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# COMPLEXITY OF PRODUCTS AND THEIR ASSEMBLY SYSTEMS

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*University of Windsor*

# COMPLEXITY OF PRODUCTS AND THEIR ASSEMBLY SYSTEMS

by

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ABSTRACT

Many manufacturing and assembly challenges emerged due to the increased demand for products variety. Increased product variety caused by product evolution, customization and changes in their manufacturing systems. Variety allows manufacturers to satisfy a wide range of customer requirements, but it can also be a major contributing factor to complexity of assembly. Complexity is generally believed to be one of the main causes of the present challenges in manufacturing systems. Complex assembly systems are costly to implement, run, control and maintain. Complexity of assembly is an important characteristic worth exploring and modeling in the early design stage. Assessing complexity of a product is essential in being able to predict the cost and time needed to implement it. There is a relationship between the complexity of assembled products and the complexity of their assembly equipment and systems. The main objective of this research is to the complexity of assembly by: (1) Assessing the complexity of assembled products, (2) Assessing the complexity of their assembly systems, and (3) Derive the relationship between products and assembly systems complexities.

*First*, a product complexity model has been developed by incorporating the information amount, content and diversity as well as the Design for Ease of Assembly (DFA) principles for assembled products. The new product complexity model assesses the total product assembly complexity using aggregated index for individual parts complexity. The new measure accounts for the different parts' assembly attributes as well as their number and variety. *Second*, a structural classification coding (SCC) scheme has been extended to measure assembly systems complexity. It considers the inherent structural complexity of typical assembly equipment. The derived assembly system's complexity accounts for the number, diversity and information content within each class of assembly system modules. *Third*, a dependency matrix which represents the interactions between parts assembly attributes and assembly system functions has been developed. It is used to predict the complexity of corresponding assembly equipment

used for a certain product. A relationship between parts complexity and assembly equipment complexity has been developed using regression analysis.

This research is applicable to the mechanical assembly of medium size products. An automobile piston, a domestic appliance drive, a car fan motor and a family of three-pin electric power plugs and their assembly systems were used as case studies to demonstrate the proposed approach and complexity assessment tools.

The significance and importance of these research contributions is that: the developed complexity metrics can be used as decision support tools for products and systems designers to compare and rationalize various alternatives and select the design that meets the requirements while reducing potential assembly complexity and associated cost. Assessing complexity of assembly helps and guides designers in creating assembly-oriented product designs and following steps to reduce and manage sources of assembly complexity. On the other hand, reducing complexity of assembly helps lower assembly cost and time, improve productivity and quality, and increase profitability and competitiveness.

DEDICATION

*To my parents, brothers and sisters, and all those who made this work possible.*

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

APPREVIATIONS

| | |
|---|---|
| AD | Axiomatic Design |
| AECM | Assembly Equipment Complexity Matrix |
| BCC | Buffers Classification Code |
| DEA | Data Envelopment Analysis |
| DFA | Design for Assembly |
| DM | Dependency Matrix |
| DPs | Design Parameters |
| ECC | Equipment Classification Code |
| FMS | Flexible Manufacturing System |
| FRs | Functional Requirements |
| GT | Group Technology |
| LCC | Layout Classification Code |
| MCC | Machines Classification Code |
| OCC | Operator Choice Complexity |
| PCAM | Parts Complexity Attributes Matrix |
| SCC | Structural Classification Code |
| TCC | Transporters Classification Code |

NOMENCLATURE

| | |
|---|---|
| $A$ | Total area of the radar plot |
| $C_{\text{equip.}}$ | Average complexity of assembly equipment |
| $C_{\text{f}}$ | Average complexity factor |
| $C_{\text{h}}$ | average handling complexity factor |
| $C_{\text{h,f}}$ | Relative handling complexity factor |
| $C_{\text{i}}$ | Average insertion complexity factor |
| $C_{\text{i,f}}$ | Relative insertion complexity factor |
| $C_{\text{part}}$ | Part assembly complexity |
| $C\mathrm{I}_{\text{part}}$ | Part assembly complexity index |
| $C_{\text{product}}$ | Product assembly complexity |
| $CI_{\text{product}}$ | Product assembly complexity index |
| $C_{\text{system}}$ | Assembly system complexity |
| $CI_{\text{system}}$ | Assembly system complexity index |
| $I$ | Complexity index |
| $\bar{I}$ | Average complexity index |
| J | Number of handling attributes |
| $K$ | Number of insertion attributes |
| $N$ | Total number of units |
| $x_{\text{p}}$ | Percentage of the $x^{\text{th}}$ dissimilar parts |
| $a$ | Shaded area of the radar plot |
| $n$ | Distinct number of units |
| $w$ | Relative weight |
| $\alpha$ | Alpha rotational symmetry angle of part |

| | |
|---|---|
| $\beta$ | Beta rotational symmetry angle of part |

**Subscripts**

| | |
|---|---|
| $B$ | Buffer |
| $M$ | Machine |
| $MHS$ | Material Handling System |
| $f$ | factor |
| $i$ | insertion |
| $h$ | handling |
| $j$ | Class type, $j = M, MHS, B$ |
| $p$ | part |
| $s$ | fasteners |

CHAPTER ONE

INTRODUCTION

This chapter presents the research motivation and main objectives followed by a description of the dissertation outline.

## 1.1 Motivation

In today's manufacturing environment change has become a constant. Mangers strive to cope with fluctuations in technology, environmental requirements, regulatory policies, societal needs, and the economy. They respond to fluctuation in these conditions by controlling product variety, production volume, manufacturing lead time, product cost and quality. Figure 1. 1 illustrates those external and internal change drivers.

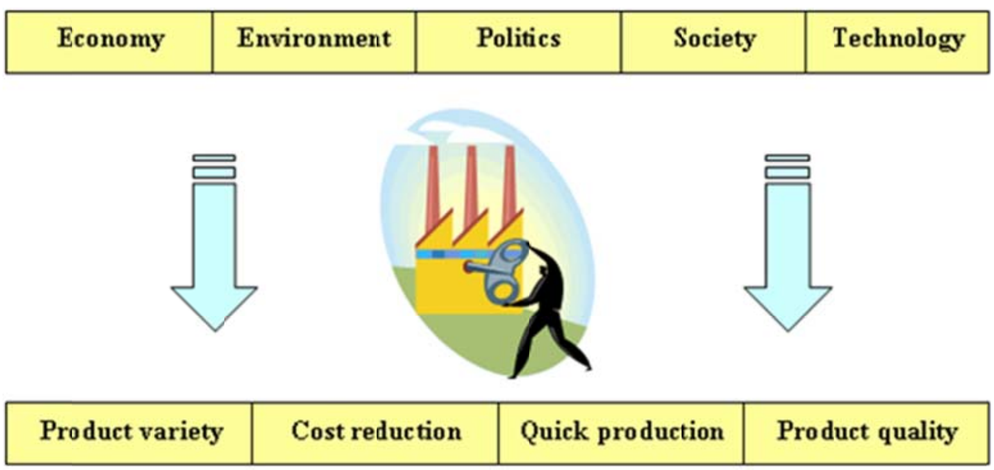



Figure 1. 1 Change drivers in today's manufacturing environment

Many manufacturing and assembly challenges emerged due to the spread of product variety caused by product evolution, increased customization and changes in their manufacturing systems. ElMaraghy H. (2009b) introduced a hierarchy of variations from individual product features to product families, portfolios and platforms and illustrated the effect of these variations on several manufacturing support functions and enablers of change at the levels of product design, process planning and parts/subassemblies/product families' definition. Increased product variety adds more complexity to the manufacturing system and increases the production cost (S. Hui, 2010, X. Zhu *et al.*, 2008, X. Zhu *et al.*, 2007). The manufacturing process complexity and equipment cost increase because of the need for additional equipment or the required flexibility in handling components or subassemblies of different shapes or configurations. Moreover, because of the differences in the design and number of components, additional assembly stations and floor space may also be required, resulting in low utilization of the facility.

