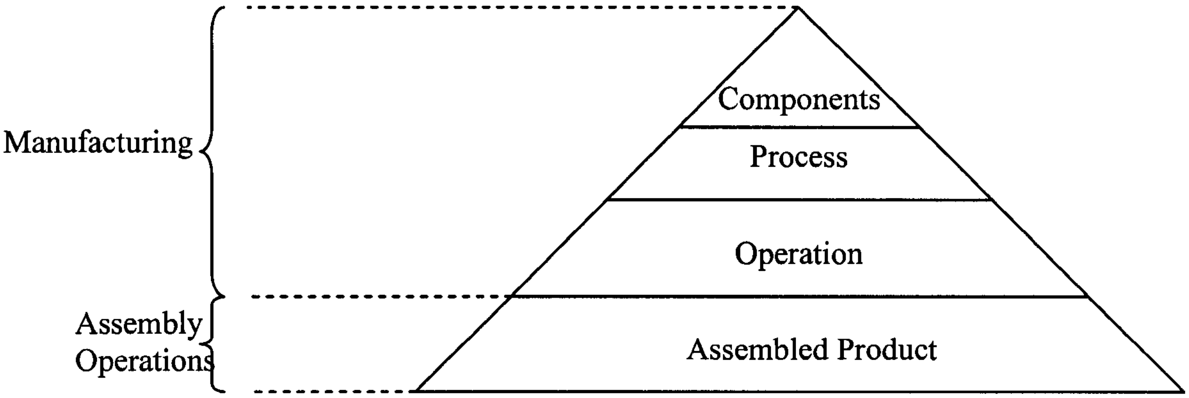


Figure 6.4: Assembly complexity pyramid

Manufacturing complexity is well defined by ElMaraghy and Urbanic [2003, 2004] through product, process, and operational complexity.

In their approach, ElMaraghy and Urbanic [2003] suggested that complexity is a function of three elements: quantity of information, diversity of information, and the information content, as in figure 6.5.

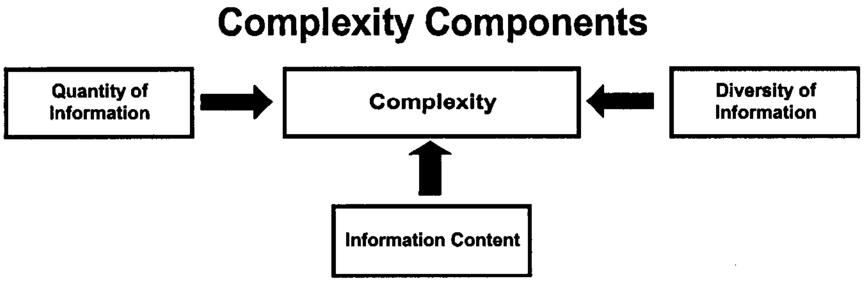


Figure 6.5: Elements of complexity [ElMaraghy and Urbanic, 2003]

The same elements will be considered in the proposed model. However, the coupling between components or features is an important factor in measuring complexity, which will be included in the proposed model.

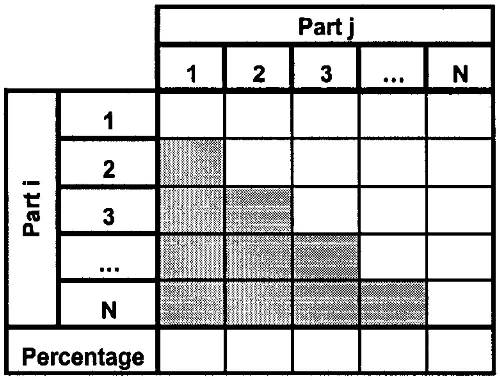
To measure complexity, it is essential to define the main tasks related to the selected operation. Typical assembly consists of four main tasks: selection of the component, its handling, alignment, and insertion. These four tasks will be considered in measuring the assembly complexity.

6.2.1. Component Coupling

Component coupling is an important element that results in more complexity in assembly. In other words, coupling is the effort added to insertion of a part by assembling the other parts.

To define the coupling between components, it is important to measure the dependence between assembling each pair of components. Dependence chart, illustrated in figure 6.6, is generated to measure the dependence between components. If part i affects the assembly processes of its consequent part(s) j, number 1 will be assigned for the interrelation matrix. If not, 0 will be assigned.

To define the coupling of each part, it is suggested to measure the percentage of the other components' effects on part j. In other words, the percentage of 1s in each column shows the amount of coupling of that part with other parts.



		Part j				
		1	2	3	...	N
Part i	1					
	2	▨				
	3	▨	▨			
	...	▨	▨	▨		
	N	▨	▨	▨	▨	
Percentage						

Figure 6.6: Dependence chart

This percentage shows the effort associated with manipulating the part because of the other parts. Therefore, the coupling complexity is considered as an element that physically influences the assembly operation.

6.3. Primary Proposed Model

Quantity of information, diversity of information, and the information content are three factors that affect assembly complexity.

In the presented model, total number of parts and fastenings shows the Quantity of Information. The "absolute quantity of information" may contain redundancy. Therefore, the information entropy measure is used as a compression factor to define the "information quantity" element, as illustrated in equation 6.1:

$$H_{assy}= Log_2\,(N+1) \qquad (6.1)$$

where N is the summation of the total number of parts/sub-assemblies and fastenings.

Diversity of information is defined by the parts/subassemblies/fastenings diversity ratio, which is the ratio of distinct parts and fastenings counts to the total number of parts/sub-assemblies and fastenings. Equation 6.2 shows diversity:

$$D_{assy} = n/N \tag{6.2}$$

where n is the summation of distinct number of parts/sub-assemblies and distinct number of fastenings,

and N is the summation of the total number of parts/sub-assemblies and total number of fastening points.

The information content is defined as an amount of effort to accomplish the assembly task, not a measure of probability of success. Therefore, in assembly, the information content is the effort to perform the assembly operation tasks: selection, handling, alignment, and insertion.

6.3.1. Effort Measurement

The effort associated with each task is a function of physical or cognitive element that influences the task.

As we mentioned earlier, there are three main tasks in each station: handling, alignment, and insertion. However, we need to correctly select the part to manipulate. Therefore, the first task is to select the appropriate part/sub-assembly.

As a result, the complexity of assembling each component is a function of:

- Part Selection
- Handling
- Alignment
- Insertion

6.3.1.1. Physical Elements

The physical elements that influence complexity of handling, alignment, and insertion are part geometry, its surface specifications, tools or fixtures used to manipulate the part and the added effort because of the assembly of previous parts.

Part Geometry

Complexity is a function of the part size: in the case that it is too small or too large, more effort is needed to handle, align, and insert that part. In some cases, the part cannot be moved because of its large size requiring the operator to move around the part to assemble other components.

Surface Specifications

If the parts are slippery or have sharp edges, it is more complex to do the assembly task. Thus, part surface specification is important to define the effort of manipulating the part.

Tools/Fixtures

If any tool or fixture is needed in order to handle, align, and insert the part, the task will need more effort to be carried out.

Relativity

Finally, if the previously assembled components affect the assembly of a part, the manipulation of that part will be more complex. The relativity amount can be achieved using dependence chart.

Assessing the physical elements' effort is based on a scoring system of 0, 0.5, and 1, which corresponds to no or low/medium/high effort level.

6.3.1.2. Cognitive Elements

The cognitive elements that influence the complexity of handling, alignment, and insertion are part symmetry, fastening points, and procedures.

Part Symmetry

The more symmetric a product is, the easier the assembly operation becomes. The notion of α-symmetry and β-symmetry is used to evaluate the cognitive effort of performing assembly. According to the DFA method, α-symmetry and β-symmetry are defined as:

α-symmetry: is a rotational symmetry of a part about an axis perpendicular to the axis of insertion.

β-symmetry: is a rotational symmetry of a part about its axis of insertion.

The larger amounts for α-symmetry and β-symmetry mean that there are less symmetrical planes; therefore, more rotations are needed to appropriately manipulate the part.

Table 6.1 shows the task effort level based on α-symmetry and β-symmetry.

α-symmetry	0	72	90	120	180	360
Effort Level	0	0.2	0.4	0.6	0.8	1

β-symmetry	0	72	90	120	180	360
Effort Level	0	0.2	0.4	0.6	0.8	1

Table 6.1: Effort level based on symmetry

α-symmetry equal to 360 means that the part can be manipulates only in one direction; therefore, more effort is needed to define the correct direction for the handling, alignment, and insertion tasks. The same approach applies to β-symmetry.

Fastening Points

According to Richardson et al. [2004], the number of fastenings may add to the complexity, increasing the connections between parts; a high number of fastening points leads to a high cognitive load.

A scoring system that ranges from 0 to 1, with 0 to be the least effort and 1 the most, will be used to demonstrate the effect of fastenings points on effort.

The chart shown in Figure 6.7 will be used to determine the complexity associated with the physical and cognitive elements of handling, alignment, and insertion.

	Physical Elements						Cognitive Elements						Task Effort
	Geometry	Surface specificatiosn	Tools/ fixtures	parts relativity	Sum	Average	α-symmetry	β-symmetry	Fastenings	Procedures	Sum	Average	
Handling													
Alignment													
Insertion													

Figure 6.7: Effort chart for assembly operations

6.3.1.3. Selection

Selection of the parts/subassemblies/fastenings is related to the number of parts/subassemblies/fastenings and the way they are supplied. For example, if the parts are in separate packaging, it is less complex to identify parts than when they are all piled.

To define the effect of parts' diversity, the probability of picking the correct part is used. Figure 6.8 shows j part types to be assembled and the number of parts in each category (nj) at stations i. Total number of parts (N) equals to $\sum_j n_j$.

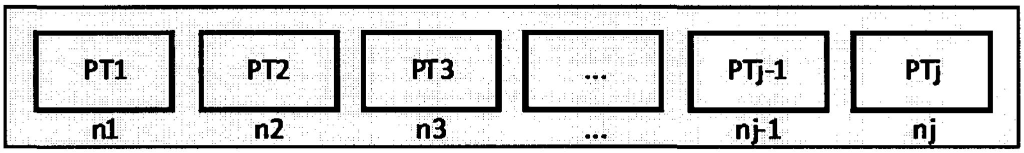


Figure 6.8: Available parts at station i, based on different part types

The probability of selecting a part of the first kind is shown in equation 6.3:

$$P1 = n1/N; \text{ if the parts are piled} \tag{6.3}$$

$$P1 = 1/j; \text{ if the parts are separated according to their type}$$

As it can be inferred from the above formula, the first part has the least probability (p1) to be chosen; therefore, its appropriate selection is the most cognitively complex.

Selection of parts is a time-dependent reduced combinatorial complexity. As the selection task continues, the probability of selecting the correct part increases and its cognitive effort decreases. Therefore, we can measure the cognitive effort of selection of part i by equation 6.4:

$$Eff_{selection\,,i} = 1 - p_i \tag{6.4}$$

This formula gives zero for the effort of selection of the last part, which is reasonable, as there is not any other part left to be selected.

To determine the complexity of assembly operations, we introduce the assembly operation's relative effort chart in figure 6.9.

Part	No.	Persentage	Selection	Handling	Alignment	Insertion	Sum	Average	Part Share
							Overall relative effort		

Figure 6.9: Assembly operation's relative effort chart

The procedure of filling up the assembly operation's relative effort chart is as follows:

- First, define the parts, their count, and percentage
- Define relativity amount using the dependence chart
- Calculate the effort for part handling, alignment, and insertion (using the effort chart, figure 6.7)
- Define the insertion effort
- Finally, using assembly operation's relative effort chart, figure 6.9, calculate the average effort of each part and its share in the total effort. The part share equals to its percentage multiplied by its average effort.

Since the quantity of information, diversity, and overall relative effort is measured, the assembly complexity can be determined from equation 6.5.

$$C_{assy} = (D_{assy} + REff) * H_{assy} \qquad (6.5)$$

where, REff represents the overall relative effort.

In the following section, the proposed method is applied on the pneumatic piston subassembly before and after implementing DFA method. In addition, the method described by ElMaraghy and Urbanic [2003] is applied to measure the manufacturing complexity.

6.4. Illustration Example- Pneumatic Piston Sub-assembly (Before/After DFA)

In this section, a pneumatic piston sub-assembly is used to measure the assembly complexity. Figure 6.10 illustrates Example 1- Pneumatic Piston sub-assembly before applying DFA method.

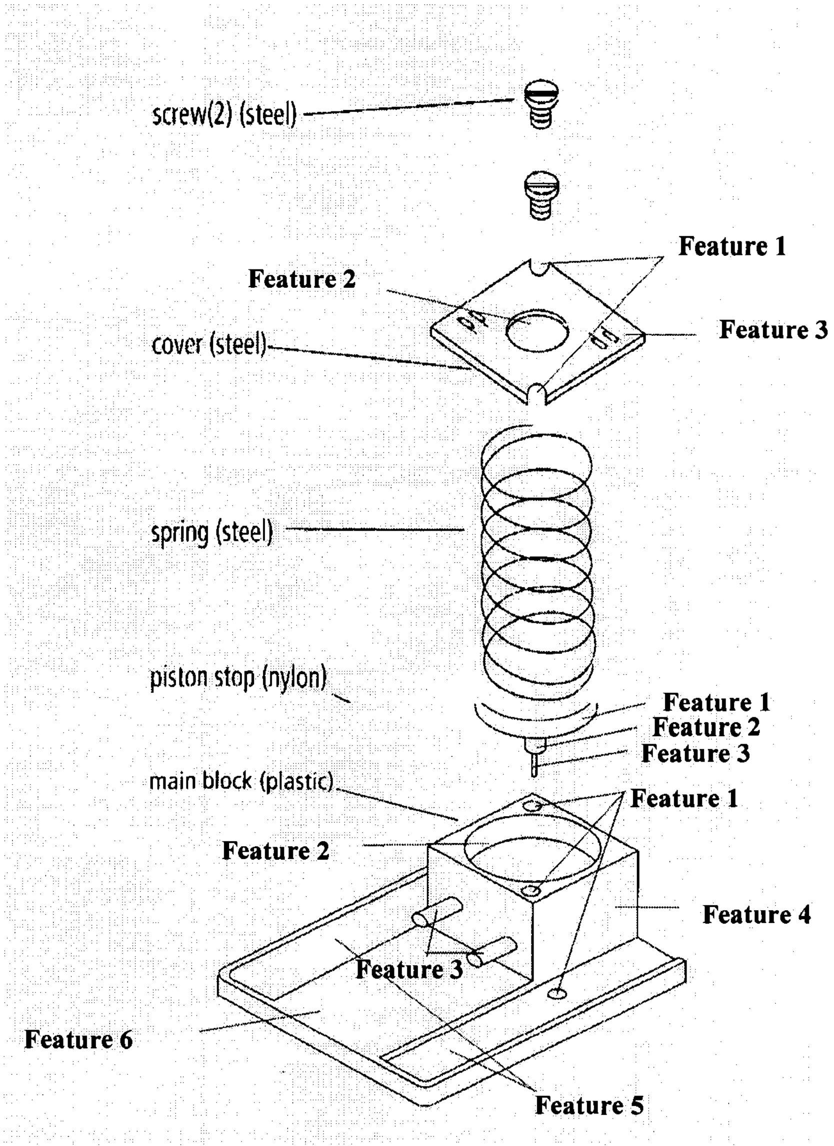


Figure 6.10: Example 1- Pneumatic piston sub-assembly (Before DFA) [Boothroyd and Dewhurst, 1987]

The product, process, and operational complexity are measured to show the manufacturing complexity, and next the assembly complexity is measured for Pneumatic piston sub-assembly using the proposed model.

The summary of product, process, and operational complexity for the pneumatic piston assembly before implementing DFA method is shown in table 6.2.

	Main Block	**Piston Stop**	**Cover**
$\mathbf{CI_{product}}$	4.58	5.48	4.17
$\mathbf{\Sigma Pc_x}$	6.77	6.25	5.00
$\mathbf{PI_{process}}$	11.35	11.73	9.17
$\mathbf{PI_{operation}}$	5.30	6.40	7.99
$\mathbf{C_{assy}}$	3.26		

Table 6.2: Manufacturing and assembly complexity before applying DFA method

Figure 6.11 illustrates Example 2- Pneumatic Piston sub-assembly after applying DFA method.

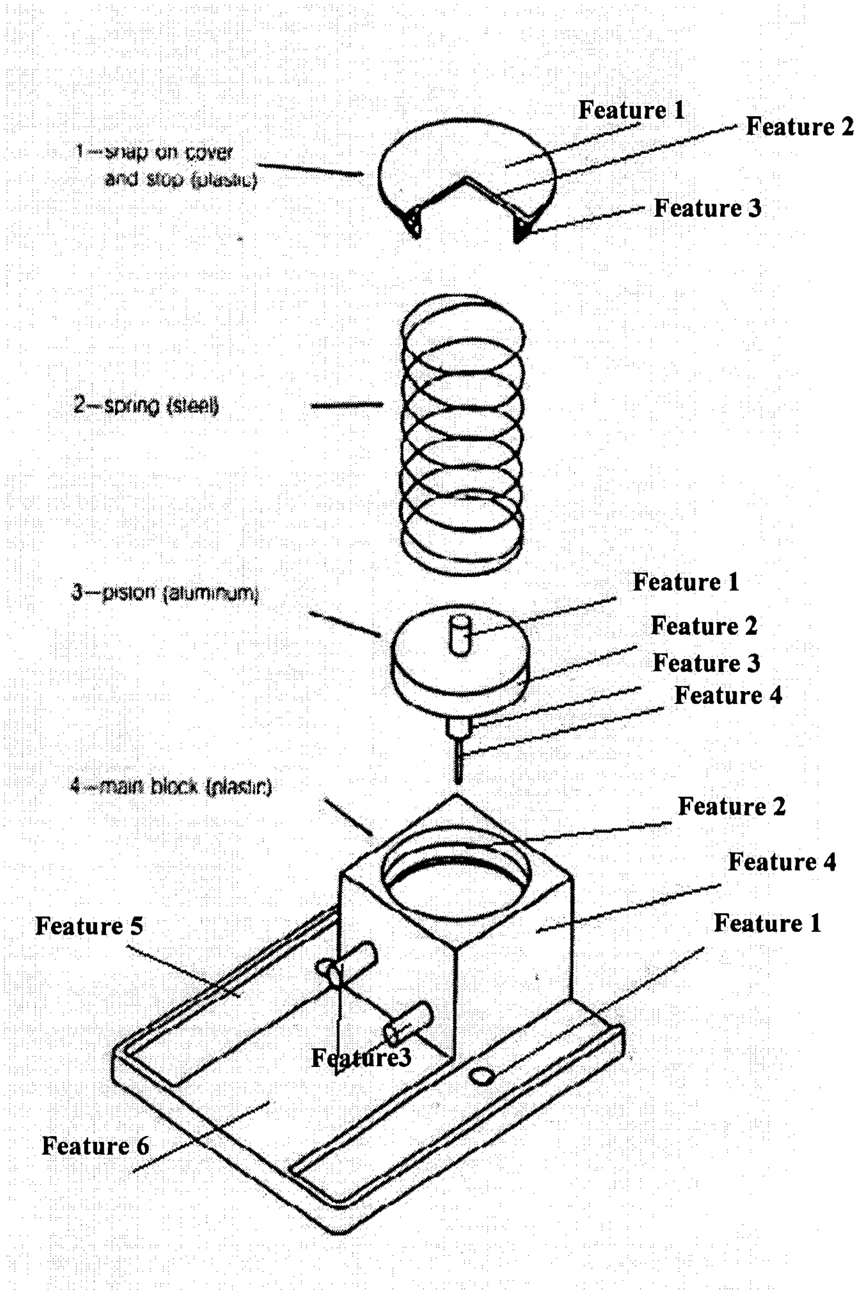


Figure 6.11: Example 2- Pneumatic piston sub-assembly (After DFA), [Boothroyd and Dewhurst, 1987]

After applying the DFA method on the pneumatic piston subassembly example, the product, process, and operational complexity, as well as the assembly complexity are calculated.