Mechanical assembly of discrete part products is a very important manufacturing process; most great industrial nations consider assembly, especially that of heavy equipment such as automobile , aerospace, machine tools, etc., vital to their gross domestic product (A. Azab *et al.*, 2008). Assembly tasks account for over 50% of total production time and for 20% of the total unit production cost (Figure 1. 2).

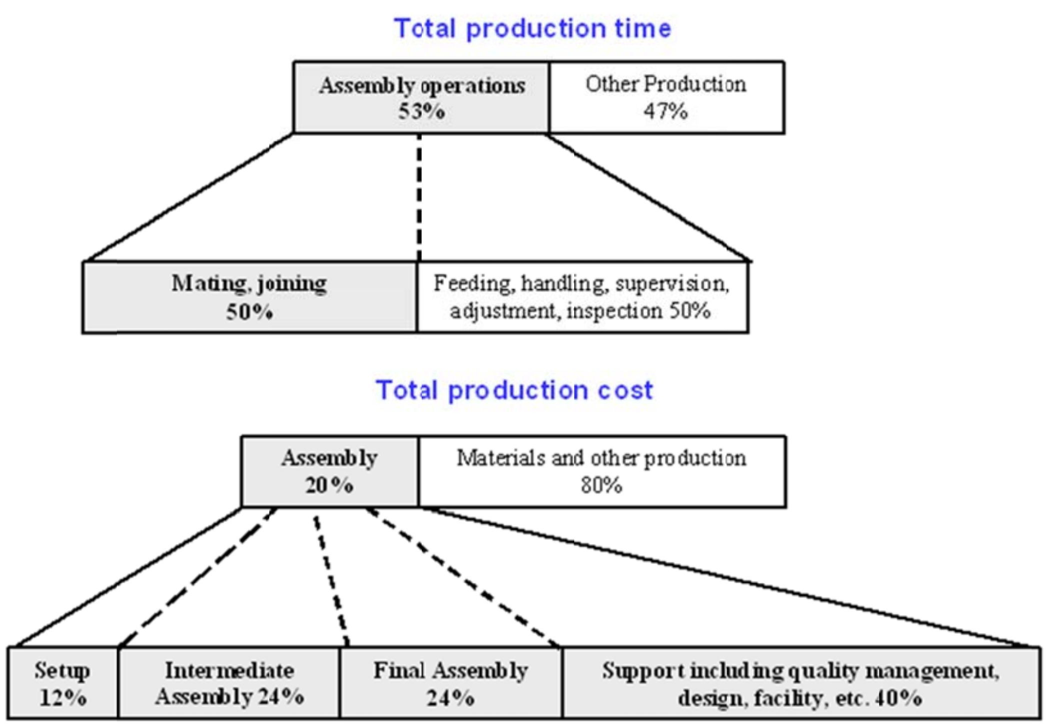



Figure 1. 2 Typical average breakdown of production time and cost (adapted from S.Y. Nof *et al.*, 1997)

Typically, about one-third of a manufacturing company's labour is involved in assembly. In the automobile industry, 50% of the direct labour costs are attributed to assembly; this indicates the potential savings that can be generated by improving assembly technology and systems (S.Y. Nof *et al.*, 1997). Assembly process greatly affects a product's final quality and cost. The continuously shortening product life cycle requires a faster response speed as well as a lower defect rate in assembly production. In this situation, assembly quality control is becoming one of the most demanding problems in the modern manufacturing. (Q. Su *et al.*, 2010).

Designing individual components with ease of assembly in mind can reduce assembly time significantly. This leads to savings in both equipment and human resources (A. Mital *et al.*, 2008). Assembly systems must be designed to be responsive to new needs for increased variety and changeability while at the same time achieving quality and productivity. Mixed-model assembly lines have been recognized as a major enabler for handling product variety. Variety affects product design and structure, process planning, production planning and control, and manufacturing systems layout and material flow patterns (H. ElMaraghy, 2009c). As a result, the manufacturing environment becomes more complex when the number of product variants is high, which in turn, may impact the system performance. The significance and benefits of an appropriate complexity measure is obvious.

To design successfully requires complexity be recognised and understood. Understanding complexity allows designers and design managers to identify complexity as a root cause of some of their problems and take steps to reduce or manage it. This complexity can be understood and described through a number of formal approaches.

## 1.2 Research Objectives

Managing complexity is very important for both products and their assembly systems development. The main objective of this research is to help manage complexity through:

- Defining assembly complexity for both products and systems.
- Developing complexity metrics for products as well as for assembly systems.
- Investigating the relationship between product and system complexities.

The expected benefits are:

- Support decision makers to rationalize the various design alternatives.
- Managing drivers or sources of complexity of assembly will help in reducing assembly cost and time, improving productivity and quality, and increasing profitability and competitiveness.

## 1.3 Dissertation outline

The dissertation consists of the following six chapters:

- Chapter one: introduces the research motivation, objective, and the outline.
- Chapter two: presents a detailed literature review of the research work related to complexity, product assembly complexity, assembly system complexity. The chapter highlights the opportunities for contribution in assessing complexity of assembly.
- Chapter three: presents a complexity metric for assessing product assembly complexity. The metric was illustrated with a case study.
- Chapter four: presents a static complexity metric for assessing system assembly complexity. The metric was illustrated with a case study.
- Chapter five: presents a developed model to map the relationship between product complexity and assembly system complexity. The model was developed using regression analysis to predict assembly equipment complexity due to individual part complexity.
- Chapter six: presents the conclusions and contribution of this research work and gives recommendations for further research work.
- Appendices include the handling and insertion complexity attributes of individual parts and the structural classification code analysis of assembly equipment of the presented case studies.

## CHAPTER TWO

## LITERATURE REVIEW

This chapter provides a review directly related to complexity, and assembly. The various complexity definitions and measures are reviewed.

### 2.1 Complexity

Complexity is seen as a core challenge for present and future manufacturing companies. Complexity cannot just be made simple and will not disappear in the near future. Managing complexity must therefore become a core ability of top executives and managers (U. Steger, 2007). Schleich et al (2007) showed in a survey conducted in the automotive industry (Figure 2. 1) that complexity has been identified as an important cost driver in production by 64% of the votes of managers.

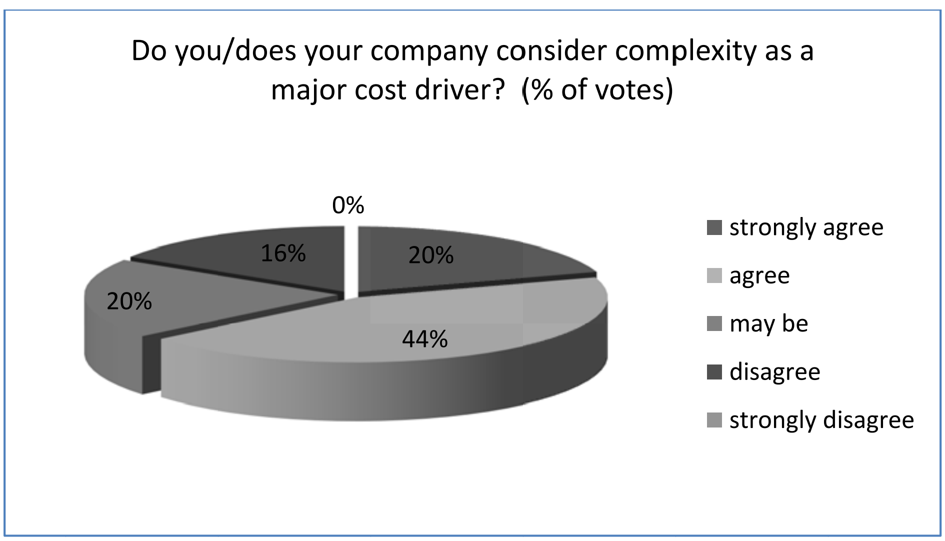



Figure 2. 1 Managers consider complexity to be a major cost driver (adapted from Schleich H. *et al.*, 2007)

The original Latin word *complexus* signifies "entwined" or "twisted together". This may be interpreted in the following way: in order to have a complex object you need two or more components, which are joined in such a way that it is difficult to separate them. Cambridge Dictionary defines "complexity" as "involving a lot of different but related parts" or "difficult to understand or find an answer to because of having many different parts". Similarly, the Oxford Dictionary defines something as "complex" if it is "made of (usually several) closely connected parts". This implies that complex entities will be difficult to model, that eventual models will be difficult to use for prediction or control, and that problems will be difficult to solve. This accounts for the implication of difficult, which the word "complex" has been associated with in later periods.