Table 6.3 shows the summary of manufacturing and assembly complexity for this example.

	Main Block	**Piston Stop**	**Cover**
$CI_{product}$	4.94	6.09	5.40
ΣPc_x	6.77	6.17	6.38
$PI_{process}$	11.71	12.26	11.78
$PI_{operation}$	5.30	6.08	6.81
C_{assy}	2.88		

Table 6.3: Manufacturing and assembly complexity after applying DFA method

6.5. DFA/ Complexity Comparison

Comparing the results shows that the manufacturing complexity including product, process, and operational complexity has an increasing trend after applying DFA method: As the part numbers were reduced, the parts became more complex, and their manufacturing difficulty was increased.

Figure 6.12 shows the increased trend in each manufacturing complexity element.

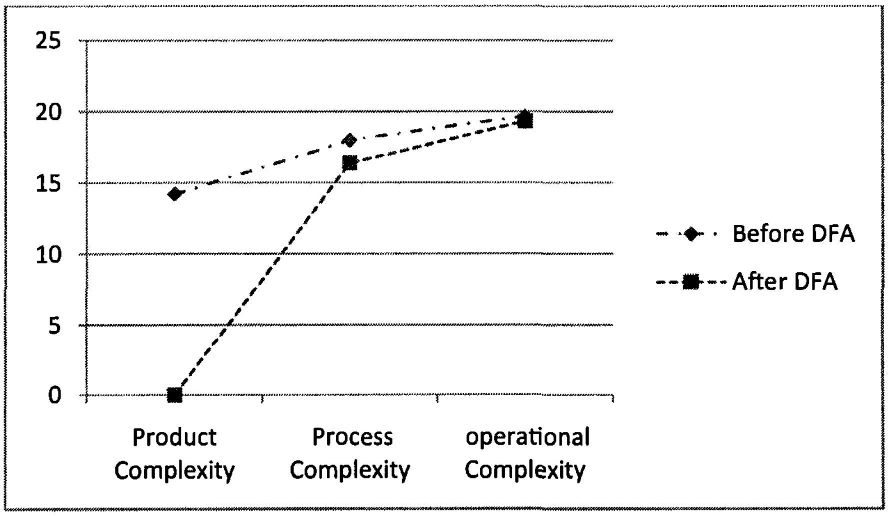


Figure 6.12: Comparison of product, process, and operational complexity (After/Before DFA)

The operational complexity of the piston cover is reduced after applying DFA method. This can be a result of changing the manufacturing process of the cover. Before applying assembly, the cover is made of metal whereas after assembly it is made of plastic.

Figure 6.13 illustrates the changes in the manufacturing and assembly complexity before and after applying DFA.

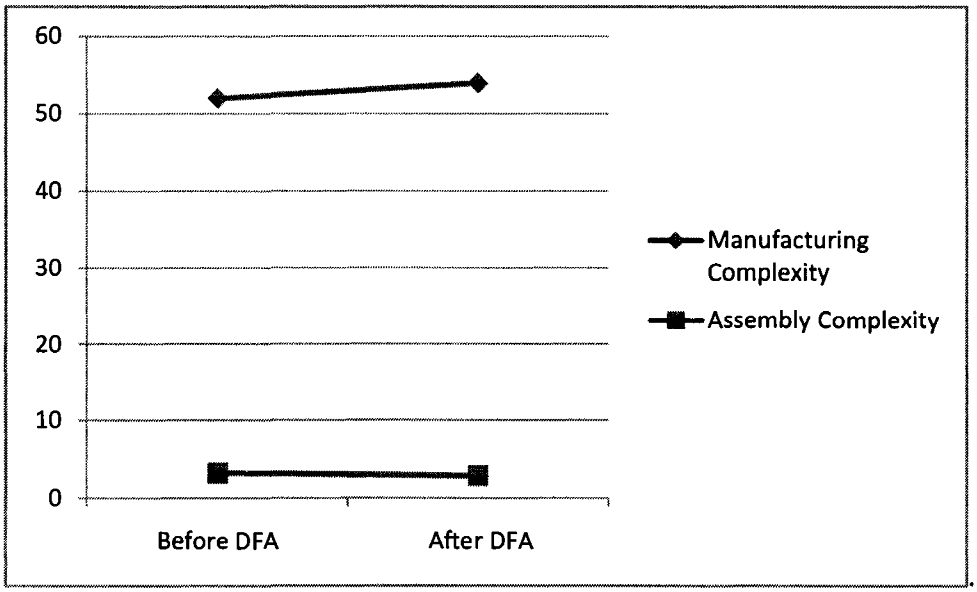


Figure 6.13: Comparison of manufacturing and assembly complexity (After/Before DFA)

This chart shows that the total manufacturing complexity has increased by reducing part count whereas the assembly complexity has decreased, which is in accordance with the assumptions.

6.6. Improved Model- Based on Components and Assembly Process

In-depth analysis of the assembly complexity provides that the component is not the only factor that affects assembly complexity. In fact, the assembly complexity is also affected by the decisions made in the phase of determining the assembly sequence. The required effort to assemble a component is a function of the assembly direction, assembly accessibility, the part situation during assembly, and the needed force to assemble the component. Hence, the assembly complexity model is improved; so that both the components and assembly process effects on effort will be considered.

In the improved model, the "information quantity" and "information diversity" is the same as the one presented in the primary model.

The total number of parts and fastenings represent the quantity of Information. As discussed by ElMaraghy and Urbanic [2003], the "absolute quantity of information" may contain redundancy. Therefore, the information entropy measure is used as a compression factor to define the "information quantity" element as shown in equation 6.6:

$$H_{assy} = \log_2(N + 1) \tag{6.6}$$

where, N is the summation of total number of parts/sub-assemblies and fastenings.

Diversity of information is defined by the parts/subassemblies/fastenings diversity ratio, which is the ratio of distinct parts and fastenings counts to the total number of parts/sub-assemblies and fastenings. Equation 6.7 shows the diversity:

$$D_{assy} = \frac{n}{N} \tag{6.7}$$

where, n is the summation of distinct number of parts/sub-assemblies and distinct number of fastenings, and

N is the summation of total number of parts/sub-assemblies and total number of fastening points.

The information content is defined as an amount of effort to accomplish the assembly tasks, not a measure of probability of success. In the proposed model at section 6.3, only the effect of components on the assembly information content was considered. However, in addition to the components, the assembly process also adds to the effort amount of performing the assembly.

As we mentioned earlier, there are three main tasks in each station: handling, alignment, and insertion. However, we need to correctly select the part to manipulate. Hence, the first task is to select the appropriate part/sub-assembly.

Consequently, the complexity of each workstation is the complexity of:

- Part Selection
- Handling
- Alignment
- Insertion

Figure 6.14 shows the assembly complexity based on the number and diversity of the components and the task effort.

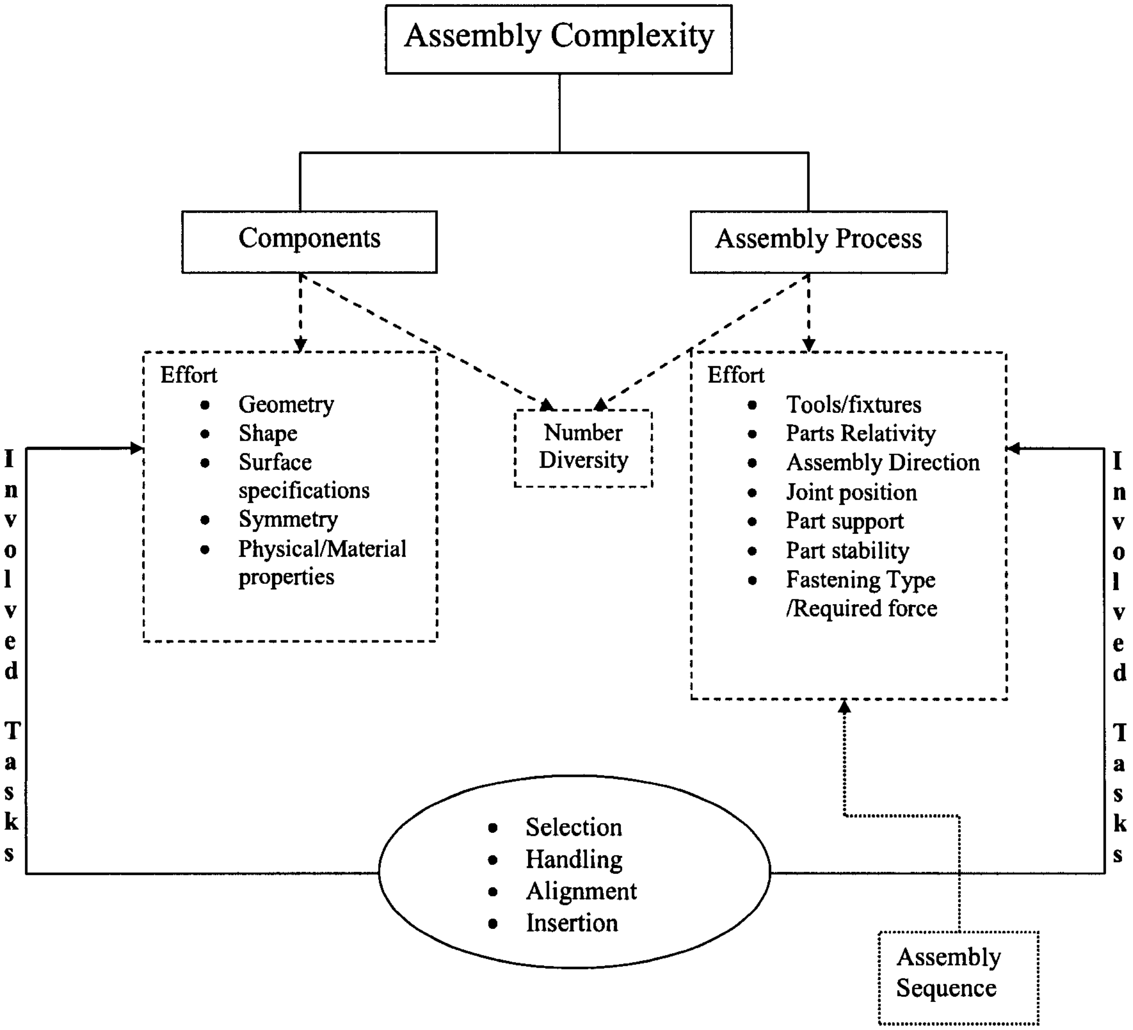


Figure 6.14: Assembly complexity elements

6.6.1. Effort Measurement

Considering components, the following factors affect the effort amount in measuring complexity:

- Geometry
- Surface specifications
- Symmetry
- Physical/Material properties

One of the main issues in assembly is the selection of the most appropriate assembly sequence. Assemble sequence highly affects the elements defining the assembly process effort. The following elements highly affect the effort in the assembly process complexity:

- Tools/Fixtures
- Parts relativity
- Assembly direction
- Joint position
- Part support
- Part stability
- Fastening type/ Required force

According to ElMaraghy and Urbanic [2003], effort is a function of physical or cognitive element that influences the task effort. In the following step, the physical and cognitive elements of each component or process-related factors are recognized.

6.6.1.1. Physical Elements

Some factors in the component and process-related complexity physically affect the effort amount. In the following section, first, we describe the component related factors, and then the process related factors.

Component Related

- *Part Geometry*

  The complexity is a function of the part size: in the case that it is too small or too large, more effort is needed to handle, align, and insert the part. In some cases, the part cannot be moved and the operator needs to move around the part to assemble other components.

- *Surface Specifications*

  If the parts are slippery or have sharp edges, it is more complex to do the assembly task. Thus, the part surface specification is important to define the effort of manipulating the part.

- *Physical/Material Properties*

  Handling, alignment, and insertion of a component depend on its material. If the component is fragile, then it needs more effort to manipulate.

Assessing the physical elements effort is based on a scoring system of 0, 0.5, and 1, which correspond to no or low/medium/high effort level.

Assembly Process Related

- *Tools/Fixtures*

  If any tool or fixture is used in order to handle, align, and insert the part, the task will need more effort to perform.

- *Relativity*

  If the previously assembled parts affect the assembly of a part, the manipulation of the part would be more complex. The relativity amount can be achieved using dependence chart.

- *Assembly direction*

  Assembly with different directions needs more effort. If the assembly direction changes – e.g. from vertical to horizontal – from a part to another, there is more effort in this process.

- *Joint position*

  If the joint is positioned in the back of the part so that it is not visible or easily accessible, more effort is required to perform the assembly.

- *Part Support*

  If a part needs to be supported with hand, tools, or fixtures during the assembly process, then the assembly task needs more effort compared to the situation where there is no need for any support.

- *Part stability*

  If the part is not stable after assembling and needs additional support, then the assembly task needs more effort.

- *Fastening type/ Required force*

  The assembly effort is related to the fastening type or the force required for assembling the part. For instance, snapping the part needs less effort compared to welding the parts.

Assessing the effort level of physical elements is based on a scoring system of 0, 0.5 and 1 which corresponds to no or low/medium/high effort level.

6.6.1.2. Cognitive Elements

Some factors in the component and process-related complexity cognitively affect the effort amount. In the following section, first we describe the component related factors, and then the process-related factors.

Component Related

- *Part Symmetry*

  Recognition of the appropriate part alignment cognitively affects the assembly. The more symmetric the product is, the easier the assembly operations becomes. α-symmetry and β-symmetry is used to evaluate the cognitive effort to perform assembly. According to DFA method, α-symmetry and β-symmetry are defined as:

  α-symmetry: is a rotational symmetry of a part about an axis perpendicular to the axis of insertion.

  β-symmetry: is a rotational symmetry of a part about its axis of insertion.

  The larger amounts for α-symmetry and β-symmetry mean that there are less symmetrical planes; therefore, more rotations are needed to appropriately manipulate the part. Table 6.4 shows the task effort level based on α-symmetry and β-symmetry.

α-symmetry	0	72	90	120	180	360
Effort Level	0	0.2	0.4	0.6	0.8	1

β-symmetry	0	72	90	120	180	360
Effort Level	0	0.2	0.4	0.6	0.8	1

Table 6.4: Effort level based on symmetry

An α-symmetry equal to 360 means that we can manipulate the part only in one direction; therefore, more effort is needed to define the correct direction for the handling, alignment, and insertion tasks. The same approach is applicable to β-symmetry.

Assembly Process Related

All the elements related to assembly operation, except for part relativity factor, cognitively affect the assembly effort. The appropriate recognition of elements and applying the appropriate procedure to perform the assembly operation cognitively increases the assembly effort.

To measure the effort, first, it is necessary to recognize the total number of parts. As mentioned before, the main tasks in assembly are handling, alignment, and insertion. Therefore, for each part, we have to calculate the component related effort, the assembly process-related effort, and the total effort of each task.

To measure the component-related and process-related task effort, we need to determine the effect of each of the physical and cognitive elements on the effort. A scoring system of 0, 0.5 and 1, which respectively represents no or low, medium and high effect, is assigned for each element. Figure 6.15 illustrates the component and process-related effort, which is based on physical and cognitive elements.

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling										
Alignment										
Insertion										

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling									
Alignment									
Insertion									

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling								
Alignment								
Insertion								

Figure 6.15: Component and process related effort

Since the component and process-related task effort is defined, the task effort for each part should be measured. Here, we assume that the component and product-related task effort have equal weights on the part's total effort. Figure 6.16 shows the total task effort for each part, i.e. handling, alignment, and insertion, which is based on the component and process related efforts.

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling							
Alignment							
Insertion							

Figure 6.16: Part task effort

After defining the handling, alignment, and insertion effort for all parts, the relative effort of assembly can be calculated applying the chart illustrated in figure 6.17, relative effort of assembly.

Part	No.	Percentage	Selection	Handling	Alignment	Insertion	Sum	Average	Part Share
Part 1									
Part 2									
Part 3									
Part 4									
Part 5									
Part 6									
							Assembly Relative Effort		

Figure 6.17: Relative effort of assembly

6.6.2. Effort Measurement: Mathematical Model

To mathematically model the effort, at first we need to define the variables.

j: component, j= 1 to P_j

n_j: number of component j

$$N = \sum_{j=1}^{Pj} nj$$

i: the assembly tasks, i= 0, 1, 2 and 3

i(0, 1,2,3)= (selection, handling, alignment, insertion)

k: the component-related factors affect assembly effort

k_{ph}: the physical element

k_{cg}: the cognitive elements

m: the assembly process-related factors that affect the assembly effort

m_{ph}: the physical element

m_{cg}: the cognitive elements

The assembly relative task effort, REff, equals to:

$$REff = \sum_{j=1}^{P_j} PEff_j \tag{6.8}$$

where PEff is the effort related to each component.

$$PEff_j = \frac{n_j}{N} * \frac{\sum_{i=0}^{4} TE_i}{4} \tag{6.9}$$

where TE_i is the i^{th} task effort for part j.

$$TE_i = \frac{TE_{i,com} + TE_{i,pro}}{2} \tag{6.10}$$

where $TE_{i,com}$ is the i^{th} task effort related to the component.

where $TE_{i,pro}$ is the i^{th} task effort related to the assembly process.

$$TE_i, com = \frac{Ph_{com} + Cg_{com}}{2} \tag{6.11}$$

where Ph_{com} is the component related physical effort level.

where Cg_{com} is the component related cognitive effort level.

$$Ph_{com} = \frac{\sum_{k_{ph}=1}^{K_{ph}} Factor - level}{K_{ph}} \tag{6.12}$$

$$Cg_{com} = \frac{\sum_{k_{cg}=1}^{K_{cg}} Factor - level}{K_{cg}} \tag{6.13}$$

$$TE_i, pro = \frac{Ph_{pro} + Cg_{pro}}{2} \tag{6.14}$$

where Ph_{pro} is the process related physical effort level.

where Cg_{pro} is the process related cognitive effort level.

$$Ph_{pro} = \frac{\sum_{m_{ph}=1}^{M_{ph}} Factor - level}{M_{ph}} \tag{6.15}$$

$$Cg_{pro} = \frac{\sum_{m_{cg}=1}^{M_{cg}} Factor - level}{M_{cg}} \tag{6.16}$$

Therefore, the assembly complexity is:

$$C_{assy} = (D_{assy} + REff) * H_{assy} \tag{6.17}$$

After formulation of assembly complexity metric, the metric is analyzed based on its sensitivity to changes in different influencing elements. Figures 6.18, 6.19, and 6.20 illustrate the reaction of assembly complexity with respect to changes in the number of components, diversity of the components, and assembly effort, respectively. In this analysis, the elements are assumed independent. In other words, changing one element does not affect the other elements.

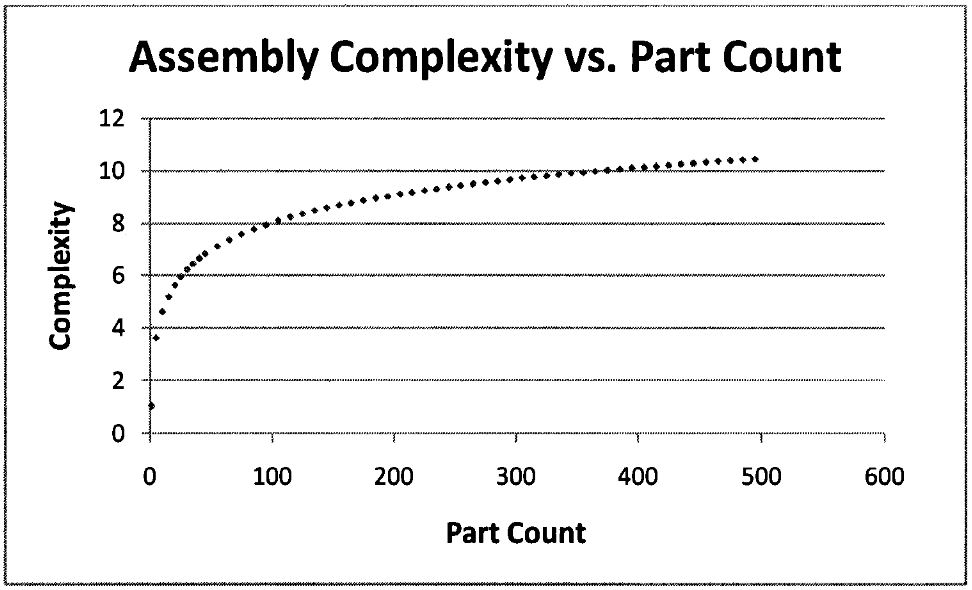


Figure 6.18: Assembly complexity vs. changes in part count

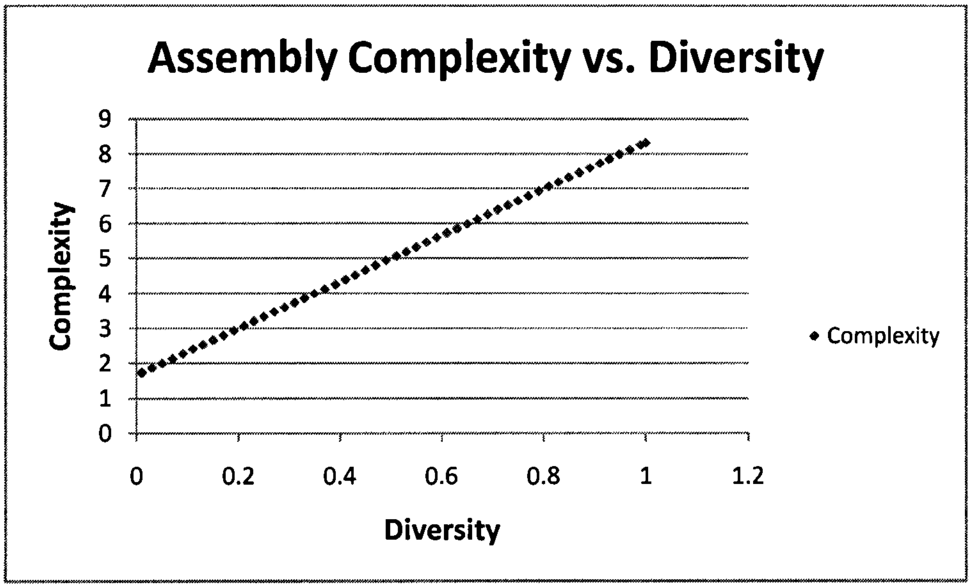


Figure 6.19: Assembly complexity vs. changes in diversity

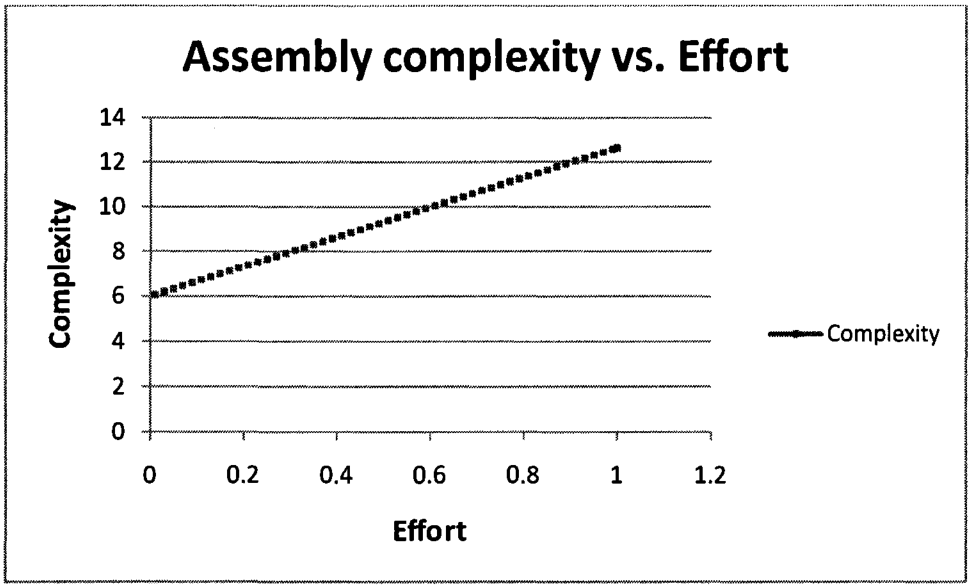


Figure 6.20: Assembly complexity vs. changes in effort

6.7. Illustration Example- Pneumatic Piston Sub-assembly (Before/after DFA)

To show how the model works, Pneumatic Piston sub-assembly is used to measure complexity both before and after applying the DFA method.

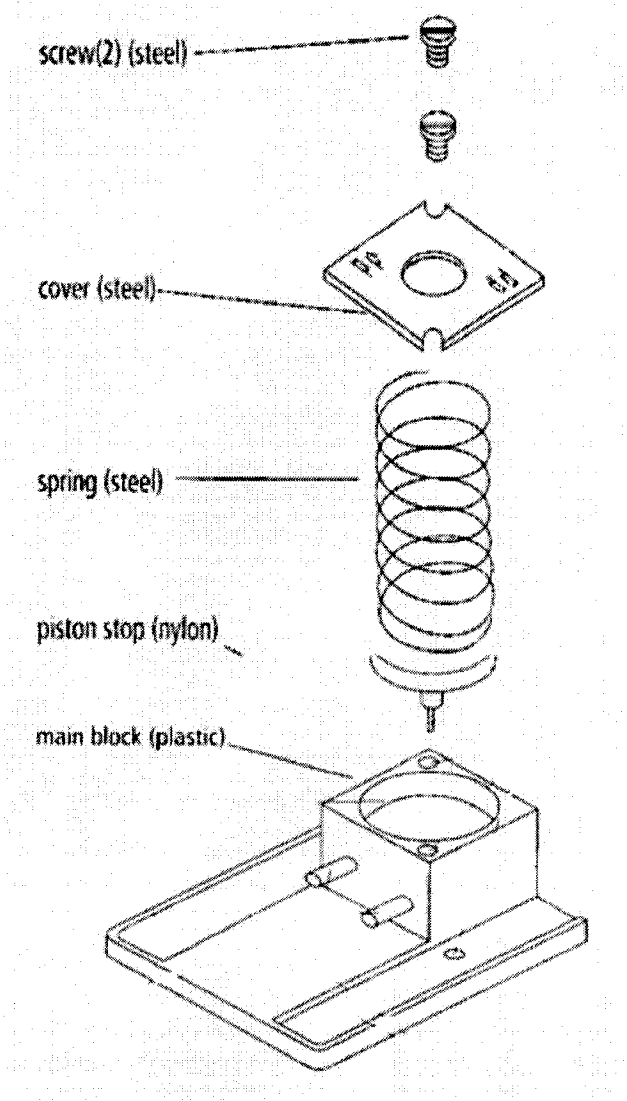


Figure 6.21: Pneumatic piston sub-assembly (Before DFA), [Boothroyd and Dewhurst, 1987]

Figure 6.21 illustrates the pneumatic piston sub assembly before applying DFA method. Figures 6.22, 6.23, 6.24, 6.25, 6.26, and 6.27 show the calculations of defining the assembly task effort.

Part 1- Main Block

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	0.80	0.00	1.80	0.60
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	0.80	0.00	1.80	0.60

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.60	0.30	0.00	0.00	0.00	**0.15**
Insertion	0.00	0.60	0.30	0.00	0.00	0.00	**0.15**

Figure 6.22- Task effort analysis for parts 1, (Before DFA)

Part 2- Piston

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.50	0.00	0.50	0.17	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	1.00	0.00	1.50	0.50	1.00	0.00	0.00	1.00	0.33
Insertion	1.00	1.00	0.00	2.00	0.67	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.00
Insertion	0.00	0.00	0.50	0.00	0.50	0.00	0.00	1.00	0.14

Cognitive Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.50	0.00	0.00	0.50	1.00	0.17

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.17	0.00	0.09	0.00	0.00	0.00	**0.04**
Alignment	1.50	0.33	0.92	0.00	0.00	0.00	**0.46**
Insertion	0.67	0.33	0.50	0.14	0.17	0.16	**0.33**

Figure 6.23- Task effort analysis for parts 2, (Before DFA)

Part 3- Spring

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.50	0.00	0.50	0.17	0.80	0.00	0.00	0.80	0.27
Insertion	0.50	0.50	0.50	1.50	0.50	0.80	0.00	0.00	0.80	0.27

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.33	0.00	0.83	0.12

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.17	0.27	0.22	0.00	0.00	0.00	**0.11**
Insertion	0.50	0.27	0.39	0.12	0.00	0.06	**0.22**

Figure 6.24- Task effort analysis for parts 3, (Before DFA)

Part 4- Piston Cover

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.50	0.00	0.50	0.17	0.80	0.80	0.00	1.60	0.53
Insertion	0.00	0.50	0.00	0.50	0.17	0.80	0.80	0.00	1.60	0.53

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	1.00	0.25	0.00	1.25	0.18

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.17	0.53	0.35	0.00	0.00	0.00	**0.18**
Insertion	0.17	0.53	0.35	0.18	0.00	0.09	**0.22**

Figure 6.25- Task effort analysis for parts 4, (Before DFA)

Part 5- Screw 1

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.00
Insertion	0.50	0.00	0.00	0.00	0.00	0.20	0.50	1.20	0.17

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00
Insertion	0.50	0.00	0.00	0.00	0.00	0.50	1.00	0.17

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.00	0.00	0.00	**0.17**
Insertion	0.33	0.33	0.33	0.17	0.17	0.17	**0.25**

Figure 6.26- Task effort analysis for parts 5, (Before DFA)

Part 6- Screw 2

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.00
Insertion	0.50	0.00	0.00	0.00	0.00	0.33	0.50	1.33	0.19

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00
Insertion	0.50	0.00	0.00	0.00	0.00	0.50	1.00	0.17

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.00	0.00	0.00	**0.17**
Insertion	0.33	0.33	0.33	0.19	0.17	0.18	**0.26**

Figure 6.27- Task effort analysis for parts 6, (Before DFA)

Figure 6.28 shows the result of assembly relative effort, REff for piston sub assembly before applying DFA method.

Part	No.	Percentage	Selection	Handling	Alignment	Insertion	Sum	Average	Part Share
Part 1	1.00	0.17	0.83	0.00	0.15	0.15	1.13	0.28	0.05
Part 2	1.00	0.17	0.80	0.04	0.46	0.33	1.63	0.41	0.07
Part 3	1.00	0.17	0.75	0.00	0.11	0.22	1.08	0.27	0.05
Part 4	1.00	0.17	0.67	0.00	0.18	0.22	1.07	0.27	0.04
Part 5	1.00	0.17	0.00	0.00	0.17	0.25	0.42	0.11	0.02
Part 6	1.00	0.17	0.00	0.00	0.17	0.26	0.43	0.11	0.02
							Assembly Relative Effort		0.24

Figure 6.28: Relative assembly effort (Before DFA)

It shows that:

$REff = 0.24$,

$D_{assy} = 0.83$,

$H_{assy} = 2.81$

Therefore, according to equation 6.17, the assembly complexity for pneumatic piston sub assembly after applying the DFA method is:

$$C_{assy} = (D_{assy} + REff) * H_{assy}$$
$$= (0.83 + 0.24) * 2.81 = 3.01$$

Figure 6.29 illustrates the pneumatic piston sub assembly after applying DFA method. Figures 6.30, 6.31, 6.32, and 6.33 show the calculations of defining the assembly task effort.

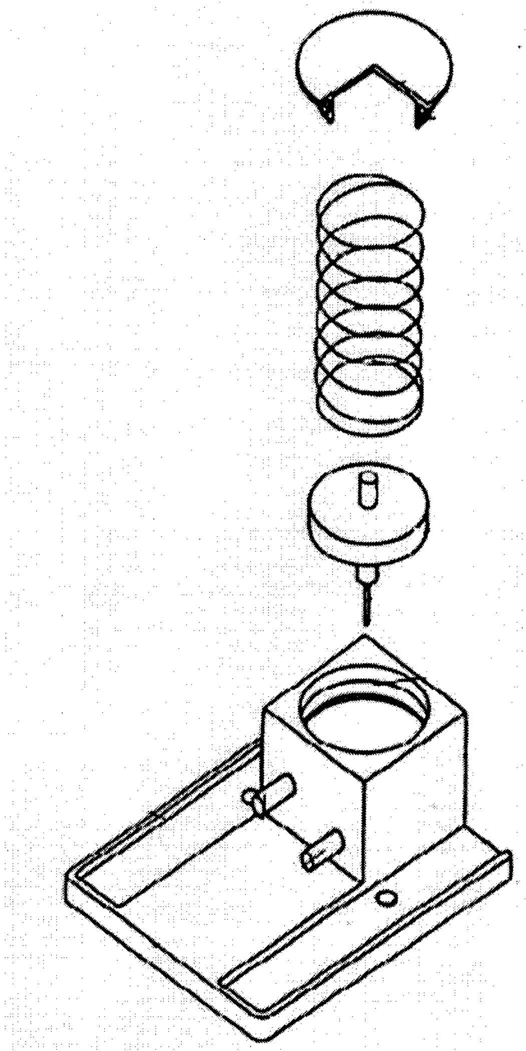


Figure 6.29: Pneumatic piston sub-assembly (After DFA), [Boothroyd and Dewhurst, 1987]

Part 1- Main Block

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	0.80	0.00	1.80	0.60
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	0.80	0.00	1.80	0.60

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.60	0.30	0.00	0.00	0.00	**0.15**
Insertion	0.00	0.60	0.30	0.00	0.00	0.00	**0.15**

Figure 6.30- Task effort analysis for parts 1 (After DFA)

Part 2- Piston

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.50	0.00	0.50	0.17	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	1.00	0.50	0.00	1.50	0.50	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.00
Insertion	0.00	0.00	0.50	0.00	0.50	0.00	0.00	1.00	0.14

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.50	0.00	0.00	0.50	1.00	0.17

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.17	0.00	0.09	0.00	0.00	0.00	**0.04**
Alignment	0.33	0.33	0.33	0.00	0.00	0.00	**0.17**
Insertion	0.50	0.33	0.42	0.14	0.17	0.16	**0.29**

Figure 6.31- Task effort analysis for parts 2 (After DFA)

Part 3- Spring

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.50	0.00	0.50	0.17	0.80	0.00	0.00	0.80	0.27
Insertion	0.50	0.50	0.50	1.50	0.50	0.80	0.00	0.00	0.80	0.27

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.33	0.00	0.83	0.12

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.17	0.27	0.22	0.00	0.00	0.00	**0.11**
Insertion	0.50	0.27	0.39	0.12	0.00	0.06	**0.22**

Figure 6.32- Task effort analysis for parts 3 (After DFA)

Part 4- Piston Cover

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.50	0.00	0.50	0.17	1.00	0.00	0.00	1.00	0.33
Insertion	0.00	0.50	0.00	0.50	0.17	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.25	0.50	0.75	0.11

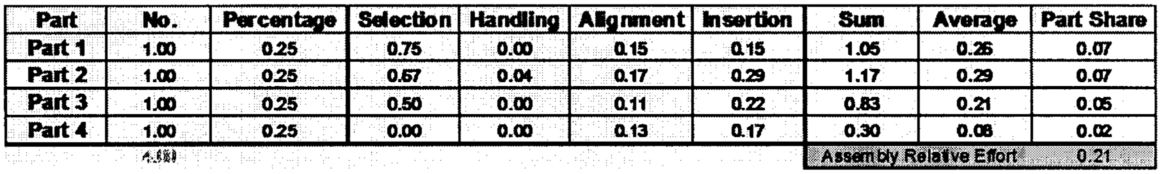
	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.08

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.17	0.33	0.25	0.00	0.00	0.00	**0.13**
Insertion	0.17	0.33	0.25	0.11	0.08	0.10	**0.17**

Figure 6.33- Task effort analysis for parts 4 (After DFA)

Figure 6.34 shows the result of the relative assembly effort, REff.



Part	No.	Percentage	Selection	Handling	Alignment	Insertion	Sum	Average	Part Share
Part 1	1.00	0.25	0.75	0.00	0.15	0.15	1.05	0.26	0.07
Part 2	1.00	0.25	0.67	0.04	0.17	0.29	1.17	0.29	0.07
Part 3	1.00	0.25	0.50	0.00	0.11	0.22	0.83	0.21	0.05
Part 4	1.00	0.25	0.00	0.00	0.13	0.17	0.30	0.08	0.02
	4.00						Assembly Relative Effort		0.21

Figure 6.34: Relative assembly effort (After DFA)

It shows that:

REff= 0.21,

D_{assy}= 1,

H_{assy}= 2.32

Therefore, according to equation 6.17, the assembly complexity for pneumatic piston sub assembly after applying the DFA method is:

$C_{assy} = 2.81$

6.8. DFA/ Complexity Comparison

In addition to the piston assembly, the proposed method is applied on diaphragm assembly before and after redesign through DFA method. Figure 6.35 illustrates the diaphragm assembly.