Defining the meaning of complexity itself is difficult. The definitions that have been offered are either only applicable to a very restricted domain, or so vague as to be almost meaningless. There are many attempts to provide a universally admitted definition of complexity. However, a single and generally acceptable definition does not exist (T. Blecker and N. Abdelkafi, 2005). The question, "what is complexity" remains vague until the target of the question is specified. A metric that works very well for a certain subject may not be suitable at all for other subjects (T.-S. Lee, 2003). The definitions of Complexity are as diverse as the world that they involve (Table 2. 1).

Table 2. 1 Various complexity measures and their applications (adapted from T.-S. Lee, 2003)

| Complexity definition/measure | Object |
|---|---|
| Information/entropy | An object with information, e.g. pattern |
| Size (size in many different context) | General |
| Variety, Irreducibility | (Biological) System |
| Dimension, Irreducibility | System (as an object of modeling) |
| Connectivity, Cyclomatic number, Ease of decomposition | System with network characteristic |
| Stochastic complexity | Physical processes or data |
| Size of rules (or grammars), Sophistication | Pattern (rules in a language) |
| Boltzmann-Gibson entropy | (Thermodynamic) System or state |
| Logical complexity | Statement, Language, (Theory) |
| Cognitive complexity | Personality, Cognitive/behavioral |
| Time (processing/execution/preparation) | A task |
| Resources (time/memory/others), Ignorance | Solving a problem |

Concepts of complexity have been considered in disciplines including psychology, physics, management, engineering, and biological and information sciences (T.-S. Lee, 2003, C. Rodriguez-Toro *et al.*, 2002).

The aspects of *distinction* and *connection* determine two dimensions characterizing complexity. Distinction corresponds to variety, to heterogeneity, to the fact that different parts of the complex object behave differently. Connection corresponds to the fact that different parts are not independent, but that the knowledge of one part allows the determination of features of the other parts. Distinction leads in the limit to disorder, chaos or entropy. Connection leads to order, like in an array, where the position of an object is completely determined by the positions of the adjacent objects to which it is bound. Complexity can only exist if both aspects are present. It can be concluded that complexity increases when the variety (distinction) and dependency (connection) of parts or objects increase. The process of increase of variety may be called differentiation; the process of increase in the number of connections may be called integration.

Empirical studies show that there is a strong positive correlation between the measured complexity and the number of errors found in the implemented system (M.J. Kinnunen, 2006, M.V. Martin and K. Ishii, 1996, H. Shibata *et al.*, 2003). Sarkis (1997) showed in his empirical analysis of productivity and complexity for flexible manufacturing systems that there is a continuous drop in productivity as the systems becomes more complex.

To manage complexity, one should make the distinction between three measures to be taken, which are: complexity reduction, complexity prevention and complexity control. Complexity reduction aims at simplifying structures. Complexity prevention targets e.g. developing methods capable of assessing complexity. Complexity control deals with the rest of complexity that cannot be reduced (T. Blecker *et al.*, 2004).

Having an accurate definition of complexity is a necessary condition for being able to discuss and measure complexity. In terms of manufacturing processes, assembly costs and quality of the end product, complexity plays a very important role in the achievement of the best product design that not only takes into account the assembly planning but also the selection of the most suitable manufacturing process (C. Rodriguez-Toro *et al.*, 2002). Measuring and understanding complexity is very important for the product development activity. Reducing complexity almost always reduces direct and indirect costs. The more complex the product is the more complex the supporting system.

In many approaches complexity is only considered as a negative concomitant of product design; consequently, such approaches aim at avoiding or at least minimizing complexity by suitable strategies. However, complexity does not represent axiomatically negative characteristics in product design. The enhancement of complexity may also allow more flexibility; if, for example, the implied complexity refers to the quantity of product variants offered, an increased product variety can better match different customer requests that arise. This demands effective possibilities for controlling this kind of complexity, which enable enterprises to benefit from a wider range of products offered. For this reason, the structural complexity management is not only focused on complexity reduction, but aims at the creation of competitive advantages due to the control of complexity (H. Wang *et al.*, 2011).

### 2.1.1 Complexity in an engineering context

A helicopter rotor blade is complex not only in its form and manufacture, but also in its functions. Its design process is complex to the extent that it avoids conventional process modelling, with a large number of closely interdependent and related shape and material parameters which are determined iteratively. Off-road diesel engine designs are customised for users and subject to environmental impact legislation. Their complexity lies in the interactions between product and users (and the logistical effort involved in designing and producing thousands of slightly different products). Power generation switchgears are customisations of standard products. Managing several different products through the design and manufacture process produces complex scheduling problems under constraints of uncertainty and finite capacity resources (H. Wang *et al.*, 2009).

A design may be structurally complex – an engine has many parts and specific functional relations between parts. Parts and relations between parts form a hierarchical structure which is not necessarily tree-like but may display more connected network properties. A rotor shaft in a jet engine belongs to both the turbine and the compressor.

The shaft itself has two parts, one for the turbine rotor and another for the compressor rotor. This kind of relationship among parts is not captured by a tree-like hierarchy, but requires a network hierarchy (H. Wang *et al.*, 2009).

### 2.1.2 Complex System

Manufacturing systems are a complicated combination of tools, machines, computers, human workers and managers. Modern Manufacturing systems are becoming more and more complex. Complex manufacturing systems (Figure 2. 2) share certain features, such as comprising a large number of elements, having high dimensionality, and representing an extended space of possibilities. The increase in complexity due to the introduction of new technologies and the integration of different components of manufacturing systems is only justifiable by improved system performance but should otherwise be minimized (O. Kuzgunkaya and H. ElMaraghy, 2006).

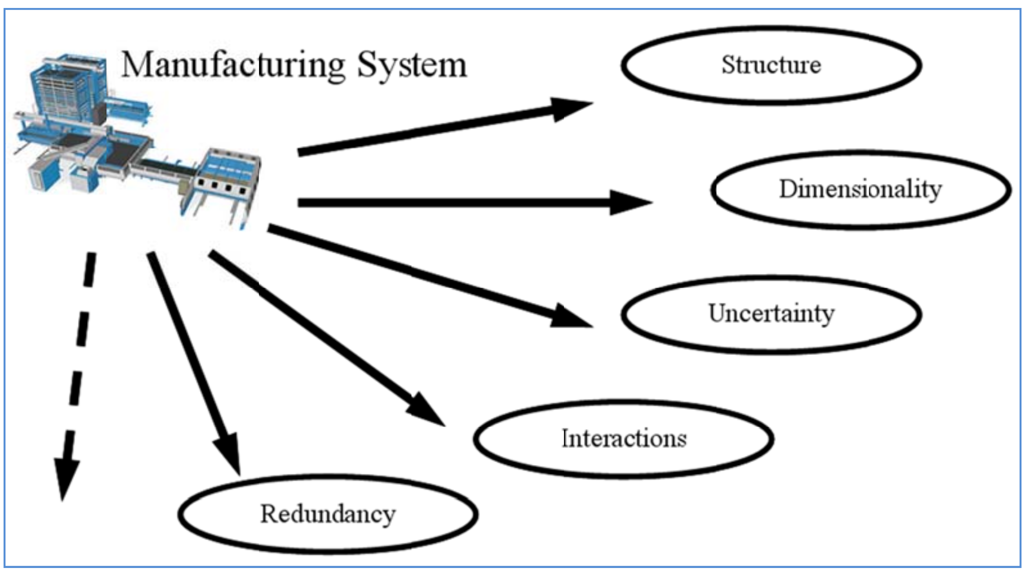



Figure 2. 2 Complex manufacturing system (adapted from S.N. Samy and H. ElMaraghy, 2008)

The complexity of a physical system can be characterized in terms of its static structure or dynamic behaviour. Static complexity accounts for the structure of the system and the relationships among elements of the system, along with the variety of components, and the strengths of interactions. Dynamic complexity deals with the operational behaviour and the unpredictability in the behaviour of the system over a time period (A.V. Deshmukh *et al.*, 1998, O. Kuzgunkaya and H. ElMaraghy, 2006, C. Rodriguez-Toro *et al.*, 2004). When both complexities are low, then the system is simple. In the case of a high (or a low) structural complexity and a low (or a high) dynamic complexity, the system is considered to be relatively complex. When both complexities are high, then the system is said to be extremely complex. (T. Blecker *et al.*, 2004).

Despite the lack of formal definition of complexity, it is well accepted that modern engineering systems are becoming more and more complex. Typical examples of using the term complexity or complex would be Boeing-737 is a complex system; and an automobile is less complex than an aircraft. A large system has large complexity; a system with modular design has lower complexity (T.-S. Lee, 2003).

The concept of complexity is relative to two dimensions: uncertainty and time (A. De Toni and S. Tonchia, 1998). Uncertainty may be informative (lack of information) and cognitive (subjective limits of the agents taking the decisions). Time intervenes in terms of sequence (for the irreversible nature of the decisions) and accumulation (for the increasing wealth of knowledge which can improve decision-making performances). For example, a manufacturing system may have thousands of part types during a year while the demand for these products arrives and varies almost randomly. There may be hundreds of machines in a plant that might fail at any time. At each moment, the managers are faced with hundreds of decisions, such as which part should loaded onto each machine next and must make decisions in spite of insufficient information. The sequences of each decision are hard to predict.

### 2.1.3 Reasons for Measuring Complexity

Modern manufacturing systems that are highly automated, many devices such as material processing, handling and transportation are integrated together to produce highly complicated products. These devices are integrated using information technology and this has increased the complexity in decision making under disruptive events, for example, machine break-downs (S. Cho *et al.*, 2009). Complexity cannot increase indefinitely. For any given system there exists a critical upper threshold of complexity beyond which it is impossible to evolve. At critical complexity, the system will experience loss of functionality and fitness. Critically complex systems are fragile. Once we're close to such a threshold, the system becomes fragile and can suddenly transition to another state; it can run out of hand or even fail. It is evident, therefore, that if we wish to sustain the development of a system we must know to what limits this development may be safely pushed. Consequently, it becomes imperative to study complexity, its evolution, and to understand at what peak levels of complexity a manufacturing system becomes fragile and stay away from these upper complexity thresholds.

Some Facts about Complexity:

- Complexity is a natural property of every system. It is defined as a mix of interdependency and uncertainty. Humans instinctively try to stay away from highly complex scenarios because of one fundamental reason – high complexity implies a capacity to deliver surprising behaviour.
- 'Complex' does not imply 'complicated'. A highly complicated system may possess numerous components (e.g, a watch movement) and yet be unable to behave in an unexpected manner. Systems with very few components, on the other hand, may be extremely difficult to manage and without being complicated.
- A more complex system is less responsive to change (Ontonix, 2010) the amount of functionality of a system is proportional to complexity, a complex system can perform more functions but at a price: they are not easy to manage and control.
- You can't make precise statements about a highly complex system (Ontonix, 2010).
- Clear definition of the complexity concept that properly addresses the causes of complexity leads to a systematic approach for complexity reduction (M.J. Kinnunen, 2006, T.-S. Lee, 2003).
- An effective method for controlling complexity allows for the prediction of change impact extending to different domains, e.g. departments and people in charge (U. Lindemann and M. Maurer, 2007).

- The complexity is strongly correlated with manufacturing cost and performances and can be evaluated in cases where cost-based models fail (M.L. Fisher and C.D. Ittner, 1999, J.P. MacDuffie et al., 1996).
- Complexity is often inherent in systems and cannot be eradicated. However, it is possible to take active steps to reduce complexity in the hope of reducing the risk of problems occurring in the design process (H. Wang et al., 2009).

Measuring complexity for the sake of measurement would be worthy sincere academic interest but of no value for practicing systems architects. Measuring and understanding complexity of systems architecture models is, however, very important for the whole product development activity. The more complex a system, the more expensive and risky is the design and implementation effort. Any unnecessary complexity is a risk for the final result and lowers the overall efficiency. Given a measure of complexity, systems architects and product development managers should strive for even distribution of complexity. Such a distribution will help in managing and balancing their available resources and avoid bottle necks in their systems. If this is not possible, they should assign extra resources and attention to the more complex subsystems. Measuring complexity of a product is essential in being able to predict the cost and time needed to implement it.

Research has been done in the area of developing some sort of quantification as described in the following section.

### 2.1.4 Complexity Measures

Research has been done to measure and quantify complexity using either entropy/information content approach (A. Calinescu *et al.*, 2000, A.V. Deshmukh *et al.*, 1998, O. Kuzgunkaya and H. ElMaraghy, 2006, N.P. Suh, 2005) or heuristics approaches and indices (W. ElMaraghy and R.J. Urbanic, 2003, W. ElMaraghy and R.J. Urbanic, 2004, Y.-S. Kim, 1999, M.V. Martin and K. Ishii, 1996, H. Shibata *et al.*, 2003). Complexity, uncertainty and information are linked to each other. One might suspect that the concept of complexity is not different from the information content: complexity is defined as a measure of uncertainty, and the information content is defined in terms of probability of success for certain functional requirement(s) that is, in fact, uncertainty. As uncertainty grows, the system becomes more complex since more information is required to describe and monitor each state of the system (T.-S. Lee, 2003).

2.1.4.1 Entropy / information approach

The concept of information, originally developed by Shannon (C.E. Shannon, 1948), which expresses uncertainty about an information source in terms of probability, is much used in literature. The basic idea behind most definitions of information entropy approaches is that the more information that an expression or a model contains the more complex it is (M.J. Kinnunen, 2006), i.e.,

$$I(M1) > I(M2) \rightarrow C(M1) > C(M2)$$

where *M1* and *M2* are models, $I(M1)$, $I(M2)$ are the amount of information in *M1* and *M2* respectively, and $C(M1)$, $C(M2)$ are complexities of *M1* and *M2* respectively.

The definitions differ in the way they measure the amount of information.

Two basic assumptions in entropy approaches are:

1. Complexity is a universal quantity that exists, to some degree in all objects, and there is a uniform metric for measuring the complexity of a system.
2. Independence between components is usually assumed to make the metric simple.

The advantage of the entropy/information approach is that it produces one number indicating the amount of complexity. This advantage facilitates the comparison between several systems options in terms of their level of complexity given by a single number. This is possible since the information is measured by the logarithm of probability function that has the same dimension while representing many different characteristics of a system.

On the other hand, there are two major problems in the information/entropic approach:

1. It is difficult to obtain the data required to calculate probabilities in this approach.
2. The assumption of independence between variables, which is not true in real systems and limits its applicability.

2.1.4.2 Axiomatic design approach

The axiomatic design approach (N.P. Suh, 2005) defines complexity as a measure of uncertainty in achieving the desired functional requirements. In axiomatic design, the design process is described as the mapping between four domains (Figure 2. 3): (1) customer domain, (2) functional domain, (3) physical domain, (4) process domain.

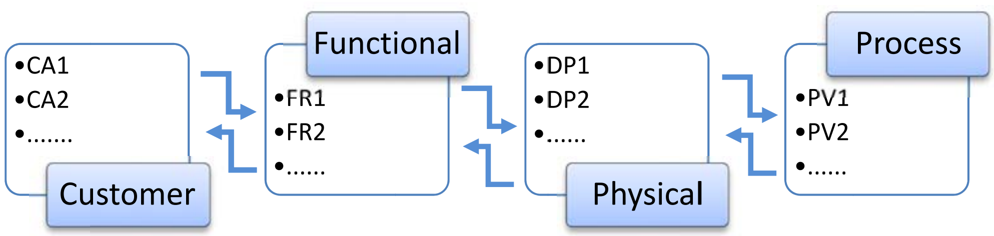



Figure 2. 3 Four mapping domains (adapted from N.P. Suh, 2005)

There are two axioms:

1. The independence axiom which tells to maintain the independence of the functional requirements (FRs).
2. The other axiom is the information axiom and it tells to minimize the information content of the design.