According to the calculations, the relative effort of diaphragm assembly before applying DFA method is:

REff= 0.26,

D_{assy}= 0.625,

H_{assy}= 3.17

Therefore, the complexity of assembly before applying DFA method is:

$C_{assy} = 2.81$

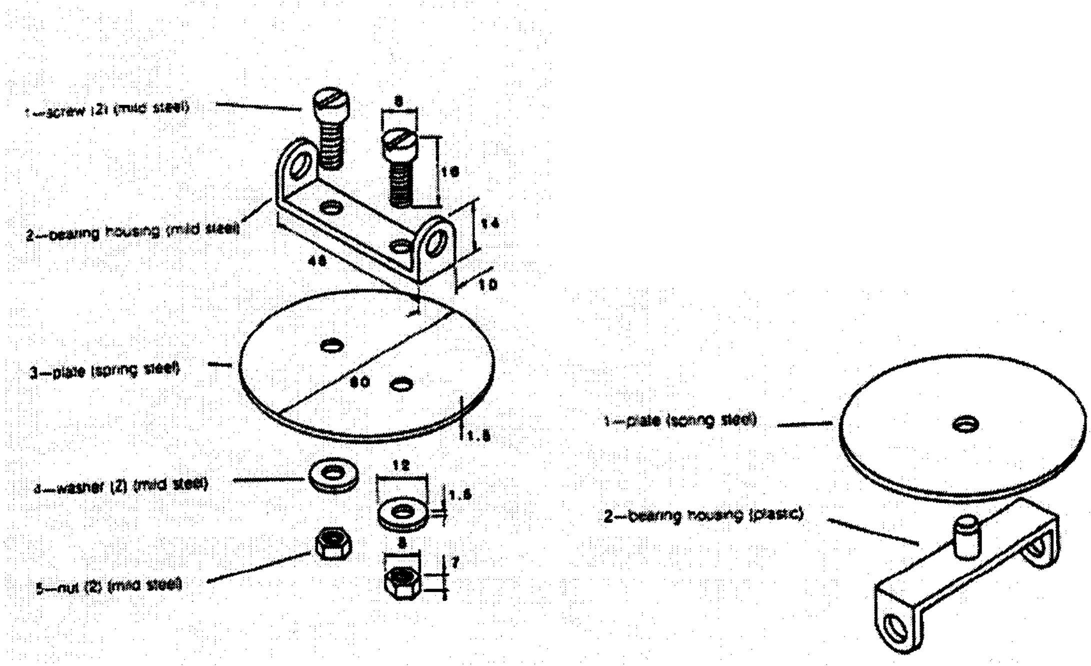


Figure 6.35: Diaphragm assembly- Before DFA (left) and after DFA (right) [Huekstra, 1992]

The relative effort of diaphragm assembly after applying DFA method is:

REff= 0.11,

D_{assy}= 1,

H_{assy}= 1.58

Therefore, the complexity of assembly after applying DFA method is:

$C_{assy} = 1.75$

In addition, the proposed model is applied on other examples. Summary of the results are shown in table 6.5.

	Product	**Assembly Complexity (Before DFA)**	**Assembly Complexity (After DFA)**
1	Pressure recorder	4.19	3.75
2	Motor Drive	3.93	3.33
3	Piston	3.01	2.81
4	Diaphragm	2.81	1.75

Table 6.5: Summary of complexity results

Figure 6.36 illustrates the reduction in complexity after applying the DFA method in all the case studies.

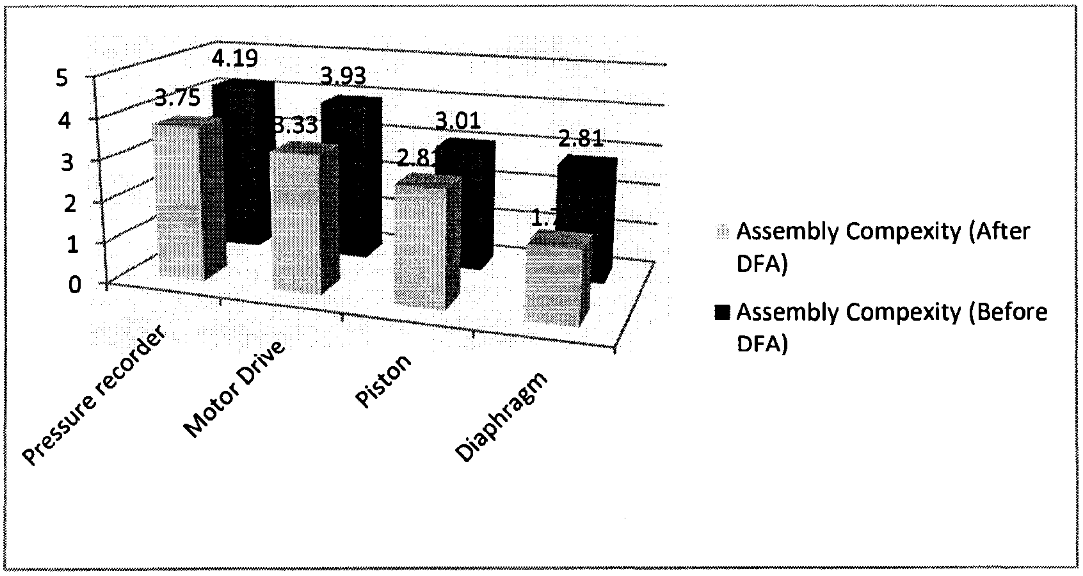


Figure 6.36: Complexity comparison with regard to DFA

Complexity is a function of the number of components in the product. Increasing the number of products results in an increase in complexity. Figure 6.37 illustrates the effect of component quantity on complexity in the tested case studies.

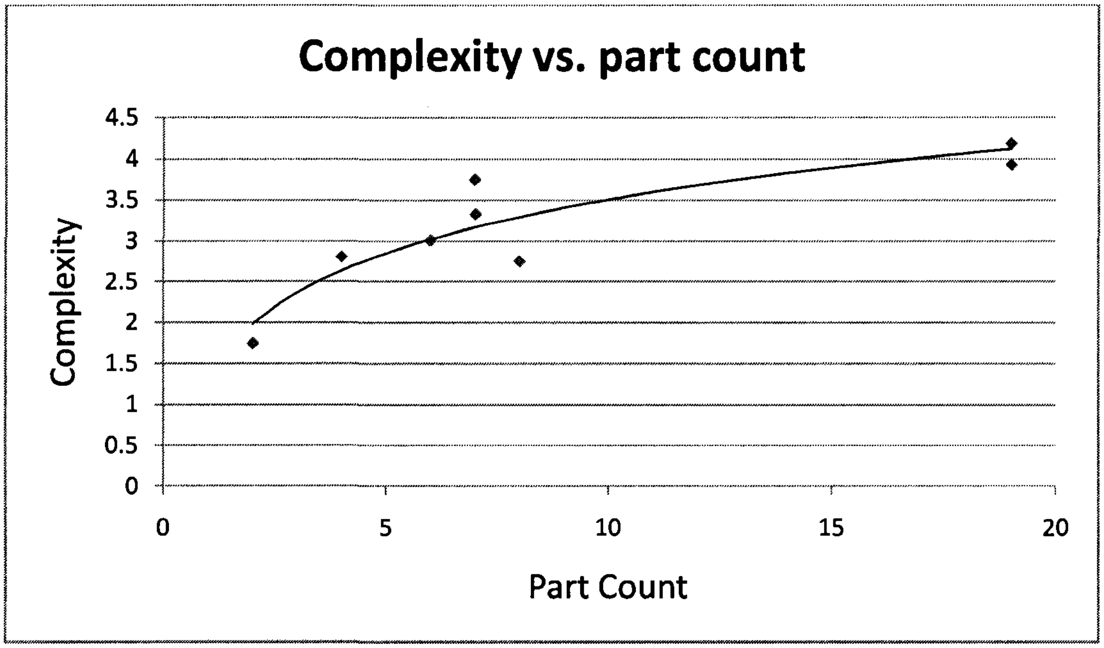


Figure 6.37: Complexity vs. part count

Cost is also related to the complexity of the system. In assembly, reduction in complexity results in cost reduction. The cost formula defined in DFA method is used to compare cost versus part count in the considered case studies. Figure 6.38 illustrates the comparison between an increase in part count and cost.

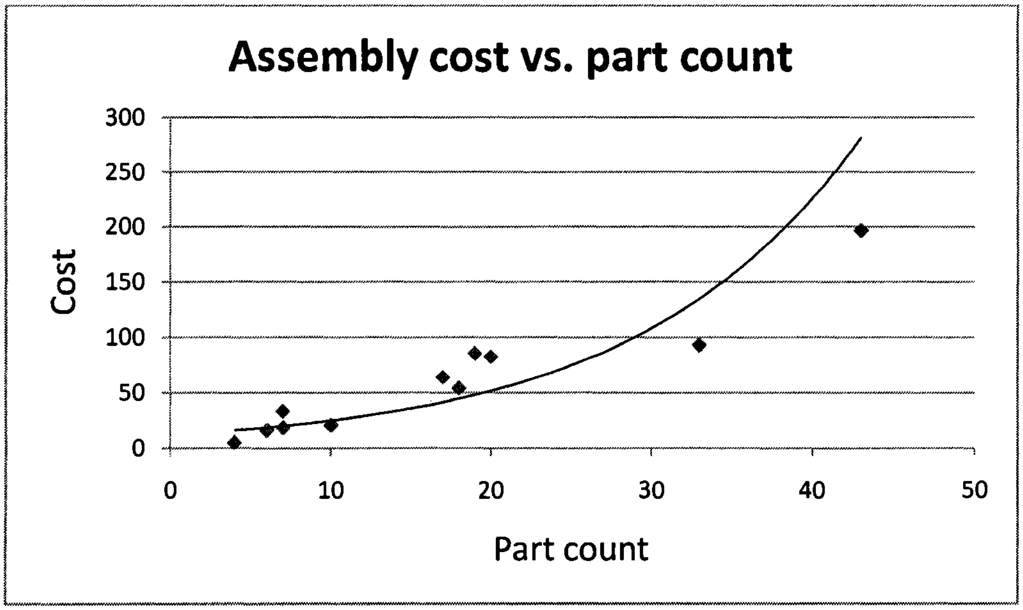


Figure 6.38: Assembly cost vs. part count

Chapter 7

Reduced Combinatorial Complexity

One of the main approaches in manufacturing complexity was introduced by Suh [1999, 2005]. He mentioned that the complexity is found in the "physical domain" and the "functional domain". The former deals with the complexity added to system because of the inherent characteristic of physical elements, including algorithms, products, processes, and manufacturing systems. In the second domain, the complexity is a measure of uncertainty in achieving the specified FRs.

Suh proposed that complexity can be a function of time or can be independent of time. The classification proposed by Suh [1999], and ElMaraghy et al. [2005] is presented in figure 7.1.

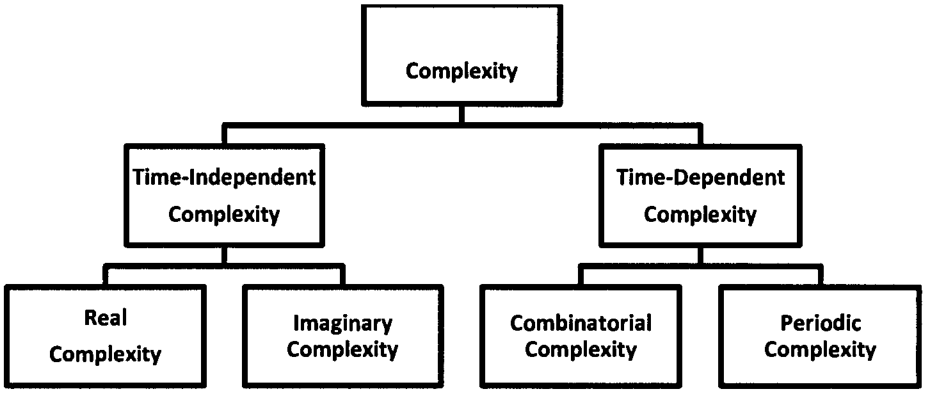


Figure 7.1: Complexity classification [ElMaraghy et al., 2005]

The real complexity is a result of the system range being outside of design range.

The imaginary complexity is the lack of knowledge in satisfying FRs at all times. In this kind of complexity, FRs can be satisfied at all times, if the DPs are reorganized in the right order.

Combinatorial complexity is a complexity that increases as a function of time due to a continued expansion in the number of possible combinations with time, which may lead to a chaotic state or a system failure. [Suh, 2005]

The periodic complexity is defined as the complexity that results in the limited number of possible combinations in a limited time period.

The goal of system design is to reduce the total complexity of the system in order to achieve higher productivity. Suh suggested that the time-dependent combinatorial complexity could be reduced by changing it to time-dependent periodic complexity, using the concept of functional periodicity.

Some authors such as Matt [2006] proposed a methodology to reduce the time-independent real complexity and time-dependent combinatorial complexity by using the concept of axiomatic design.

To reduce time-independent real complexity, he suggested that the system designer must firstly try to achieve an uncoupled or decoupled design. Then, each DP's design range should be fitted to its corresponding FR's system range. The imaginary complexity in the case of uncoupled design is zero. However, in the case of decouple design; the designer should select the design with the least information content.

7.1. Reduced Combinatorial Complexity in Assembly

Assembly is a stage in production cycle that both time-dependent and time-independent complexity can be easily identified. Thoroughly analyzing the assembly system provides that there is another kind of time-dependent complexity, which has not been identified before in any system. This kind of complexity is called time-dependent Reduced Combinatorial Complexity (RCC).

To clarify RCC, a simple illustration example is used. Jigsaw puzzle is an example that simulates the assembly system very well.

At first, when we begin solving a jigsaw puzzle, we have to select the parts from a large number of parts. In addition, each piece has different connectivity option to its neighbor part(s). However, as we continue solving the puzzle, we have fewer parts to select from and more information to define the orientation of the part. As a result, the complexity of solving the puzzle decreases as a function of time due to the less number of combinations.

Figure 7.2 shows a jigsaw puzzle at the first and last steps of solving.

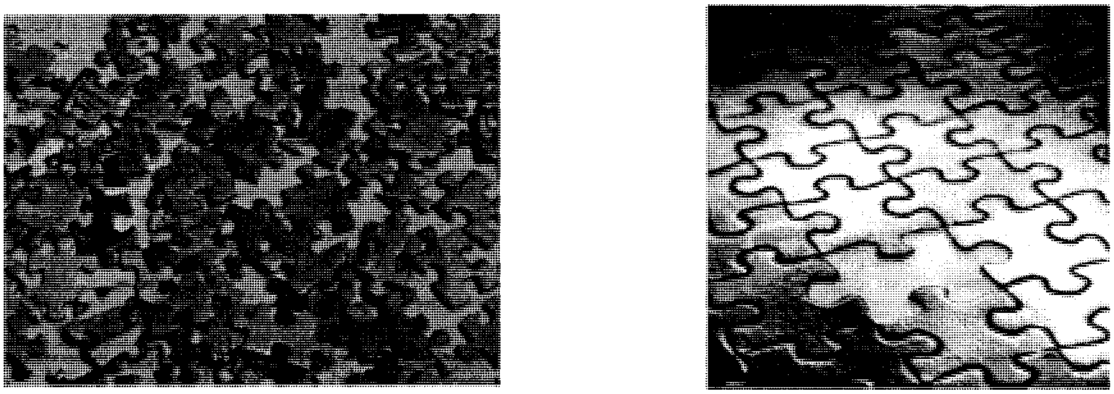


Figure 7.2: Jigsaw puzzle at first and last step of its solving

Figure 7.3 shows the new classification of complexity.

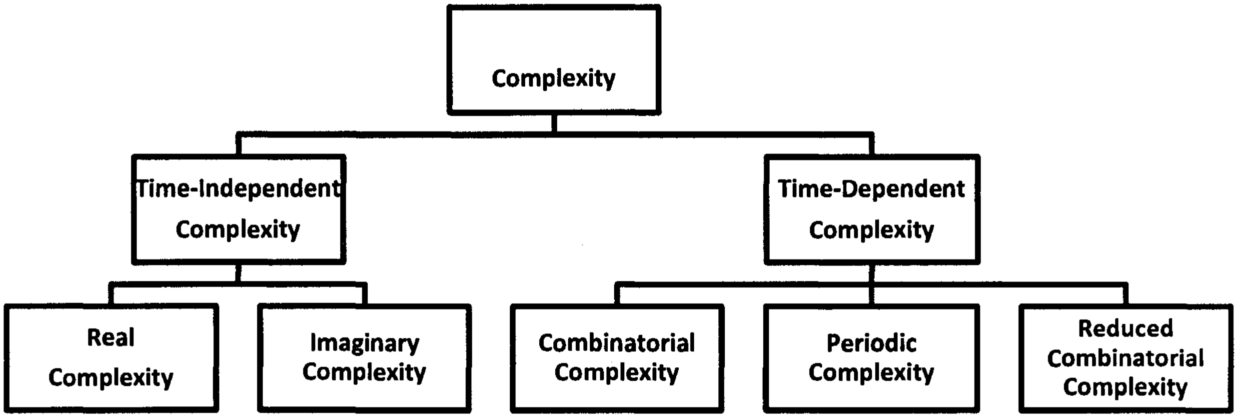


Figure 7.3: New complexity classification

Using the same definition introduced by Suh for combinatorial complexity, in this section RCC will be further explained.

Time-dependent Reduced Combinatorial Complexity is a complexity that decreases as a function of time due to a continuous reduction in the number of possible combinations with the time.

7.2. Model of Reduced Combinatorial Complexity in Assembly

In assembly, the number of parts/sub-assemblies, fastenings, available fastening points, and orientations affect RCC.

As RCC is defined in functional domain, it is necessary to define the functional requirements that affect the assembly. In other words, the purpose of an assembly process is to assemble a product with accepted quality. To define the functional requirements, Axiomatic Design is employed. Figure 7.4 illustrates the functional requirements and design parameters to produce an accepted product. The results show that in order to have an accepted quality product, the components are required to be appropriately selected, oriented, and inserted.