To satisfy the independence axiom, the design should be an uncoupled design or decoupled design. Uncoupled design is characterized by a diagonal design matrix and decoupled design is characterized by the triangular design matrix. In this context, complexity is related to the information content that is defined as a logarithmic function of the probability of success design parameters $(DPs)$ to meet the specified functional requirements$(FRs)$. The probability of success is determined by computing the area of the common range as a fraction of the area of the system range. The information content is inversely proportional to the probability of success via the logarithmic function. A design that is achieved with minimum information content is a design that has a maximum probability of success ($Axiom$ 2). There are four different sub-categories of axiomatic design complexity: time-independent real complexity, time-independent imaginary complexity, time-dependent periodic complexity, and time-dependent combinatorial complexity (Figure 2. 4). The cause of real complexity is due to random variations associated in a design. The cause of imaginary complexity is in the ignorance of the structure of design matrices. For both combinatorial and periodic complexity, the causes are time-varying system range and time-dependent functional requirements.

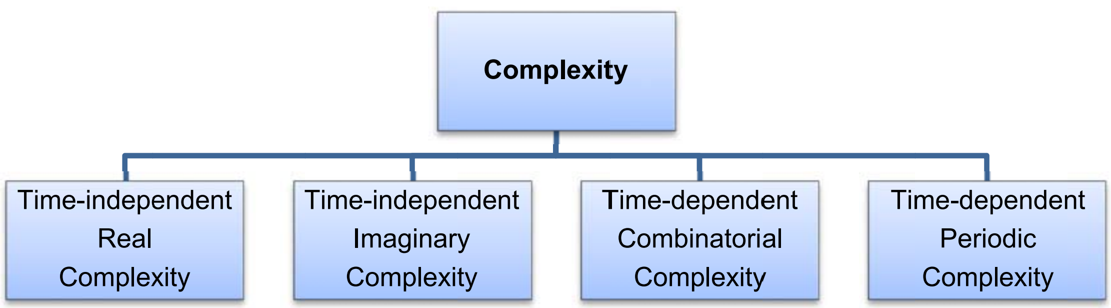



Figure 2. 4 Four types of complexity (adapted from N.P. Suh, 2005)

Among the four types of complexity, only the time–independent real complexity has a metric to quantify it. The metric defines the probability of success of satisfying the $FRs$ by calculating the area of the common range as a fraction of the area of the system range (Figure 2. 5). Axiomatic design explains explicitly the probability that should be calculated and how. It also suggests that time-dependent combinatorial complexity should be changed to time-dependent periodic complexity to reduce system complexity. One problem with the axiomatic approach, it is sometimes difficult to estimate the system range because it is decided by several design parameters $(DPs)$ in decoupled designs.

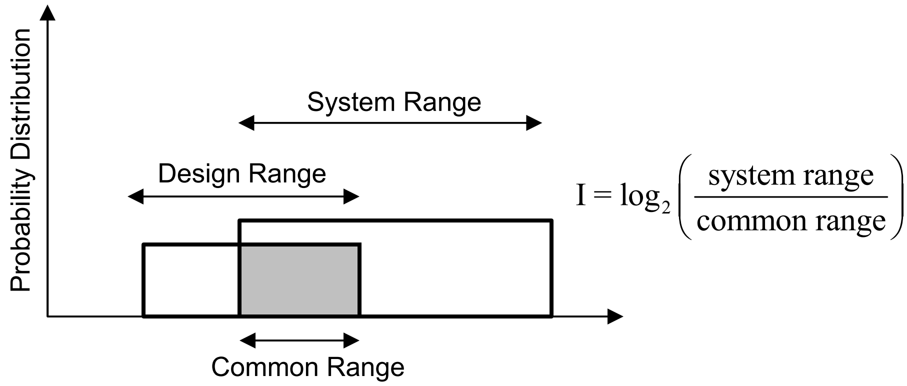



Figure 2. 5 Common range as a fraction of system range (adapted from N.P. Suh, 2005)

The gained complexity of existing technical systems with time-independent $FRs$ consists of real complexity due to system ranges fail to meet design ranges for some FRs, and imaginary complexity due to lack of knowledge of system's functional structures and operation sequences. The key to reduce or eliminate gained complexity for these systems to achieve design ideality is to achieve functional independence among multiple $FRs$ This can be done through new design or design modifications to ensure that system ranges are always inside design ranges for all $FRs$ at all times (Schleich H. *et al.*, 2007).

2.1.4.3 Heuristic approaches

Heuristic approaches use metrics based on personal experiences. They are easy to apply to real systems, easy to collect data, interpret, and eventually improve systems. However, the extent to which certain metrics reflect the actual system complexity can be argued. Also, they are usually not universally applicable to different types of systems as for each system we may have different parameters or constants. Calinescu et al. (2000) have proposed some formulae for the assessment of complexity. Their study is based on entropic measures of information, divided into static (structural) and dynamic (operational) aspects of complexity. They proposed a methodology for measuring the complexity of manufacturing systems and their supply chains. Their research is directed more at management of the manufacturing processes, rather than the details of the processes themselves. Braha and Maimon (1998) introduced two definitions of design complexity; structural and functional complexities. Structural Design Complexity states that design complexity is a function of the design's information content. Defining information in the structural way states that the quantity of information may be measured directly based on its internal structure. Functional Design Complexity states that information is a distinct notion, independent of representation. Information serves as the specification of what a structure should be able to do. Defining design process complexity in the functional way means information can be described in terms of its operation to satisfy the goals of the system. Alternatively, two design processes may be compared based on their output. W. ElMaraghy and Urbanic (2003) presented a methodology to assess product and process complexity and their interrelations in a systematic manner and derived product and process complexity indices. They used three basic elements of complexity: 1) the absolute quantity of information, 2) the diversity of information, and 3) the information content as illustrated in Figure 2. 6. Their model was applied to measure product and process complexity in machining.

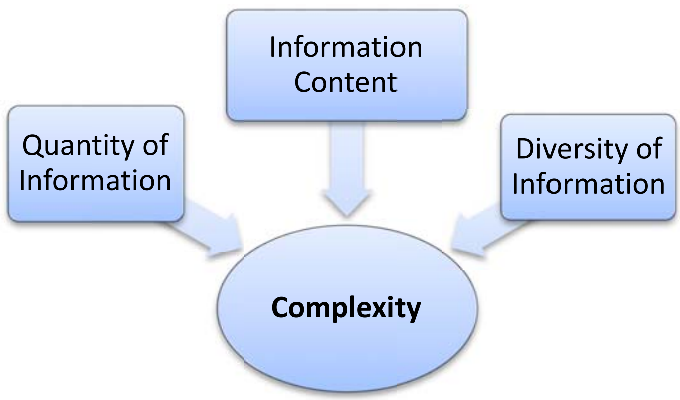



Figure 2. 6 Elements of Complexity (adapted from W. ElMaraghy and Urbanic, 2003)

This complexity model was also extended by W. ElMaraghy and Urbanic (2004) to consider complexity in machining at the operational level by including some aspects of cognitive complexity related to the operator's perception in manual tasks. Cho et al. (2009) developed an information entropy model to assess the complexity of manufacturing systems including assembly and disassembly systems. The model uses probability distribution of information regarding resource allocations such as part processing times, part mix ratios and process plans or routings. The complexity model identifies a manufacturing system that has evenly distributed interactions among resources as being more complex, because in this case more information is required to identify source of the disruption.