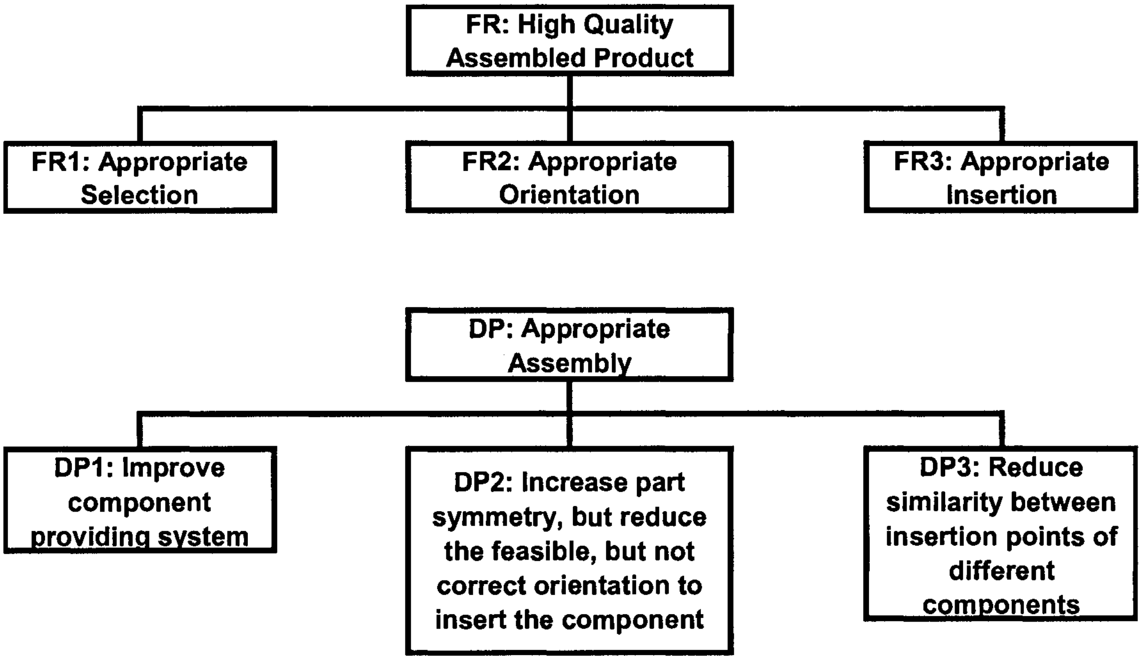


Figure 7.4: Axiomatic Design to identify functional requirements for good assembly

It is clear that by continuing the assembly operation, the number of parts to be selected from is reduced and there is fewer number of selection combination.

In some assemblies, there can be a number of similar fastening points, where only some of them are specifically meant for the part to be assembled. For instance, assume we intend to assemble part X, and there are three available fastening points. In this case, we face three options to choose from the fastening points. However, if there is a part Y that has to be assembled to the base in two of the fastening points, the RCC of assembling part X in this case would be lower than when no part has been assembled yet.

The last factor that affects RCC is the part orientation. In some cases where the other parts are not assembled, the part can be assembled in different orientations. However, after assembling the other parts, there is only one orientation left for the first part to be assembled.

As RCC is a function of time, a time period should be set in the proposed model. Here, time period is defined as the period in which one part is assembled to the base/ previously assembled parts. In other words, time represents an assembly step in which one part is assembled.

As RCC is defined in the functional domain, the best model to describe it is by using the amount of information, H.

The total RCC is a function of complexity of selection, orientation, and insertion. Equations 7.1.a, 7.1.b, and 7.1.c illustrate the possible formats for the total RCC at each step.

$$RCC = w_s H_s + w_o H_o + w_{in} H_{in} \tag{7.1.a}$$

$$RCC = w_s H_s \times w_o H_o \times w_{in} H_{in} \tag{7.1.b}$$

$$RCC = w_s H_s \times (w_o H_o + w_{in} H_{in}) \tag{7.1.c}$$

where, H_s is the selection complexity, H_o represents orientation complexity, and H_{in} stands for insertion complexity. w_s, w_o, and w_{in} are the relative weights of the three kind of complexities. Considering various situations, it is concluded that equation 7.1.a is more reasonable for this case than the equations 7.1.b and 7.1.c.

Consider a situation where one screw should be fastened to the base part: there are three similar fastening points on the base part. Therefore, the selection and orientation complexity equal to zero, and the insertion complexity is H_{in}= 0.52. In another case, suppose that there are two different screws, which should be assembled to two distinct fastening points. In this case, the orientation complexity is zero, but the selection and insertion complexity are both 0.5 at the first step. In table 7.1 different scenarios for RCC are analyzed according to the above-mentioned cases as well as other estimated amounts for each kind of complexity.

H_s	**H_o**	**H_{in}**	**Eq. 7.1.a**	**Eq. 7.1.b**	**Eq. 7.1.c**
0	0	0.52	0.52	0	0
0	0	0.46	0.46	0	0
0.5	0	0.5	1	0	0.25
∞	a	∞	∞	∞	∞

Table 7.1: Exploring possible equations for assembly complexity

Table 7.1 suggests that if the selection complexity equals to zero, then the RCC will be zero using the equations 7.1.b and 7.1.c, regardless of the amount of orientation and insertion complexity. Therefore, in format 7.1.b and 7.1.c the effect of insertion and orientation complexities is neglected with a zero selection complexity, which is not reasonable. Furthermore, exploiting equation 7.1.b will result in a total RCC of zero if any of the complexity kinds equals to zero. As a result, equation 7.1.a seems the best option to represent RCC.

H_s is the complexity associated with the selection of the components and fastenings. Equation 7.2 determines the selection complexity at each step.

$$H_s = -\sum_{i=1}^{N} p_{s,i} \log_2 p_{s'i} \quad (7.2)$$

where, $p_{s,i}$ is the probability of appropriate selection of the part i to be assembled, and N is the total number of parts and fastenings.

H_o is the complexity associated with the orientation of the components and fastenings. Equation 7.3 represents the selection complexity at each step.

$$H_o = -\sum_{i=1}^{N} p_{o,i} \log_2 p_{o'i} \quad (7.3)$$

where, $p_{o,i}$ is the probability of appropriate orientation of the part to be assembled, and N is the total number of parts and fastenings

H_{in} is the complexity associated with the insertion of the components and fastenings. Equation 7.4 indicates the selection complexity at each step.

$$H_{in} = -\sum_{i=1}^{N} p_{in,i} \log_2 p_{in'i} \quad (7.4)$$

where, $p_{o,i}$ is the probability of appropriate insertion of the part i to be assembled, and N is the total number of parts and fastenings

RCC should be calculated at every step for each part. Therefore, the total RCC conveys the reduced combinatorial complexity associated with that step. The benefit of the step-based model is that it is easier to track where there is more reduction in RCC in the different assembly sequences. In addition, the complexity type that affects the total RCC more can be easily inferred.

It is assumed that part i along with its precedent parts have been assembled at step i. Therefore, the RCC of the remaining N–i parts is calculated considering the fact that the previous i parts are already assembled.

The following algorithm describes how to calculate the RCC_{total} for each time interval.

1. Define the total number of parts to be assembled
2. It is assumed that at step 1, part 1 is assembled. At this step, for the remaining parts calculate H_s, H_o, and H_{in} from equations 7.2, 7.3 and 7.4
3. Calculate the total RCC for step 1, from equation 7.1
4. At step i, it is assumed that the part i along with its precedent parts have been assembled. Therefore, for the next N-i parts, calculate the selection, orientation, and insertion complexity from equations 7.2, 7.3, and 7.4 respectively. The total RCC is derived from equation 7.1
5. Continue step 4 until all the parts are assembled

7.3. Illustration Example- Bracket/ Base/ Spindle Assembly

The example shown in figure 7.5 is used to illustrate the mentioned algorithm. Note that the relative weights are assumed identical.

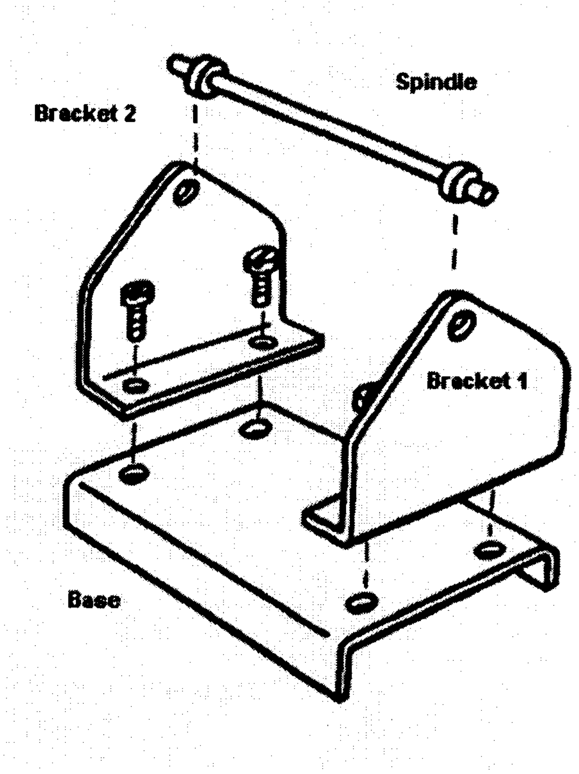


Figure 7.5: Illustration example for RCC

In this example, there are four main parts. At each step, the first table shows the number of parts. The second table shows the Probability of selection, orientation, and insertion for each part. Furthermore, the third table at each step illustrates the amount of H_s, H_o, H_{in}, and the total amount of RCC associated with that step.

The calculations for measuring RCC are shown in figures 7.6, 7.7, 7.8, and 7.9.

Number of part to be assembled

Total # of parts	# base	# bracket	# Spindle	# Screw
8	1	2	1	4

Step 1: The first part (base) is assembled

Step 2: One bracket is assembled

	Part	#	Selection Probability	Orientation Probability	Insertion Probability
Step 1	Each Bracket (2)	2	0.29	0.50	0.50
Base part is selected and fixed	Spindle	1	0.14	1.00	1.00
	Each Screw (4)	4	0.57	0.50	0.25

	Part	#	Selection Complexity	Orientation Complexity	Insertion Complexity	RCC
Step 1	Each Bracket (2)	2	0.516	0.500	0.500	1.52
Base part is selected and fixed	Spindle	1	0.401	0.000	0.000	0.40
	Each Screw (4)	4	0.461	0.500	0.500	1.46
Total Complexity			**3.28**	**3.00**	**3.00**	**9.28**

	Part	#	Selection Probability	Orientation Probability	Insertion Probability
Step 2	Bracket 2	1	0.17	0.50	1.00
one bracket is assembled	Spindle	1	0.17	1.00	1.00
	Each Screw (4)	4	0.67	0.50	0.25

	Part	#	Selection Complexity	Orientation Complexity	Insertion Complexity	RCC
Step 2	Each Bracket 1	1	0.431	0.500	0.000	0.93
one bracket is assembled	Spindle	1	0.431	0.000	0.000	0.43
	Each Screw (4)	4	0.390	0.500	0.500	1.39
Total Complexity			**2.42**	**2.50**	**2.00**	**6.92**

Figure 7.6: Calculation steps 1 and 2 of RCC

Step 3: The first screw of first bracket is assembled

Step 4: The second screw of first bracket is assembled

	Part	#	Selection Probability	Orientation Probability	Insertion Probability
Step 3	Bracket 2	1	0.20	0.50	1.00
One screw is assembled (for bracket 1)	Screw	3	0.60	0.50	0.33
	Spindle	1	0.20	1.00	1.00

	Part	#	Selection Complexity	Orientation Complexity	Insertion Complexity	RCC
Step 3	Bracket 2	1	0.464	0.500	0.000	0.96
One screw is assembled (for bracket 1)	Screw	3	0.442	0.500	0.528	1.47
	Spindle	1	0.464	0.000	0.000	0.46
Total Complexity			**2.26**	**2.00**	**1.58**	**5.84**

	Part	#	Selection Probability	Orientation Probability	Insertion Probability
Step 4	Bracket 2	1	0.25	0.50	1.00
Second screw is assembled (for bracket 1)	Screw	2	0.50	0.50	0.50
	Spindle	1	0.25	1.00	1.00

	Part	#	Selection Complexity	Orientation Complexity	Insertion Complexity	RCC
Step 4	Bracket 2	1	0.500	0.500	0.000	1.00
Second screw is assembled (for bracket 1)	Screw	2	0.500	0.500	0.500	1.50
	Spindle	1	0.500	0.000	0.000	0.50
Total Complexity			**2.00**	**1.50**	**1.00**	**4.50**

Figure 7.7: Calculation steps 3 and 4 of RCC

Step 5: The second bracket is assembled

Step 6: The first screw of second bracket is assembled

Step 5	Part	#	Selection Probability	Orientation Probability	Insertion Probability
2nd bracket is assembled	Screw	2	0.67	0.50	0.50
	Spindle	1	0.33	1.00	1.00

Step 5	Part	#	Selection Complexity	Orientation Complexity	Insertion Complexity	RCC
2nd bracket is assembled	Screw	2	0.39	0.50	0.50	1.39
	Spindle	1	0.53	0.00	0.00	0.53
	Total Complexity		1.31	1.00	1.00	3.31

Step 6	Part	#	Selection Probability	Orientation Probability	Insertion Probability
One screw is assembled (for bracket 2)	Screw	1	0.50	0.50	1.00
	Spindle	1	0.50	1.00	1.00

Step 6	Part	#	Selection Complexity	Orientation Complexity	Insertion Complexity	RCC
One screw is assembled (for bracket 2)	Screw	1	0.50	0.50	0.00	1.00
	Spindle	1	0.50	0.00	0.00	0.50
	Total Complexity		1.00	0.50	0.00	1.50

Figure 7.8: Calculation steps 5 and 6 of RCC

Step 7: The second screw of second bracket is assembled

	Part	#	Selection Probability	Orientation Probability	Insertion Probability
Step 7 2nd screw is assembled (for bracket 2)	Spindle	1	1.00	1.00	1.00

	Part	#	Selection Complexity	Orientation Complexity	Insertion Complexity	RCC
Step 7 2nd screw is assembled (for bracket 2)	Spindle	1	0.00	0.00	0.00	0.00
Total Complexity			**0.00**	**0.00**	**0.00**	**0.00**

Figure 7.9: Calculation step 7 of RCC

Table 7.2 and figure 7.10 show the summary of the total RCC in each time interval.

Summary- RCC

Step	Total System RCC
1	9.28
2	6.92
3	5.84
4	4.5
5	3.31
6	1.5
7	0

Table 7.2: Results of RCC

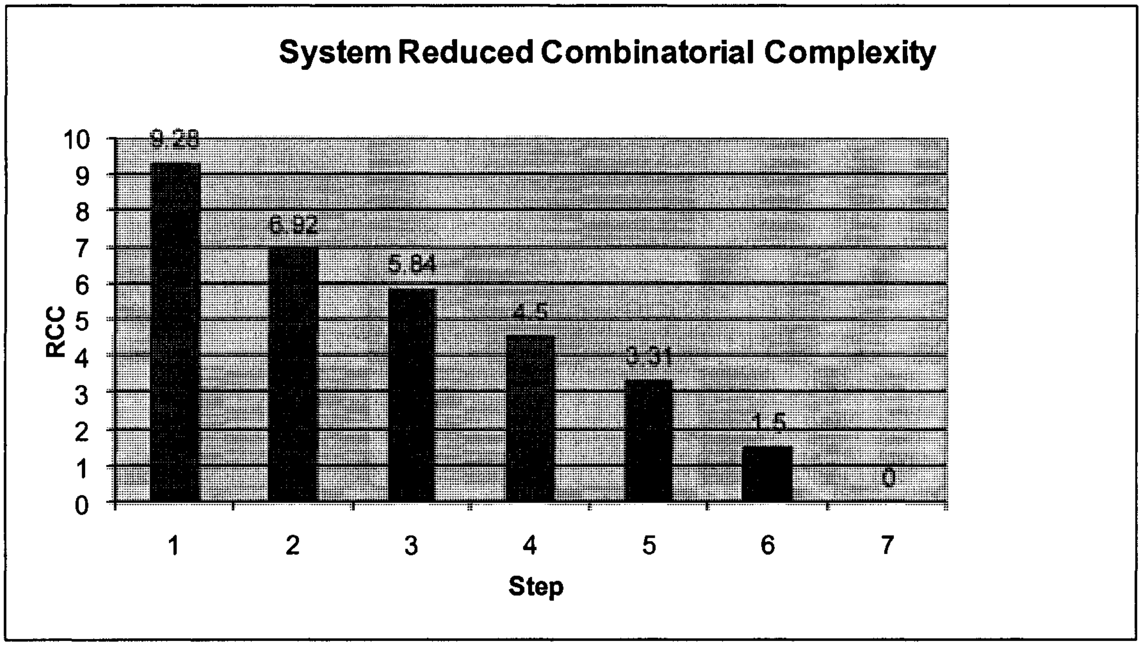


Figure 7.10: Results of RCC

7.4. RCC and "Divide and Conquer" Algorithm

In computer science, "divide and conquer" (D&C) algorithm is defined by recursively breaking down a problem into two or more sub-problems of the same (or related) type, until they become simple enough to be solved directly.

In assembly, one of the solutions to reduce complexity is by introducing the concept of subassemblies into the assembly system. According to the D&C algorithm, in assembly systems, some parts are suitable candidates to be assembled out of the main sequence and then be joined to the main sequence as a subassembly. Applying the RCC algorithm on assembly systems with subassemblies confirms the advantages of exploiting D&C method in assembly.

Figure 7.11 illustrates a main assembly sequence and an assembly sequence with a subassembly.

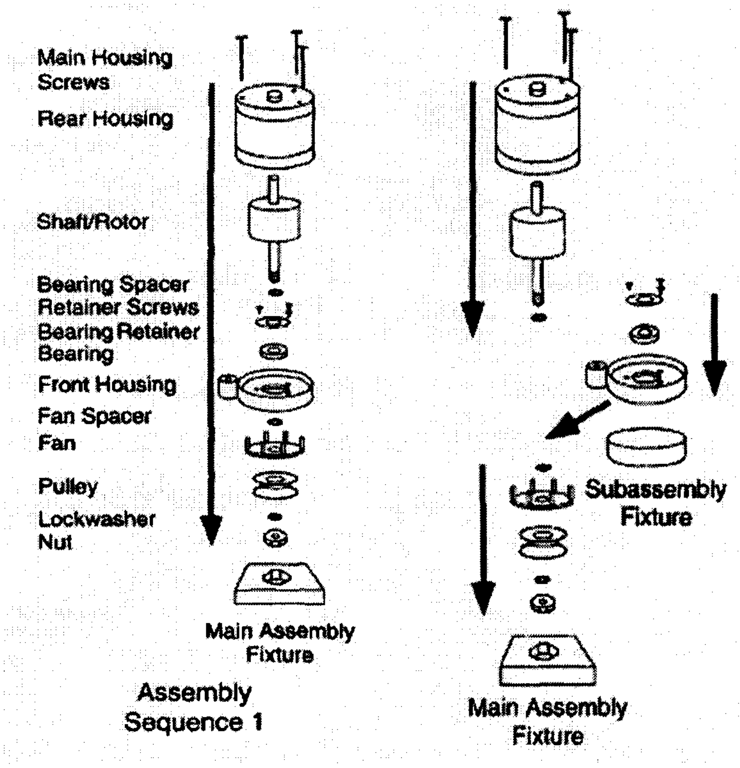


Figure 7.11: An example of assembly sequence without subassembly (left hand side sequence) and with assembly (right hand side sequence)

Figure 7.12 illustrates the result of applying RCC on the assembly sequences shown in figure 7.11. The results confirm that RCC of the assembly sequence with subassembly is less than that of a sequence without subassembly.