### 2.1.5 Structural Systems Complexity Code

H. ElMaraghy (2006) developed a novel manufacturing systems Structural Classification Code (SCC), which captures the inherent structural and operation-related complexity due to the characteristics of manufacturing system modules and layout configuration. It consists of fields representing equipment, such as machines, buffers and transporters and the type of system layout. Each field contains a string of digits, the value of which depends on the degree of structural, control, programming and operation complexity of these entities. The resulting code string (Figure 2. 7) is similar to a biological *DNA* identifier for the system characteristics (H. ElMaraghy *et al.*, 2005). It accounts for the complexity inherent in the various modules in the manufacturing system. The use of the SCC code was illustrated for metal removal machine tools.

| Digit number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Machine |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Digit value | **4** | **3** | **1** | **4** | **20** | **160** | **1** | **4** | **6** | **0** |  |

Figure 2. 7 Machine type code string

Kuzgunkaya and H. ElMaraghy (2006) used that complexity code in developing a metric for assessing the structural complexity of manufacturing system configurations and applied it to machining systems for illustration. This structural system complexity metric incorporates the quantity of information using an entropy formulation. Later, H. ElMaraghy et al. (2010) extended the original code to include assembly-specific structural features of various assembly equipment and used the extended version to develop a code-based complexity metric (S.N. Samy and H. ElMaraghy, 2010c) incorporates information content, diversity and quantity of information.

### 2.1.6 Complexity and Variety

Variety of products introduced in today's market place has increased significantly. However, increase of variety does not mean necessarily mean increase of profit from increased sales. Initially, variety increases sales and profit as product offerings become more attractive. As variety keeps growing, the profit may decrease as a result of increased cost and complexity of manufacturing. In order to keep the maximal profit of the increased variety, manufacturing system cost and complexity should be considered with the introduced variety.

It has been shown that increased product variety has a negative impact on the performance of the assembly process, such as quality and productivity. Such an impact can result from the assembly system design as well as people performance in the presence of high variety (X. Zhu *et al.*, 2008). Product variety causes changes in the product structure. The impact of structural change of the product on the manufacturing processes may cause an increase in complexity. The process complexity and equipment cost increase because of the required flexibility in handling components, or subassemblies of different shapes or configurations. Additional equipment may need to be installed to assemble the parts of different types. Moreover, because of the differences in the number of components, additional assembly stations and floor space may also be required, resulting in low utilization of the facility. Increased product variety adds more complexity to the manufacturing system and will be followed by increased production cost (Y.-S. Kim, 1999). High product complexity can have a significant impact on many cost areas in manufacturing, inventory and distribution. The significance of an appropriate complexity measure that reflects the impact of variety on complexity is obvious.

Recently, complexity has been defined in an analytical form for manufacturing systems as a measure of how product variety can complicate the process. MacDuffie et al. (1996) used multiple product complexity measures derived from the statistical analysis of the productivity of 70 auto assembly plants worldwide to test the impact of product variety on productivity and quality. Similar work was done by Fisher and Ittner (1999).

Their research was performed from a managerial perspective. They used empirical tests of data from an automotive assembly plant and simulation analyses of a generic auto assembly line to examine the impact of product variety on automobile assembly plant performance. Their analyses indicated that greater day-to-day variability in option content has a significant adverse impact on total labour hours per car produced, overhead hours per car produced, assembly line downtime, minor repair and major rework, and inventory levels, but doesn't have a significant short-run impact on total direct labour hours. Martin and Ishii (M.V. Martin and K. Ishii, 1996) developed metrics to measure and compare the costs of product variety. They developed three indices: commonality of the parts index, differentiation point in manufacturing processes index and the setup costs index. The costs related to the increased product variety can be decreased by increasing the commonality of parts, postponing the differentiation point, and decreasing setup costs.

Shibata et al. (2003) developed a design-based complexity factor derived from the DFA method for evaluating product complexity. Fujimoto, et al. (2003) introduced a systematic information entropy-based methodology to strategically manage product variety by synthesizing product-based and process-based varieties measures. Ding et al. (2010) and Sun and Ding used Data Envelopment Analysis (DEA) models for comparing the relative product complexities related to product variety among similar products and to prioritize attributes for complexity reduction consideration related to product variety for an automobile assembly plant. Sarkis (1997) studied the productivity of flexible manufacturing systems as they become more complex. Complexity was measured by the number of numerically controlled machine tools and industrial robots in the system. In a flexible manufacturing system (FMS), a larger number of numerically controlled machine tools and industrial robots requires more operation and control efforts, including scheduling and transportation, which may lead to higher complexity. Productivity was analyzed by using data envelope analysis with the inputs consisting of complexity measures and the outputs consisting of process/inventory reduction, lead time reduction, unit cost reduction and personnel reduction measures. This complexity analysis may not be generally applicable to systems other than FMS. Wang et al. (2010) proposed a complexity model to find the best combination of product variants to maximize market share and minimize manufacturing complexity in serial, manual, mixed-model assembly lines where operators have to make choices of parts, tools, fixtures. Their model is then extended by Wang and Hu (2010) to include assembly systems with parallel and hybrid assembly lines. They showed that variety induced complexity impacts the reliability of the assembly line. H. ElMaraghy (2009a) introduced a hierarchy of variations from products features to products families, portfolios and platforms and illustrated the effect of these variations on several manufacturing support functions and enablers of change at the product design, process planning and product families definition. The concept of evolving families for varying parts and products was introduced and led to developing innovative perspectives on process planning in this environment (A. Azab and H. ElMaraghy, 2007). H. ElMaraghy et al. (2008) introduced for the first time a novel approach for studying the evolution of products and their manufacturing systems using a biological analogy. AlGeddawy and H. ElMaraghy (2009) used this biological metaphor and cladistics models to design assembly systems that effectively achieve delayed products differentiation while satisfying the desired products variations.

Samy and H. ElMaraghy (2008) considered variety at three levels; product, process and system as shown in Figure 2. 8. Two types of variety were defined: 1) independent variety, 2) dependent variety. Independent variety is the variety introduced directly to each level. Dependent variety is the corresponding variety arising in other levels as a result of introducing the first type of variety. A mapping between the three different levels (Figure 2. 9) was also introduced as a matrix representation of the two types of variety in product, process and system levels. The shaded areas represent a dependency between the two types of variety in each level. The product level includes the variety of parts features, number of parts, number of modules, number of subassemblies; the process level includes variety of sequence, precedence relations; the system level includes variety in system type, handling, insertion, fixtures, feeders. In order to quantify the impact of variety on the complexity of assembly, the impact of variation in each level on the complexity of all levels is considered. The variety introduced at each level affects the complexity of that level and may affect the complexity of other levels. The result is that, independent variety-based complexity components ($C\ product$, $C\ process$, $C\ system$) representing product, process and system complexities resulting from introducing variety directly to these levels respectively. Other dependent variety-based complexity components are:

- "$C_{\text{product AND process}}$, $C_{\text{product AND system}}$" represent process and system complexities respectively due to the introduction of variety to the product level,
- "$C_{\text{process AND product}}$, $C_{\text{process AND system}}$" represent product and system complexities respectively due to the introduction of variety to the process level,
- "$C_{\text{system AND product}}$, $C_{\text{system AND process}}$" represent product and process complexities respectively due to the introduction of variety to the system level.

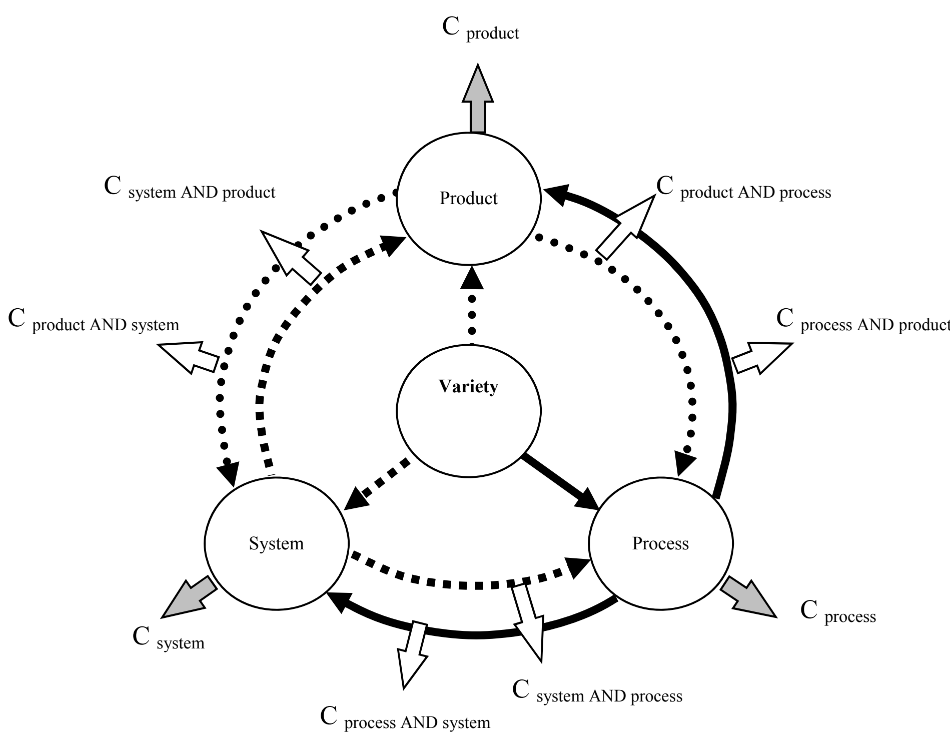



Figure 2. 8 Independent variety (straight arrows) dependent variety (curved arrows) and resulting complexity (adapted from S.N. Samy and H. ElMaraghy, 2008)