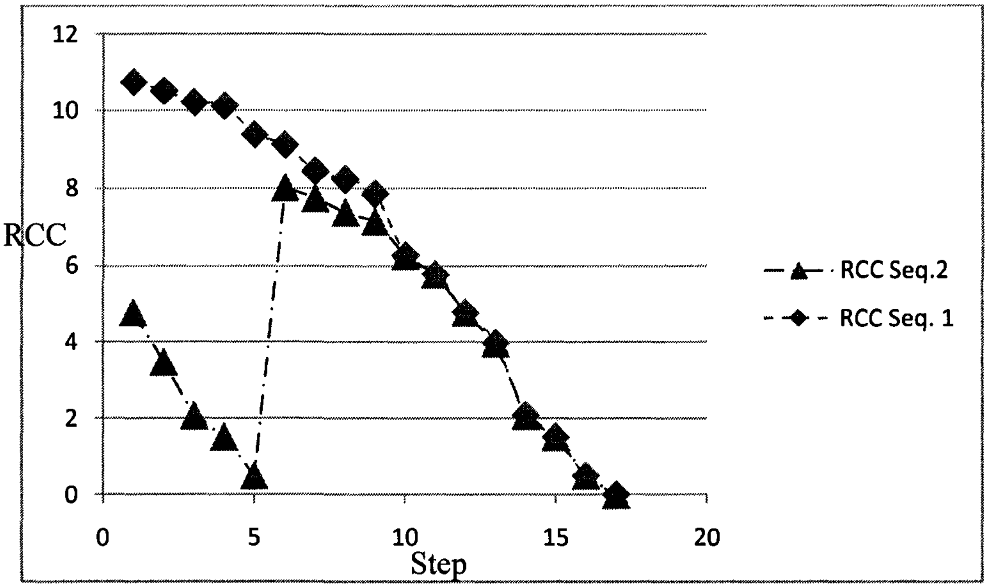


Figure 7.12: Effect of subassembly on RCC

7.5. Normalization of RCC

As mentioned earlier, RCC is a step-based method that measures the selection, orientation, and insertion complexity of each component and total assembly complexity at every assembly step. One question that may arise here is whether it is possible to normalize the RCC amount. To answer this question, one needs to measure the maximum amount of selection complexity, H_s, orientation complexity, H_o, and insertion complexity, H_{in}. In the following section, selection complexity will be analyzed to determine the possibility of finding a maximum for selection complexity.

Generally, selection complexity is defined in equation 7.5 as:

$$H_s = -\sum_{i=1}^{N} p_i \log_2 p_i \qquad (7.5)$$

where, p_i is the probability of selecting the i^{th} part.

If we assume that there are N different parts to be selected and the probability of selecting the parts are equal, i.e. $p_i = \frac{1}{N}$, then H_s will be determined as:

$$H_s = -\sum_{i=1}^{N} \frac{1}{N} \log_2 \frac{1}{N} \tag{7.6}$$

$$H_s = -N \times \frac{1}{N} \log_2 \frac{1}{N} \tag{7.7}$$

$$H_s = \log_2 N \tag{7.8}$$

To find the maximum of H_s, it is necessary to determine the derivative of H_s.

$$H_s{}' = \frac{1}{N \times \ln 2} \tag{7.9}$$

$H'_s = 0$ gives that $N \rightarrow \infty$. This means that the higher number of parts result in more selection complexity. As a result, it is not possible to find a maximum for the selection complexity in order to normalize it, since generally there is no constraint on N. However, it is worthwhile to mention that for a particular N, the maximum amount of H_s is the case where all parts have the same probability. In this situation, the operator faces more complexity in choosing the appropriate part.

The same analysis approach for selection complexity can be applied on the orientation and insertion complexity. To sum up, it is not possible to normalize the RCC when comparing two different assemblies.

Although it is not possible to normalize RCC to compare two different assemblies, the RCC of a particular assembly can be normalized over its different assembly steps. According to the definition of RCC, the complexity of assembly at step i is measured with the assumption that part i and all its precedent parts have been assembled. Therefore, the maximum amount of RCC of an assembly takes place at step zero, where no part has been assembled yet.

Once the RCC of step zero is measured, the Normalized RCC (NRCC) of the subsequent steps can be determined as:

$$NRCC_i = \frac{RCC_i}{RCC_{max}} \tag{7.10}$$

where, $NRCC_i$ is the normalized RCC of step i,

and RCC_{max} is the RCC of assembly at step zero.

The discussed approach is applied on the assembly sequences illustrated in figure 7.11. According to the calculations, the RCC of the assembly at step zero is 10.57. Table 7.3 and figure 7.13 demonstrate the effect of subassembly on NRCC.

Summary- Normalized RCC (RCCmax= 10.57)

Step	Normalized RCC-Sequence 1	Normalized RCC-Sequence 2
1	0.99	0.36
2	0.95	0.29
3	0.94	0.15
4	0.88	0.09
5	0.84	0.00
6	0.79	0.73
7	0.77	0.68
8	0.75	0.67
9	0.64	0.60
10	0.50	0.54
11	0.46	0.46
12	0.41	0.41
13	0.29	0.29
14	0.15	0.15
15	0.09	0.09
16	0.00	0.00

Table 7.3: Effect of subassembly on NRCC

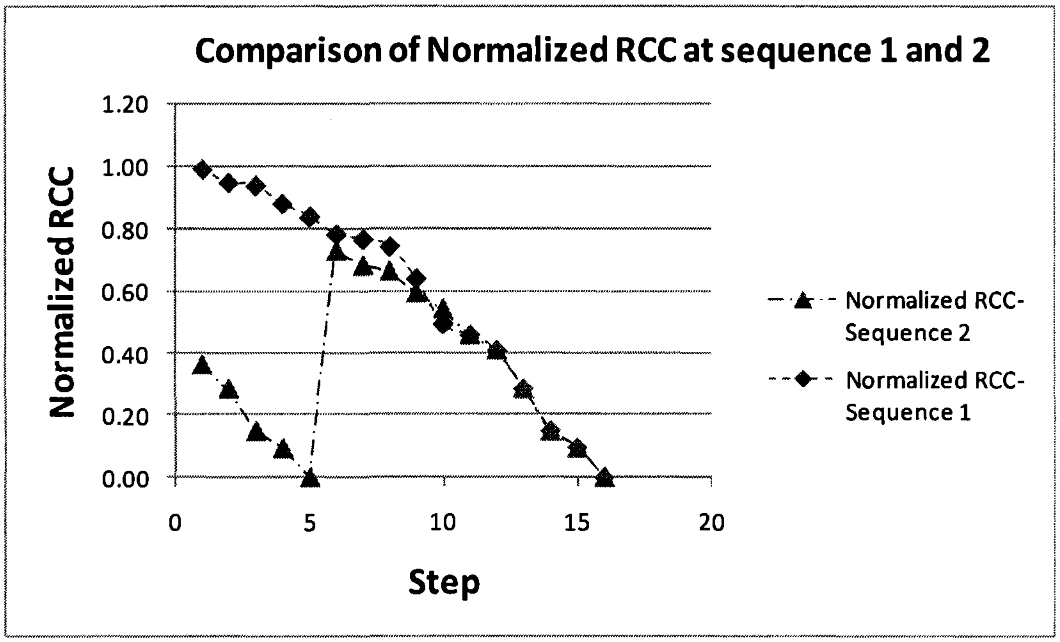


Figure 7.13: Effect of subassembly on NRCC

7.6. RCC and Product Variety

As mentioned before, RCC and NRCC measure the effect of each part on the system complexity at each step. Therefore, it can be leveraged as a tool to assist system designers to identify the step to introduce product variation.

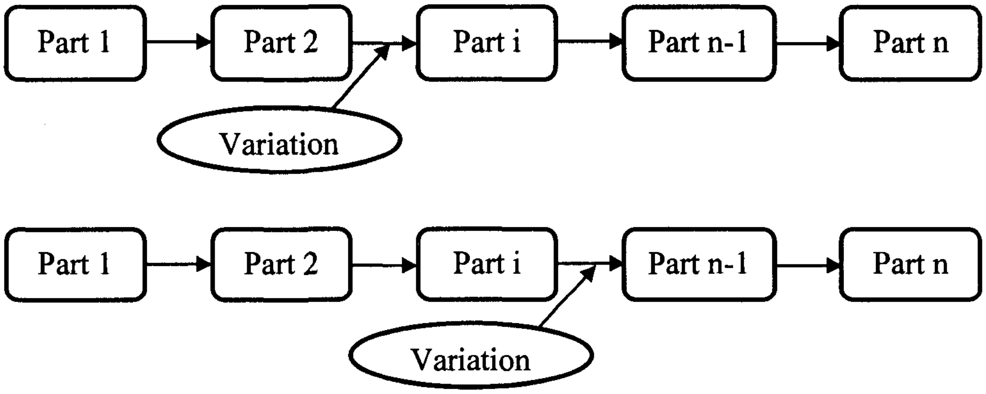


Figure 7.14: Product variation in assembly

Figure 7.14 is a schematic illustration that shows the possible choices to insert product variation. Determining the step to insert the variation from a list of candidates (e.g. step “i” or “n-1”) is a very hard and critical task. System complexity can be considered as a possible approach to address this issue. In this regard, RCC and NRCC can be applied to measure the complexity of each candidate step to determine the step with the lowest complexity.

Chapter 8

Conclusion

8.1. Conclusion

Assembly is a complex process because of the various numbers of components, intricate relation among components, assembly techniques, and different assembly sequences. Modeling of manufacturing assembly is a field of study that has not been completely covered. Measuring the assembly complexity helps system designers to recognize the sources of complexity in the system, and to reduce the system cost. There are many aspects to be considered in measuring the assembly complexity. Some of these aspects are considering the effect of product, assembly process, assembly sequences, and variety on the assembly complexity metric. Developing an integrated metric considering all aspects of the assembly complexity is considered as a future work. The important issue is that most of these factors are coupled to each other, i.e. making any change in one area affects the others.

In this study, a matrix-based method was developed to measure the complexity of assembly, which is affected by component and process-related factors. In this method, a system analysis leads to the development of an objective measure, which brings all the effective factors in assembly complexity to a single number.

The elements of complexity in this model were the diversity of information, information amount, and the relative effort to perform the assembly. The involved tasks in assembly are selection, handling, alignment, and insertion.

The implication of the proposed methodology on different case studies demonstrates that the assembly complexity and its related cost will rise with increasing part count. In addition, the result of applying complexity metric confirms that the complexity of product before applying DFA method is higher than the complexity after applying DFA method.

In this thesis, another complexity metric was introduced in the functional domain, i.e. Reduced Combinatorial Complexity (RCC). Applying the Axiomatic Design principles yields that in order to assemble an accepted quality product, it is necessary to appropriately select, orient, and insert the product with respect to the feasible and available choices.

RCC should be calculated at each assembly step, in which a component is assembled. RCC provides a good measure to determine which step, or component, has higher impact on the assembly complexity. The other benefit of RCC is to evaluate the feasible assembly sequences based on their complexity. In addition, RCC confirms that applying "Divide and Conquer" algorithm on assembly and dividing assembly into subassemblies will result in significant reduction in complexity. Furthermore, it can be used as a tool to compare different subassemblies and their effect on reducing the assembly total complexity.

8.2. Contributions

The contributions of this research are as follows:

- A model is developed to measure the assembly complexity, which is caused directly by components and assembly process, and indirectly by assembly sequences. In addition, this model considers the effect of assembling each part on the subsequent components.

- According to this model, the effect of component and process-related elements on each assembly task is measured for every component. Therefore, the components that result in the highest complexity of each task are identified.

- This model is completely in alliance with the DFA method, which is widely accepted as a well-defined model to reduce the assembly difficulty.

- A novel idea, i.e. Reduced Combinatorial Complexity (RCC) is introduced to capture the complexity of assembly in the functional domain. In this approach, complexity of the system at step i is measured, assuming that component "i" and its precedent components are assembled. Therefore, it provides information about the system complexity due to the remaining components.

- RCC can be used as a tool to measure the complexity of different assembly sequences, subassemblies, and product variations on assembly.

8.3. Future Works

The proposed matrix-based complexity metric is applied on manual assembly. Nevertheless, with a small amount of further alteration, it can be applied as a metric for automatic assembly complexity.

Finding feasible assembly sequences and choosing the most appropriate ones with regard to complexity is a new research area. In this study, the proposed model gives a tool to measure the complexity of different sequences, but it is not considered as a direct factor on the proposed metrics.

It is also worthwhile to develop an integrated model that considers the effect of product, assembly sequence, and variety on assembly complexity.

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Appendix A

Assembly Complexity Measurement Tool

Part k

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specification	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	a_{11}	a_{12}	a_{13}	A_1	$Ph_{1,com}$	b_{11}	b_{12}	b_{13}	B_1	$Cg_{1,com}$
Alignment	a_{21}	a_{22}	a_{23}	A_2	$Ph_{2,com}$	b_{21}	b_{22}	b_{23}	B_2	$Cg_{2,com}$
Insertion	a_{31}	a_{32}	a_{33}	A_3	$Ph_{3,com}$	b_{31}	b_{32}	b_{33}	B_3	$Cg_{3,com}$

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	c_{11}	c_{12}	c_{13}	c_{14}	c_{15}	c_{16}	c_{17}	C_1	$Ph_{1,pro}$
Alignment	c_{21}	c_{22}	c_{23}	c_{24}	c_{25}	c_{26}	c_{27}	C_2	$Ph_{2,pro}$
Insertion	c_{31}	c_{32}	c_{33}	c_{34}	c_{35}	c_{36}	c_{37}	C_3	$Ph_{3,pro}$

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	d_{11}	d_{12}	d_{13}	d_{14}	d_{15}	d_{16}	D_1	$Cg_{1,pro}$
Alignment	d_{21}	d_{22}	d_{23}	d_{24}	d_{25}	d_{26}	D_2	$Cg_{2,pro}$
Insertion	d_{31}	d_{32}	d_{33}	d_{34}	d_{35}	d_{36}	D_3	$Cg_{3,pro}$

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	$Ph_{1,com}$	$Cg_{1,com}$	$TE_{1,com}$	$Ph_{1,pro}$	$Cg_{1,pro}$	$TE_{1,pro}$	TE_1
Alignment	$Ph_{2,com}$	$Cg_{2,com}$	$TE_{2,com}$	$Ph_{2,pro}$	$Cg_{2,pro}$	$TE_{2,pro}$	TE_2
Insertion	$Ph_{3,com}$	$Cg_{3,com}$	$TE_{3,com}$	$Ph_{3,pro}$	$Cg_{3,pro}$	$TE_{3,pro}$	TE_3

For part k:

a_{ij}: Component related physical effort level for task i

b_{il}: Component related cognitive effort level for task i

c_{im}: Process related physical effort level for task i

d_{in}: Process related cognitive effort level for task i

For task i= 1, 2, 3 (Handling, Alignment, Insertion)

$A_i = \sum_{j=1}^{3} a_{ij}$, and

$Ph_{i,com} = \frac{A_i}{K_{ph}}$, and K_{ph} is the number of considered physical elements

$B_i = \sum_{l=1}^{3} b_{il}$, and

$Cg_{i,com} = \frac{B_i}{K_{cg}}$, and K_{cg} is the number of considered cognitive elements

$C_i = \sum_{m=1}^{7} c_{im}$, and

$Ph_{i,pro} = \frac{C_i}{M_{ph}}$, and M_{ph} is the number of considered physical elements

$D_i = \sum_{n=1}^{6} d_{in}$, and

$Cg_{i,pro} = \frac{D_i}{M_{cg}}$, and M_{cg} is the number of considered cognitive elements

$$TE_{i,com} = \frac{Ph_{i.com} + Cg_{i.com}}{2}$$

$$TE_{i,pro} = \frac{Ph_{i.pro} + Cg_{i.pro}}{2}$$

$$TE_i = \frac{TE_{i.com} + TE_{i.pro}}{2}$$

Part	No.	Percentage	Selection	Handling	Alignment	Insertion	Sum	Average	Part Share
Part 1	n_1	E_1	$TE_{1,0}$	$TE_{1,1}$	$TE_{1,2}$	$TE_{1,3}$	F_1	G_1	$PEff_1$
Part 2	n_2	E_2	$TE_{2,0}$	$TE_{2,1}$	$TE_{2,2}$	$TE_{2,3}$	F_2	G_2	$PEff_2$
...	...	...	...	...	...	...	...	...	...
Part k-1	n_{k-1}	E_{k-1}	$TE_{k-1,0}$	$TE_{k-1,1}$	$TE_{K-1,2}$	$TE_{k-1,3}$	F_{k-1}	G_{k-1}	$PEff_{k-1}$
Part k	n_k	E_k	$TE_{k,0}$	$TE_{k,1}$	$TE_{k,2}$	$TE_{k,3}$	F_k	G_k	$PEff_k$
							Assembly Relative Effort		0.00

For part k:

n_k: Number of component type k

$$N = \sum_{k=1}^{K} n_k$$

$$E_k = \frac{n_k}{N}$$

$T_{k,i}$: i^{th} task effort for part k

i(0, 1, 2, 3)= (selection, handling, alignment, insertion)

$$F_k = \sum_{i=0}^{3} TE_{k,i}$$

$$G_k = \frac{F_k}{4}$$

$$PEff_k = E_k \times G_k = \frac{n_k}{N} \times \frac{\sum_{i=0}^{3} TE_{k,i}}{4}$$

Assembly Relative Effort, REff:

$$REff = \sum_{k=1}^{P_k} PEff_k$$

Appendix B

Diaphragm Assembly Complexity (Before/ after DFA)

B.1. Diaphragm Assembly Complexity (Before DFA): Coupling Chart

Coupling Chart- Diaphragm Assembly Complexity (Before DFA)

		Part j							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Part i	**1**	0	0	0	0	0	0	0	0
	2		0	1	0	0	0	0	0
	3			0	1	1	0	0	0
	4				0	1	0	0	0
	5					0	0	0	0
	6						0	1	1
	7							0	1
	8								0
%		0.00	0.00	0.33	0.25	0.40	0.00	0.00	0.17

B.2. Diaphragm Assembly Complexity (Before DFA): Part Task Effort

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignmen	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.80	0.27
Insertion	0.00	0.50	0.00	0.50	0.17	0.80	0.00	0.00	0.80	0.27

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignmen	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.50	0.07

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignmen	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.00	0.50	0.08

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignmen	0.00	0.27	0.14	0.00	0.00	0.00	**0.07**
Insertion	0.17	0.27	0.22	0.07	0.08	0.08	**0.15**

Part 1- Plate

Part 2- Bearing Housing

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignmen	0.00	0.50	0.00	0.50	0.17	1.00	0.80	0.00	1.80	0.60
Insertion	0.00	0.50	0.00	0.50	0.17	1.00	0.80	0.00	1.80	0.60

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	-	0.00	0.00
Alignmen	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.50	0.07

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignmen	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.50	1.00	0.17

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignmen	0.17	0.60	0.39	0.00	0.00	0.00	**0.19**
Insertion	0.17	0.60	0.39	0.07	0.17	0.12	**0.25**

Part 3- Screw 1

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignmen	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	-	0.00	0.00
Alignmen	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.00
Insertion	0.50	0.00	0.00	1.00	0.50	0.33	0.50	2.83	0.40