The total complexity is the summation of nine variety-based complexities as:

$$C_{total} = \sum_{i=1}^{M} \sum_{j=1}^{N} C_{product} + \sum_{i=1}^{K} \sum_{j=1}^{L} C_{process} + \sum_{i=1}^{U} \sum_{j=1}^{V} C_{system}$$

(2. 1)

where: $C_t$, $Cproduct$, $Cprocess$, $Csystem$ are the total, product, process and system complexities respectively.($M$, $K$, $U$) , ($N$, $L$, $V$) are the numbers of dependent and independent varieties in product, process and system levels respectively.

| | | | Dependent Variety | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Product | | | | Process | | | | System | | | |
| | | | $V_1$ | $V_2$ | $V_3$ | $V_M$ | $V_1$ | $V_2$ | $V_3$ | $V_K$ | $V_1$ | $V_2$ | $V_3$ | $V_U$ |
| Independent Variety | Product | $V_1$ | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| | | $V_2$ | 0 | 10 | 0 | 0 | 0 | 7 | 0 | 0 | 0 | 0 | 2 | 0 |
| | | $V_3$ | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | $V_N$ | 0 | 0 | | 10 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 |
| | Process | $V_1$ | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | $V_2$ | 0 | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | $V_3$ | 0 | 0 | 1 | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 0 |
| | | $V_L$ | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 4 | 0 |
| | System | $V_1$ | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 0 |
| | | $V_2$ | 0 | 5 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 10 | 0 | 0 |
| | | $V_3$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 0 |
| | | $V_V$ | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 10 |

Figure 2. 9 Matrix representation of dependent and independent varieties and their relationships at various levels (S.N. Samy and H. ElMaraghy, 2008)

## 2.2 Assembly

A consumer product is an assemblage of individual components. Each component has been planned, designed, and manufactured separately. However, by themselves, there is very little use to component parts. Only after they are assembled into the final product they can effectively perform their planned function. Assembly of a product is a function of parameters such as, but are not limited to, shape, size, material compatibility, flexibility, and thermal conductivity. Assembly in the manufacturing process consists of putting together (joining) all the component parts and sub-assemblies of a given product, fastening, performing inspections and functional tests, labelling, and separating good assemblies from bad ones, and packaging and/or preparing them for final use. Assembly is by comparison much less studied and is by far one of the least understood processes in manufacturing. It is related to other functions (Figure 2. 10) such as material procurement and distribution, marketing, design, planning and control via the flow of material and information (R.M. Marian, 2003).

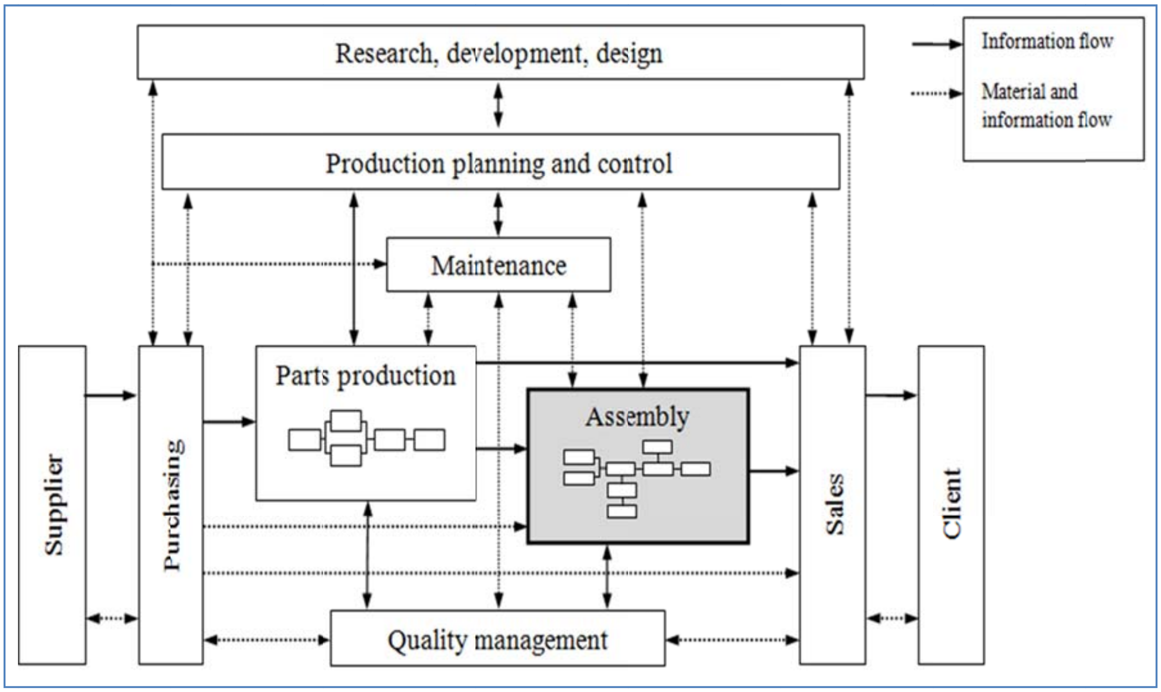



Figure 2. 10 Assembly as a subsystem of the production system (adapted fromG. Salvendy, 2001)

In addition to joining, handling of parts/subassemblies is the primary function of assembly. The assembly also contains other functions such as adjusting, inspection, and special functions as shown in (Figure 2. 11).

Joining is defined by DIN8593 as a part of manufacturing processes. In this case, the production of assembly/subassembly consisting of several parts can be achieved by merging, pressing, metal forming, primary shaping, filling, or by combining substances.

Handling is defined in VDI Guideline 2860/1 as the temporary maintaining of a prescribed 3D arrangement of geometrical defined solids in a reference coordinate system. Procedures such as ordering, carrying on, positioning, and clamping are necessary. It is easy for a worker to arrange parts into correct position or move them from one place to another. However, a significantly larger spending is necessary to automate this task. An extensive sensory mechanism often must be used. Manufacturing of components is subject to a great number of influences. As a result, deviations cannot be avoided during or after the assembly of the product. These influences must be compensated for, and thus adjusting is a process that guarantees the required operating ability of products.

Testing operations are necessary in all individual steps of assembly. Testing means the fulfillment of a given limiting condition. The result of the test operation is binary (true or false, good or bad). On the other hand, specifications are determined and controlled by given reference quantities while measuring.

Secondary functions are activities, such as marking or cleaning operations that can be assigned to none of the above functions but are nevertheless necessary for the assembly process.