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	0.00	0.00
Alignmen	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00
Insertion	0.50	0.00	0.00	1.00	0.50	0.50	2.50	0.42

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignmen	0.33	0.33	0.33	0.00	0.00	0.00	**0.17**
Insertion	0.33	0.33	0.33	0.40	0.42	0.41	**0.37**

Part 4- Washer 1

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignmen	0.50	0.50	0.00	1.00	0.33	0.80	0.00	0.00	0.80	0.27
Insertion	0.50	0.50	0.00	1.00	0.33	0.80	0.00	0.00	0.80	0.27

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	-	0.00	0.00
Alignmen	0.00	0.50	0.00	0.00	-	0.00	-	0.50	0.07
Insertion	0.50	0.50	0.00	0.00	1.00	0.25	0.00	2.25	0.32

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	0.00	0.00
Alignmen	0.00	0.50	0.00	0.00	-	0.00	0.50	0.08
Insertion	0.50	1.00	0.50	0.00	1.00	0.00	3.00	0.50

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignmen	0.33	0.27	0.30	0.07	0.08	0.08	**0.19**
Insertion	0.33	0.27	0.30	0.32	0.50	0.41	**0.36**

Part 5- Nut 1

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignmen	0.50	0.50	0.00	1.00	0.33	0.80	0.00	0.00	0.80	0.27
Insertion	0.50	0.50	0.00	1.00	0.33	0.80	0.00	0.50	1.30	0.43

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	-	0.00	0.00
Alignmen	0.00	0.50	0.00	0.00	-	0.00	-	0.50	0.07
Insertion	0.50	0.50	0.00	0.00	0.00	0.40	0.50	1.90	0.27

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	0.00	0.00
Alignmen	0.00	0.50	0.50	0.00	-	0.00	1.00	0.17
Insertion	0.00	1.00	1.00	0.00	0.00	0.00	2.00	0.33

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignmen	0.33	0.27	0.30	0.07	0.17	0.12	**0.21**
Insertion	0.33	0.43	0.38	0.27	0.33	0.30	**0.34**

Part 6- Screw 2

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatio sn	Physical/ Material Propertie s	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignmen	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	-	0.00	0.00
Alignmen	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.00
Insertion	0.50	0.00	0.00	0.00	0.50	0.00	0.50	1.50	0.21

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	0.00	0.00
Alignmen	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00
Insertion	0.50	0.00	0.00	0.00	0.50	0.50	1.50	0.25

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignmen	0.33	0.33	0.33	0.00	0.00	0.00	**0.17**
Insertion	0.33	0.33	0.33	0.21	0.25	0.23	**0.28**

Part 7- Washer 2

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignmen	0.50	0.50	0.00	1.00	0.33	0.80	0.00	0.00	0.80	0.27
Insertion	0.50	0.50	0.00	1.00	0.33	0.80	0.00	0.00	0.80	0.27

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	-	0.00	0.00
Alignmen	0.00	0.50	0.00	0.00	-	0.00	-	0.50	0.07
Insertion	0.50	0.50	0.00	0.00	1.00	0.00	0.00	2.00	0.29

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	0.00	0.00
Alignmen	0.00	0.50	0.00	0.00	-	0.00	0.50	0.08
Insertion	0.50	0.50	0.50	0.00	1.00	0.00	2.50	0.42

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignmen	0.33	0.27	0.30	0.07	0.08	0.08	**0.19**
Insertion	0.33	0.27	0.30	0.29	0.42	0.36	**0.33**

Part 8- Nut 2

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignmen	0.50	0.50	0.00	1.00	0.33	0.80	0.00	0.00	0.80	0.27
Insertion	0.50	0.50	0.00	1.00	0.33	0.80	0.00	0.50	1.30	0.43

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	-	0.00	0.00
Alignmen	0.00	0.50	0.00	0.00	-	0.00	-	0.50	0.07
Insertion	0.50	0.50	0.00	0.00	0.00	0.17	0.50	1.67	0.24

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	0.00	0.00
Alignmen	0.00	0.50	0.50	0.00	-	0.00	1.00	0.17
Insertion	0.00	0.50	0.50	0.00	0.00	0.00	1.00	0.17

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignmen	0.33	0.27	0.30	0.07	0.17	0.12	**0.21**
Insertion	0.33	0.43	0.38	0.24	0.17	0.21	**0.29**

B.3. Diaphragm Assembly Complexity (Before DFA): Assembly Relative Effort

Part	No.	Percentage	Selection	Handling	Alignment	Insertion	Sum	Average	Part Share
Part 1	1.00	0.13	0.88	0.00	0.07	0.15	1.10	0.27	0.03
Part 2	1.00	0.13	0.86	0.00	0.19	0.25	1.30	0.32	0.04
Part 3	1.00	0.13	0.67	0.00	0.17	0.37	1.21	0.30	0.04
Part 4	1.00	0.13	0.60	0.00	0.19	0.36	1.15	0.29	0.04
Part 5	1.00	0.13	0.50	0.00	0.21	0.34	1.05	0.26	0.03
Part 6	1.00	0.13	0.67	0.00	0.17	0.28	1.12	0.28	0.04
Part 7	1.00	0.13	0.50	0.00	0.19	0.33	1.02	0.26	0.03
Part 8	1.00	0.13	0.00	0.00	0.21	0.29	0.50	0.13	0.02
							Assembly Relative Effort		0.26

B.4. Diaphragm Assembly Complexity (After DFA): Part Task Effort

Part 1- Plate

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.80	0.27
Insertion	0.00	0.50	0.00	0.50	0.17	0.80	0.00	0.00	0.80	0.27

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Cognitive Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.27	0.14	0.00	0.00	0.00	**0.07**
Insertion	0.17	0.27	0.22	0.00	0.00	0.00	**0.11**

Part 2- Bearing Housing

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.33
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	0.00	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	0.00	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.50	0.07

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.00	0.50	0.08

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.33	0.17	0.00	0.00	0.00	**0.08**
Insertion	0.00	0.33	0.17	0.07	0.08	0.08	**0.12**

B.5. Diaphragm Assembly Complexity (After DFA): Assembly Relative Effort

Part	No.	Percentage	Selection	Handling	Alignment	Insertion	Sum	Average	Part Share
Part 1	1.00	0.50	0.50	0.00	0.07	0.11	0.68	0.17	0.09
Part 2	1.00	0.50	0.00	0.00	0.08	0.12	0.20	0.05	0.03
							Assembly Relative Effort		0.11

Appendix C

Motor Drive Assembly Complexity (Before/ after DFA)

C.1. Motor Drive Assembly Complexity (Before DFA): Coupling Chart

Coupling Chart- Motor Drive Assembly Complexity (Before DFA)

		Part j																		
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Part i	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
	2		0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	3			0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
	4				0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	5					0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	6						0	0	0	0	0	0	1	0	0	0	0	0	0	0
	7							0	0	0	0	0	1	0	0	0	0	0	0	0
	8								0	0	0	0	1	0	0	0	0	0	0	0
	9									0	0	0	0	0	0	0	0	0	0	0
	10										0	0	0	0	0	0	0	0	0	0
	11											0	1	0	0	0	0	0	0	0
	12												0	1	0	1	0	0	0	0
	13													0	0	0	0	0	0	0
	14														0	0	0	0	0	0
	15															0	0	0	0	0
	16																0	0	0	0
	17																	0	0	0
	18																		0	0
	19																			0
Relativity		0.00	0.00	0.00	0.25	0.00	0.33	0.14	0.00	0.00	0.00	0.00	0.33	0.08	0.00	0.20	0.00	0.00	0.00	0.00

C.2. Motor Drive Assembly Complexity (Before DFA): Part Task Effort

Part 1 - Base

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	0.80	0.00	1.80	0.60
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	0.80	0.00	1.80	0.60

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00			0.00	0.00

Cognitive Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.60	0.30	0.00	0.00	0.00	**0.15**
Insertion	0.00	0.60	0.30	0.00	0.00	0.00	**0.15**

Part 2 - Sensor

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.00	0.00	0.50	0.17	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.07

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.50	0.00	0.50	0.00	0.00	0.00	1.00	0.17

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.33	0.17	0.00	0.00	0.00	**0.08**
Insertion	0.17	0.33	0.25	0.07	0.17	0.12	**0.19**

Part 3- Set screw

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.00	0.00	0.50	0.17	0.80	0.00	0.00	0.80	0.27
Insertion	1.00	0.50	0.00	1.50	0.50	0.80	0.00	0.50	1.30	0.43

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.50	0.50	0.00	0.00	-	-	-	1.00	0.14
Insertion	0.50	0.50	0.00	0.00	0.00	0.00	0.50	1.50	0.21

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.50	0.50	0.00	0.00	-	-	1.00	0.17
Insertion	0.50	0.50	0.50	0.00	0.00	0.50	2.00	0.33

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.17	0.27	0.22	0.14	0.17	0.16	**0.19**
Insertion	0.50	0.43	0.47	0.21	0.33	0.27	**0.37**

Part 4 - Bush 1

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.80	0.27
Insertion	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.80	0.27

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	-	0.50	0.07
Insertion	0.00	0.00	0.50	0.00	0.50	0.25	0.00	1.25	0.18

Cognitive Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.50	0.00	0.50	0.00	1.00	0.17

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.27	0.14	0.07	0.00	0.04	**0.09**
Insertion	0.00	0.27	0.14	0.18	0.17	0.18	**0.16**

Part 5- Bush 2

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.80	0.27
Insertion	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.80	0.27

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	-	0.50	0.07
Insertion	0.00	0.00	0.50	0.00	0.50	0.00	0.00	1.00	0.14

Cognitive Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.50	0.00	0.50	0.00	1.00	0.17

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.27	0.14	0.07	0.00	0.04	**0.09**
Insertion	0.00	0.27	0.14	0.14	0.17	0.16	**0.15**

Part 6 - Stand off 1

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.33
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	-	0.50	0.07
Insertion	0.00	0.00	1.00	0.00	0.00	0.33	0.50	1.83	0.26

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	0.50	0.08
Insertion	0.00	0.00	1.00	0.00	0.00	0.50	1.50	0.25

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.33	0.17	0.07	0.08	0.08	**0.12**
Insertion	0.00	0.33	0.17	0.26	0.25	0.26	**0.21**

Part 7- Stand off 2

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.33
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	-	0.50	0.07
Insertion	0.00	0.00	1.00	0.00	0.00	0.14	0.50	1.64	0.23

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	0.50	0.08
Insertion	0.00	0.00	1.00	0.00	0.00	0.50	1.50	0.25

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.33	0.17	0.07	0.08	0.08	**0.12**
Insertion	0.00	0.33	0.17	0.23	0.25	0.24	**0.20**

Part 8- Motor

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	2.00	0.67
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.50	2.50	0.83

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.50	0.07

Cognitive Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.50	0.00	0.50	0.00	1.00	0.17

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.67	0.34	0.00	0.00	0.00	**0.17**
Insertion	0.00	0.83	0.42	0.07	0.17	0.12	**0.27**

Part 9- motor screw 1

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	-	0.50	0.07
Insertion	0.50	0.00	1.00	0.50	0.00	0.00	0.50	2.50	0.36

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	0.50	0.08
Insertion	0.50	0.00	1.00	0.50	0.00	0.50	2.50	0.42

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.07	0.08	0.08	**0.20**
Insertion	0.33	0.33	0.33	0.36	0.42	0.39	**0.36**

Part 10 - motor screw 2

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	-	0.50	0.07
Insertion	0.50	0.00	1.00	0.50	0.00	0.00	0.50	2.50	0.36

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	0.50	0.08
Insertion	0.50	0.00	1.00	0.50	0.00	0.50	2.50	0.42

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.07	0.08	0.08	**0.20**
Insertion	0.33	0.33	0.33	0.36	0.42	0.39	**0.36**

Part 11- Plastic bush

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.00	0.00	0.50	0.17	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.00	0.50	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Cognitive Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.50	0.00	0.00	-	-	0.50	0.08
Insertion	0.00	0.50	0.00	0.00	0.00	0.00	0.50	0.08

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.17	0.33	0.25	0.00	0.08	0.04	**0.15**
Insertion	0.33	0.33	0.33	0.00	0.08	0.04	**0.19**

Part 12-end plate

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.50	0.00	0.50	0.17	1.00	1.00	0.00	2.00	0.67
Insertion	0.00	0.50	0.00	0.50	0.17	1.00	1.00	0.00	2.00	0.67

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.33	0.00	0.83	0.12

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.50	1.00	0.17

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.17	0.67	0.42	0.00	0.00	0.00	**0.21**
Insertion	0.17	0.67	0.42	0.12	0.17	0.15	**0.28**

Part 13 - end plate screw 1

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.50	0.50	0.00	0.00	0.00	0.08	0.50	1.58	0.23

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.50	0.00	0.00	-	-	0.50	0.08
Insertion	0.50	0.50	0.00	0.00	0.00	0.50	1.50	0.25

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.00	0.08	0.04	**0.19**
Insertion	0.33	0.33	0.33	0.23	0.25	0.24	**0.29**

Part 14 - end plate screw 2

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.50	0.50	0.00	0.00	0.00	0.00	0.50	1.50	0.21

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.50	0.00	0.00	-	-	0.50	0.08
Insertion	0.50	0.50	0.00	0.00	0.00	0.50	1.50	0.25

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.08	0.00	0.04	**0.19**
Insertion	0.33	0.33	0.33	0.21	0.25	0.23	**0.28**

Part 15-Cover

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	2.00	0.67
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	2.00	0.67

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.20	0.03

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.08

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.67	0.34	0.00	0.00	0.00	**0.17**
Insertion	0.00	0.67	0.34	0.03	0.08	0.06	**0.20**

Part 16 - Cover Screw 1

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.50	0.00	0.00	-	-	-	0.50	0.07
Insertion	0.50	0.50	0.00	0.00	0.00	0.00	0.50	1.50	0.21

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.50	0.00	0.00	-	-	0.50	0.08
Insertion	0.50	0.50	0.00	0.00	0.00	0.50	1.50	0.25

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.07	0.08	0.08	**0.20**
Insertion	0.33	0.33	0.33	0.21	0.25	0.23	**0.28**

Part 17 - Cover Screw 2

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.50	0.00	0.00	-	-	-	0.50	0.07
Insertion	0.50	0.50	0.00	0.00	0.00	0.00	0.50	1.50	0.21

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.50	0.00	0.00	-	-	0.50	0.08
Insertion	0.50	0.50	0.00	0.00	0.00	0.50	1.50	0.25

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.07	0.08	0.08	**0.20**
Insertion	0.33	0.33	0.33	0.21	0.25	0.23	**0.28**

Part 18 - Cover Screw 3

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.50	0.00	0.00	-	-	-	0.50	0.07
Insertion	0.50	0.50	0.00	0.00	0.00	0.00	0.50	1.50	0.21

Cognitive Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.50	0.00	0.00	0.00	-	-	0.50	0.08
Insertion	0.50	0.50	0.00	0.00	0.00	0.50	1.50	0.25

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.07	0.08	0.08	**0.20**
Insertion	0.33	0.33	0.33	0.21	0.25	0.23	**0.28**

Part 19 - Cover Screw 4

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface	Physical/	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.50	0.00	0.00	-	-	-	0.50	0.07
Insertion	0.50	0.50	0.00	0.00	0.00	0.00	0.50	1.50	0.21

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.50	0.00	0.00	-	-	0.50	0.08
Insertion	0.50	0.50	0.00	0.00	0.00	0.50	1.50	0.25

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.07	0.08	0.08	**0.20**
Insertion	0.33	0.33	0.33	0.21	0.25	0.23	**0.28**

C.3. Motor Drive Assembly Complexity (Before DFA): Assembly Relative Effort

Part	No.	Percentage	Selection	Handling	Alignment	Insertion	Sum	Average	Part Share
Part 1	1.00	0.05	0.95	0.00	0.15	0.15	1.25	0.31	0.02
Part 2	1.00	0.05	0.94	0.00	0.08	0.19	1.21	0.30	0.02
Part 3	1.00	0.05	0.94	0.00	0.19	0.37	1.50	0.38	0.02
Part 4	1.00	0.05	0.88	0.00	0.09	0.16	1.13	0.28	0.01
Part 5	1.00	0.05	0.93	0.00	0.09	0.15	1.17	0.29	0.02
Part 6	1.00	0.05	0.86	0.00	0.12	0.21	1.19	0.30	0.02
Part 7	1.00	0.05	0.92	0.00	0.12	0.21	1.25	0.31	0.02
Part 8	1.00	0.05	0.91	0.00	0.17	0.27	1.35	0.34	0.02
Part 9	1.00	0.05	0.82	0.00	0.20	0.36	1.38	0.35	0.02
Part 10	1.00	0.05	0.90	0.00	0.20	0.36	1.46	0.37	0.02
Part 11	1.00	0.05	0.89	0.00	0.15	0.19	1.23	0.31	0.02
Part 12	1.00	0.05	0.88	0.00	0.21	0.28	1.37	0.34	0.02
Part 13	1.00	0.05	0.71	0.00	0.19	0.29	1.19	0.30	0.02
Part 14	1.00	0.05	0.83	0.00	0.19	0.28	1.30	0.33	0.02
Part 15	1.00	0.05	0.80	0.00	0.17	0.20	1.17	0.29	0.02
Part 16	1.00	0.05	0.00	0.00	0.20	0.28	0.48	0.12	0.01
Part 17	1.00	0.05	0.00	0.00	0.20	0.28	0.48	0.12	0.01
Part 18	1.00	0.05	0.00	0.00	0.20	0.28	0.48	0.12	0.01
Part 19	1.00	0.05	0.00	0.00	0.20	0.28	0.48	0.12	0.01
							Assembly Relative Effort		0.28

C.4. Motor Drive Assembly Complexity (After DFA): Coupling Chart

Coupling Chart- motor Drive Assembly Complexity (After DFA)

		Part j						
		1	**2**	**3**	**4**	**5**	**6**	**7**
Part i	**1**	0	0	0	0	0	0	0
	2		0	0	0	0	0	0
	3			0	0	0	0	1
	4				0	0	0	1
	5					0	0	0
	6						0	0
	7							0
Relativity		0.00	0.00	0.00	0.00	0.00	0.00	0.29

C.5. Motor Drive Assembly Complexity (After DFA): Part Task Effort

Part 1 - Base

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	0.80	0.00	1.80	0.60
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	0.80	0.00	1.80	0.60

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Cognitive Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.60	0.30	0.00	0.00	0.00	**0.15**
Insertion	0.00	0.60	0.30	0.00	0.00	0.00	**0.15**

Part 2 - Sensor

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.00	0.00	0.50	0.17	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.07

Cognitive Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.50	0.00	0.50	0.00	0.00	0.00	1.00	0.17

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.33	0.17	0.00	0.00	0.00	**0.08**
Insertion	0.17	0.33	0.25	0.07	0.17	0.12	**0.19**

Part 3- Set screw

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.00	0.00	0.50	0.17	0.80	0.00	0.00	0.80	0.27
Insertion	1.00	0.50	0.00	1.50	0.50	0.80	0.00	0.50	1.30	0.43

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.50	0.50	0.00	0.00	-	-	-	1.00	0.14
Insertion	0.50	0.50	0.00	0.00	0.00	0.00	0.50	1.50	0.21

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.50	0.50	0.00	0.00	-	-	1.00	0.17
Insertion	0.50	0.50	0.50	0.00	0.00	0.50	2.00	0.33

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.17	0.27	0.22	0.14	0.17	0.16	**0.19**
Insertion	0.50	0.43	0.47	0.21	0.33	0.27	**0.37**

Part 4- Motor

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	2.00	0.67
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.50	2.50	0.83

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.50	0.07

Cognitive Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.50	0.00	0.50	0.00	1.00	0.17

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.67	0.34	0.00	0.00	0.00	**0.17**
Insertion	0.00	0.83	0.42	0.07	0.17	0.12	**0.27**

Part 5- motor screw 1

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	-	0.50	0.07
Insertion	0.50	0.00	1.00	0.50	0.00	0.00	0.50	2.50	0.36

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	0.50	0.08
Insertion	0.50	0.00	1.00	0.50	0.00	0.50	2.50	0.42

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.07	0.08	0.08	**0.20**
Insertion	0.33	0.33	0.33	0.36	0.42	0.39	**0.36**

Part 6 - motor screw 2

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	-	0.50	0.07
Insertion	0.50	0.00	1.00	0.50	0.00	0.00	0.50	2.50	0.36

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	0.50	0.08
Insertion	0.50	0.00	1.00	0.50	0.00	0.50	2.50	0.42

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.07	0.08	0.08	**0.20**
Insertion	0.33	0.33	0.33	0.36	0.42	0.39	**0.36**

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	2.00	0.67
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	2.00	0.67

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.29	0.00	0.29	0.04

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.08

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.67	0.34	0.00	0.00	0.00	**0.17**
Insertion	0.00	0.67	0.34	0.04	0.08	0.06	**0.20**

C.6. Motor Drive Assembly Complexity (After DFA): Assembly Relative Effort

Part	No.	Percentage	Selection	Handling	Alignment	Insertion	Sum	Average	Part Share
Part 1	1.00	0.14	0.86	0.00	0.15	0.15	1.16	0.29	0.04
Part 2	1.00	0.14	0.83	0.00	0.08	0.19	1.10	0.28	0.04
Part 3	1.00	0.14	0.80	0.00	0.19	0.37	1.36	0.34	0.05
Part 4	1.00	0.14	0.75	0.00	0.17	0.27	1.19	0.30	0.04
Part 5	1.00	0.14	0.33	0.00	0.20	0.36	0.89	0.22	0.03
Part 6	1.00	0.14	0.50	0.00	0.20	0.36	1.06	0.27	0.04
Part 7	1.00	0.14	0.00	0.00	0.17	0.20	0.37	0.09	0.01
							Assembly Relative Effort		0.25

Appendix D

Pressure Recorder Assembly Complexity (Before/ after DFA)

D.1. Pressure Recorder Assembly Complexity (Before DFA): Coupling Chart

Coupling Chart- Pressure Recorder Assembly Complexity (Before DFA)

		Part j																		
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Part i	**1**	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	2		0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	3			0	1	0	0	0	0	0	0	0		0	0	0	0	0	0	0
	4				0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	5					0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	6						0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7							0	0	0	0	0	1	0	0	0	0	0	0	0
	8								0	0	0	0	0	0	0	0	0	0	0	0
	9									0	0	0	0	0	0	0	0	0	0	0
	10										0	0	0	0	0	0	0	0	0	1
	11											0	0	0	0	0	0	1	0	0
	12												0	0	0	0	0	0	1	0
	13													0	0	0	0	0	0	0
	14														0	0	0	0	0	0
	15															0	0	0	0	0
	16																0	1	0	0
	17																	0	0	1
	18																		0	0
	19																			0
Relativity		0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.42	0.00	0.00	0.00	0.00	0.12	0.06	0.11

D.2. Pressure Recorder Assembly Complexity (Before DFA): Part Task Effort

Part 1- Metal Frame

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	0.80	0.00	1.80	0.60
Insertion	0.00	0.50	0.00	0.50	0.17	1.00	0.80	0.00	1.80	0.60

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Cognitive Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.60	0.30	0.00	0.00	0.00	**0.15**
Insertion	0.17	0.60	0.39	0.00	0.00	0.00	**0.19**

Part 2- PCB Assembly

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	2.00	0.67
Insertion	0.00	0.50	0.00	0.50	0.17	1.00	1.00	0.50	2.50	0.83

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.50	0.07

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.00	0.50	0.08

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.67	0.34	0.00	0.00	0.00	**0.17**
Insertion	0.17	0.83	0.50	0.07	0.08	0.08	**0.29**

Part 3- Earth lead

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.80	0.27
Insertion	0.00	0.00	0.50	0.50	0.17	0.80	0.00	0.50	1.30	0.43

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.50	0.00	0.50	0.50	1.00	0.00	0.00	2.50	0.36

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.50	0.00	0.50	0.50	1.00	0.00	2.50	0.42

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.27	0.14	0.00	0.00	0.00	**0.07**
Insertion	0.17	0.43	0.30	0.36	0.42	0.39	**0.35**

Part 4- screw

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.50	0.00	0.00	0.00	-	-	-	0.50	0.10
Insertion	1.00	0.50	0.50	0.50	0.00	0.25	0.50	3.25	0.46

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.50	0.00	0.00	0.00	-	-	0.50	0.10
Insertion	1.00	0.50	0.50	0.50	0.00	0,5	2.50	0.42

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.10	0.10	0.10	**0.22**
Insertion	0.33	0.33	0.33	0.46	0.42	0.44	**0.39**

Part 5- Screw

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.50	0.50	0.50	0.00	0.00	0.00	0.50	2.00	0.29

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.50	0.50	0.50	0.00	0.00	0.50	2.00	0.33

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.00	0.00	0.00	**0.17**
Insertion	0.33	0.33	0.33	0.29	0.33	0.31	**0.32**

Part 6- Sensor

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	2.00	0.67
Insertion	0.00	0.50	0.00	0.50	0.17	1.00	1.00	0.50	2.50	0.83

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.50	0.50	0.00	0.50	0.00	0.00	1.50	0.21

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.50	0.50	0.00	0.50	0.00	1.50	0.25

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical	Cognitive	Task Effort	Physical	Cognitive	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.67	0.34	0.00	0.00	0.00	**0.17**
Insertion	0.17	0.83	0.50	0.21	0.25	0.23	**0.37**

Part 7 - Strap

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface	Physical/	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	0.80	0.00	1.80	0.60
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	0.80	0.00	1.80	0.60

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.50	0.50	0.00	0.50	0.00	0.00	1.50	0.21

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.50	0.50	0.00	0.50	0.00	1.50	0.25

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.60	0.30	0.00	0.00	0.00	**0.15**
Insertion	0.00	0.60	0.30	0.21	0.25	0.23	**0.27**

Part 8- Screw

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.50	0.50	0.50	0.50	0.00	0.00	0.50	2.50	0.36

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.50	0.50	0.50	0.50	0.00	0.50	2.50	0.42

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.00	0.00	0.00	**0.17**
Insertion	0.33	0.33	0.33	0.42	0.33	0.38	**0.35**

Part 9- Screw

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.50	0.50	0.50	0.00	0.00	0.00	0.50	2.00	0.29

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.50	0.50	0.50	0.00	0.00	0.50	2.00	0.33

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.00	0.00	0.00	**0.17**
Insertion	0.33	0.33	0.33	0.29	0.33	0.31	**0.32**

Part 10- Adaptor nut

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.33
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.50	0.50	0.00	0.00	0.00	0.50	1.50	0.21

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	0.50	0.10
Insertion	0.00	0.50	0.50	0.00	0.00	0.50	1.50	0.25

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.33	0.17	0.00	0.10	0.05	**0.11**
Insertion	0.00	0.33	0.17	0.21	0.25	0.23	**0.20**

Part 11- nut

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.80	0.27
Insertion	0.50	0.00	0.00	0.50	0.17	0.80	0.00	0.00	0.80	0.27

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.50	0.00	0.00	0.00	0.50	0.00	0.00	1.00	0.14

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.50	0.00	0.00	0.00	0.50	0.00	1.00	0.17

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.27	0.14	0.00	0.00	0.00	**0.07**
Insertion	0.17	0.27	0.22	0.14	0.17	0.16	**0.19**

Part 12- Plastic Cover

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	2.00	0.67
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	2.00	0.67

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.42	0.00	0.92	0.13

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.00	0.50	0.08

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.67	0.34	0.00	0.00	0.00	**0.17**
Insertion	0.00	0.67	0.34	0.13	0.08	0.11	**0.22**

Part 13- Screw

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.50	0.00	0.50	0.00	0.00	0.00	0.50	1.50	0.21

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.50	0.00	0.50	0.00	0.00	0.50	1.50	0.25

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.00	0.00	0.00	**0.17**
Insertion	0.33	0.33	0.33	0.21	0.25	0.23	**0.28**

Part 14- Screw

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.50	0.00	0.50	0.00	0.00	0.00	0.50	1.50	0.21

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.50	0.00	0.50	0.00	0.00	0.50	1.50	0.25

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.00	0.00	0.00	**0.17**
Insertion	0.33	0.33	0.33	0.21	0.25	0.23	**0.28**

Part 15- Screw

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33
Insertion	0.50	0.50	0.00	1.00	0.33	1.00	0.00	0.00	1.00	0.33

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.50	0.00	0.50	0.00	0.00	0.00	0.50	1.50	0.21

Cognitive Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.50	0.00	0.50	0.00	0.00	0.50	1.50	0.25

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.33	0.33	0.33	0.00	0.00	0.00	**0.17**
Insertion	0.33	0.33	0.33	0.21	0.25	0.23	**0.28**

Part 16- Connector

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	2.00	0.67
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.50	2.50	0.83

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.07

Cognitive Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.08

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.67	0.34	0.00	0.00	0.00	**0.17**
Insertion	0.00	0.83	0.42	0.07	0.08	0.08	**0.25**

Part 17- Pressure Regulator

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	2.00	0.67
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.50	2.50	0.83

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.50	0.50	0.50	0.12	0.00	1.62	0.23

	Cognitive Elements							
	Tools/	Assembly	Joint	Part	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.50	0.50	0.50	0.00	1.50	0.25

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.67	0.34	0.00	0.00	0.00	**0.17**
Insertion	0.00	0.83	0.42	0.23	0.25	0.24	**0.33**

Part 18- Knob

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.80	0.27
Insertion	0.50	0.00	0.00	0.50	0.17	0.80	0.00	0.50	1.30	0.43

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.50	0.00	0.00	-	-	-	0.50	0.10
Insertion	0.00	1.00	0.50	0.00	0.00	0.06	0.50	2.06	0.29

Cognitive Elements

	Tools/	Assembly	Joint	Part	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.50	0.00	0.00	-	-	0.50	0.10
Insertion	0.00	1.00	0.50	0.00	0.00	0.50	2.00	0.33

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.27	0.14	0.10	0.10	0.10	**0.12**
Insertion	0.17	0.43	0.30	0.29	0.33	0.31	**0.31**

Part 19- Tube Assmebly

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.80	0.27
Insertion	0.00	0.00	0.00	0.00	0.00	0.80	0.00	1.00	1.80	0.60

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	-	0.50	0.10
Insertion	0.00	0.00	1.00	0.00	0.00	0.11	0.50	1.61	0.23

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.50	0.00	-	-	0.50	0.10
Insertion	0.00	0.00	1.00	0.00	0.00		0.50	0.08

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.27	0.14	0.10	0.10	0.10	**0.12**
Insertion	0.00	0.60	0.30	0.23	0.08	0.16	**0.23**

D.3. Pressure Recorder Assembly Complexity (Before DFA): Assembly Relative Effort

Part	No.	Percentage	Selection	Handling	Alignment	Insertion	Sum	Average	Part Share
Part 1	1.00	0.05	0.95	0.00	0.15	0.19	1.29	0.32	0.02
Part 2	1.00	0.05	0.94	0.00	0.17	0.29	1.40	0.35	0.02
Part 3	1.00	0.05	0.94	0.00	0.07	0.35	1.36	0.34	0.02
Part 4	1.00	0.05	0.88	0.00	0.22	0.39	1.49	0.37	0.02
Part 5	1.00	0.05	0.93	0.00	0.17	0.32	1.42	0.36	0.02
Part 6	1.00	0.05	0.92	0.00	0.17	0.37	1.46	0.37	0.02
Part 7	1.00	0.05	0.92	0.00	0.15	0.27	1.34	0.34	0.02
Part 8	1.00	0.05	0.83	0.00	0.17	0.35	1.35	0.34	0.02
Part 9	1.00	0.05	0.91	0.00	0.17	0.32	1.40	0.35	0.02
Part 10	1.00	0.05	0.90	0.00	0.11	0.20	1.21	0.30	0.02
Part 11	1.00	0.05	0.89	0.00	0.07	0.19	1.15	0.29	0.02
Part 12	1.00	0.05	,88	0.00	0.17	0.22	0.39	0.10	0.01
Part 13	1.00	0.05	0.57	0.00	0.17	0.28	1.02	0.26	0.01
Part 14	1.00	0.05	0.67	0.00	0.17	0.28	1.12	0.28	0.01
Part 15	1.00	0.05	0.80	0.00	0.17	0.28	1.25	0.31	0.02
Part 16	1.00	0.05	0.75	0.00	0.17	0.25	1.17	0.29	0.02
Part 17	1.00	0.05	0.67	0.00	0.17	0.33	1.17	0.29	0.02
Part 18	1.00	0.05	0.50	0.00	0.12	0.31	0.93	0.23	0.01
Part 19	1.00	0.05	0.00	0.00	0.12	0.23	0.35	0.09	0.00
							Assembly Relative Effort		0.29

D.4. Pressure Recorder Assembly Complexity (After DFA): Coupling Chart

Coupling Chart- Pressure Recorder Assembly Complexity (After DFA)

		Part j						
		1	**2**	**3**	**4**	**5**	**6**	**7**
Part i	**1**	0	0	0	0	1	0	0
	2		0	0	0	0	0	0
	3			0	0	0	0	0
	4				0	0	0	0
	5					0	0	0
	6						0	0
	7							0
Relativity		0.00	0.00	0.00	0.00	0.20	0.00	0.00

D.5. Pressure Recorder Assembly Complexity (After DFA): Part Task Effort

Part 1- Pressure Regulator

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	0.80	0.00	1.80	0.60
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	0.80	0.50	2.30	0.77

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.07

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.60	0.30	0.00	0.00	0.00	**0.15**
Insertion	0.00	0.77	0.39	0.07	0.00	0.04	**0.21**

Part 2- Adaptor nut

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.80	0.27
Insertion	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.80	0.27

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.07

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.08

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.27	0.14	0.00	0.08	0.04	**0.09**
Insertion	0.00	0.27	0.14	0.07	0.08	0.08	**0.11**

Part 3- Sensor

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	2.00	0.67
Insertion	0.00	0.50	0.00	0.50	0.17	1.00	1.00	0.00	2.00	0.67

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.07

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.08

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.67	0.34	0.00	0.00	0.00	**0.17**
Insertion	0.17	0.67	0.42	0.07	0.08	0.08	**0.25**

Part4- PCB Assembly

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	2.00	0.67
Insertion	0.00	0.50	0.00	0.50	0.17	1.00	1.00	0.50	2.50	0.83

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.50	0.07

Cognitive Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.50	0.00	0.00	0.00	0.50	0.08

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.67	0.34	0.00	0.00	0.00	**0.17**
Insertion	0.17	0.83	0.50	0.07	0.08	0.08	**0.29**

Part 5- Plastic Cover

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	2.00	0.67
Insertion	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	2.00	0.67

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.20	0.00	0.70	0.10

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.00	0.00	0.00	0.00	0.50	0.00	0.50	0.08

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.67	0.34	0.00	0.00	0.00	**0.17**
Insertion	0.00	0.67	0.34	0.10	0.08	0.09	**0.21**

Part6- nut

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.80	0.27
Insertion	0.50	0.00	0.00	0.50	0.17	0.80	0.00	0.00	0.80	0.27

Assembly Process Related Effort

Physical Elements

	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00
Insertion	0.50	0.00	0.00	0.00	0.50	0.00	0.00	1.00	0.14

Cognitive Elements

	Tools/	Assembly	Joint	Part	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Insertion	0.50	0.00	0.00	0.00	0.50	0.00	1.00	0.17

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.27	0.14	0.00	0.00	0.00	**0.07**
Insertion	0.17	0.27	0.22	0.14	0.17	0.16	**0.19**

Part 7- Knob

Component Related Effort

	Physical Elements					Cognitive Elements				
	Geometry	Surface specificatiosn	Physical/ Material Properties	Sum	Average	α-symmetry	β-symmetry	Procedures	Sum	Average
Handling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alignment	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.80	0.27
Insertion	0.50	0.00	0.00	0.50	0.17	0.80	0.00	0.50	1.30	0.43

Assembly Process Related Effort

	Physical Elements								
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Part Relativity	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	-	0.00	0.00
Alignment	0.00	0.50	0.00	0.00	-	-	-	0.50	0.07
Insertion	0.00	1.00	0.50	0.00	0.00	0.06	0.50	2.06	0.29

	Cognitive Elements							
	Tools/ Fixtures	Assembly Direction	Joint Position	Part Support	Part Stability	Fasteing Type/ Required force	Sum	Average
Handling	0.00	-	-	0.00	-	-	0.00	0.00
Alignment	0.00	0.50	0.00	0.00	-	-	0.50	0.08
Insertion	0.00	1.00	0.50	0.00	0.00	0.50	2.00	0.33

Part Task Effort

	Component Reltaed			Process Related			Task Effort
	Physical Elements	Cognitive Elements	Task Effort	Physical Elements	Cognitive Elements	Task Effort	
Handling	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Alignment	0.00	0.27	0.14	0.07	0.08	0.08	**0.11**
Insertion	0.17	0.43	0.30	0.29	0.33	0.31	**0.31**

D.6. Pressure Recorder Assembly Complexity (After DFA): Assembly Relative Effort

Part	No.	Percentage	Selection	Handling	Alignment	Insertion	Sum	Average	Part Share
Part 1	1.00	0.14	0.86	0.00	0.21	0.21	1.28	0.32	0.05
Part 2	1.00	0.14	0.83	0.00	0.09	0.11	1.03	0.26	0.04
Part 3	1.00	0.14	0.80	0.00	0.17	0.25	1.22	0.31	0.04
Part 4	1.00	0.14	0.75	0.00	0.17	0.29	1.21	0.30	0.04
Part 5	1.00	0.14	0.67	0.00	0.17	0.21	1.05	0.26	0.04
Part 6	1.00	0.14	0.50	0.00	0.17	0.19	0.86	0.22	0.03
Part 7	1.00	0.14	0.00	0.00	0.11	0.31	0.42	0.11	0.02
							Assembly Relative Effort		0.25

VITA AUCTORIS

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