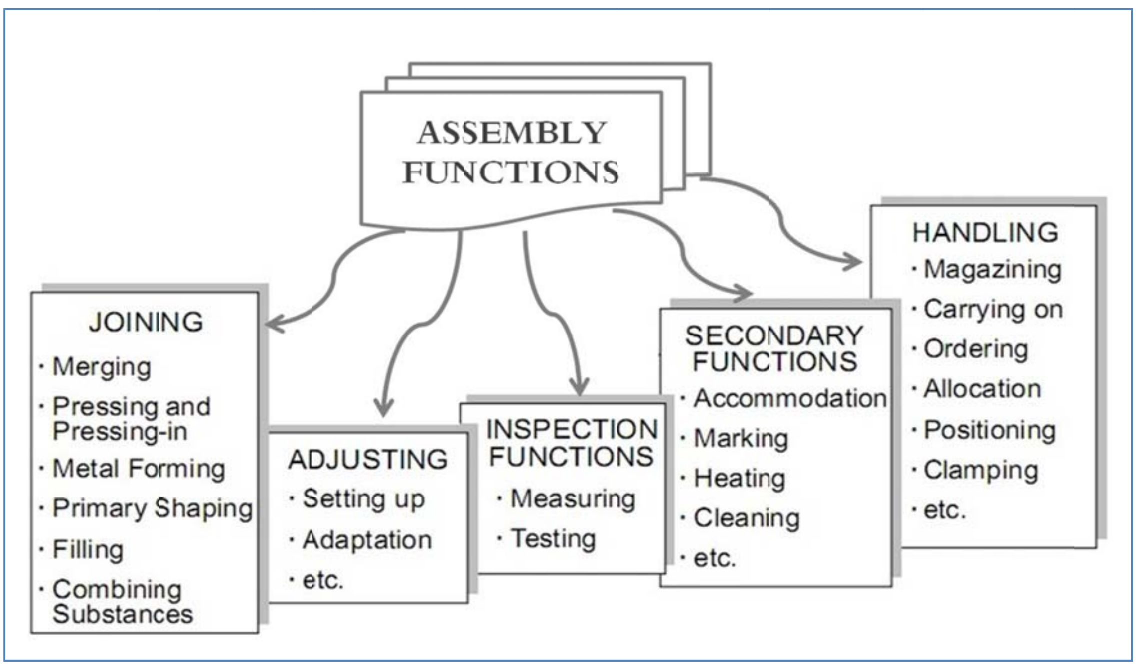



Figure 2. 11 Assembly functions (adapted from G. Salvendy, 2001)

There are different possibilities for the spatial line-up of assembly systems (G. Salvendy, 2001) . One possibility is a line structure, which is characterized by:

- Clear flow of materials
- Simple accessibility of the subsystems (e.g., for maintenance)
- Simple line-up of main and secondary lines
- Used mainly for mass production.

Alternatively, an assembly system can be arranged in a rectangular structure, which is characterized by:

- Very compact design.
- High flexibility.
- Poor accessibility to the subsystems.
- Used mainly for small and medium lot sizes.

Assembly is unique compared to the methods of manufacturing such as machining, grinding, and welding in that most of these non-assembly operations cannot be performed without the aid of equipment. Assembly is one of the highest areas of direct labour costs. It brings together all the upstream process of design, engineering, manufacturing, and logistics to create an object that performs a function.

### 2.2.1 The economic significance of assembly

In the automotive industry 50% of the direct labour costs are in the area of assembly, and in precision instruments it is between 20% and 70%. These statistics indicate the relative importance of assembly in terms of time and cost of assembled products. They also point to the potential savings that can be generated by efforts to understand and improve assembly technology and systems (S.Y. Nof *et al.*, 1997). A typical assembly system is shown in Figure 2. 12. The Figure shows automated assembly line for wristwatches using robots with vision. The assembled product takes its shape gradually starting with one part (the base part), with the remaining parts being attached at the various stations visited by the product.

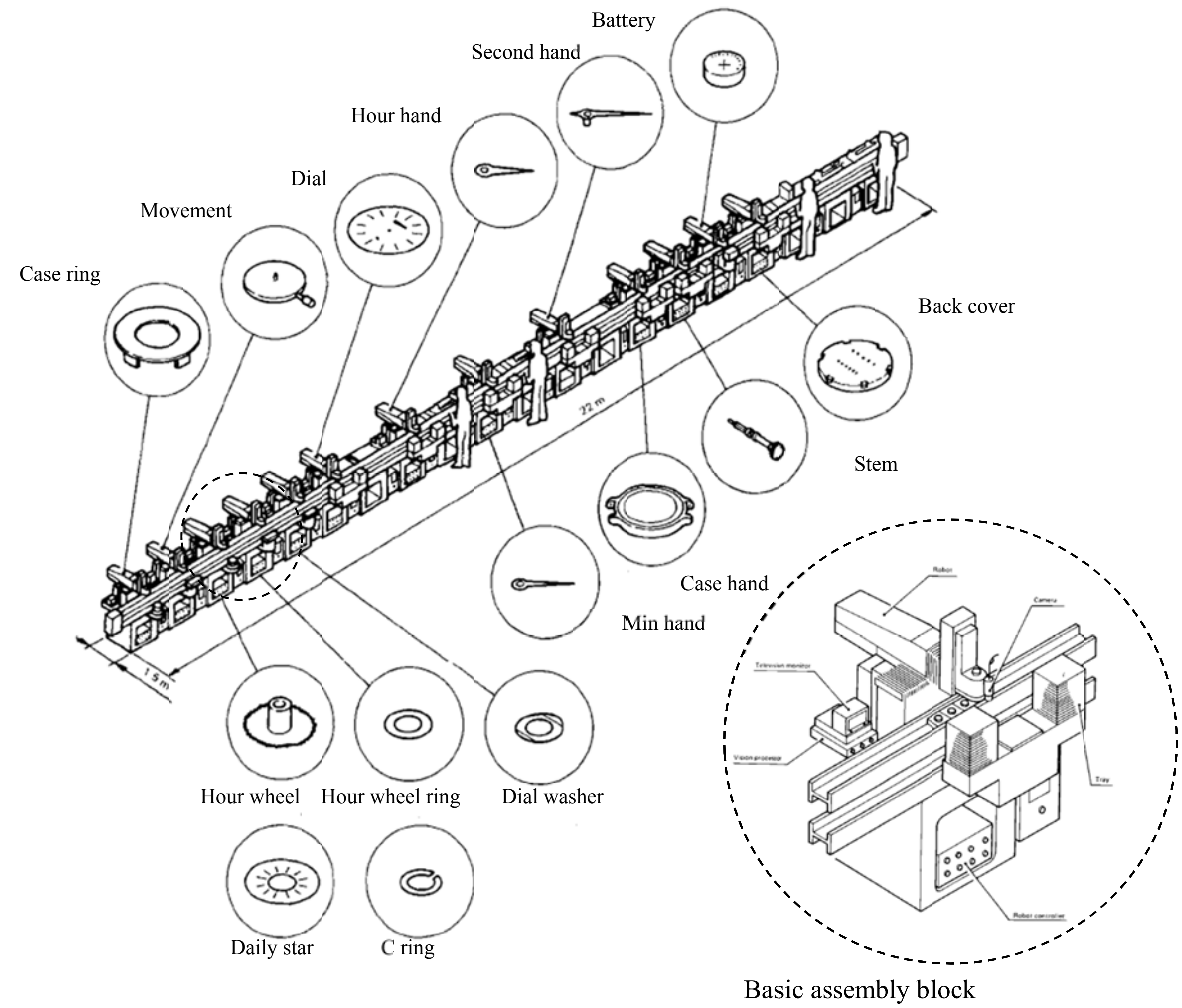



Figure 2. 12 Automated assembly line for wrist watches using robots with vision (adapted fromT. Saigo *et al.*, 1986)

The figure shows the parts for a typical casing assembly superimposed on an outline of the assembly line. The line is a combination of 20 blocks. Each block is independently controlled. The controllers are connected to a central system called the 'Line CPU', which controls the entire line. It gives instructions to the controllers in each block concerning changeover and indicates production conditions. Thirteen assembly blocks out of 20 employ robots. Eight out of the 13 blocks with robots are equipped with a vision system. The other three blocks are for the dedicated use of fixed sequence and correction. In addition to product structuring, assembly information is a key to assembly modeling and representation (Figure 2. 13).

Assembly information is any product and process information that describes the assembly of more than one component including all relevant relations, e.g. precedence relations, handling and feeding attributes, operational attributes, assembly connections, and any other non-geometric attributes such as information on processes and tooling. This information is the foundation of assembly modeling and other evaluation methods and processes.

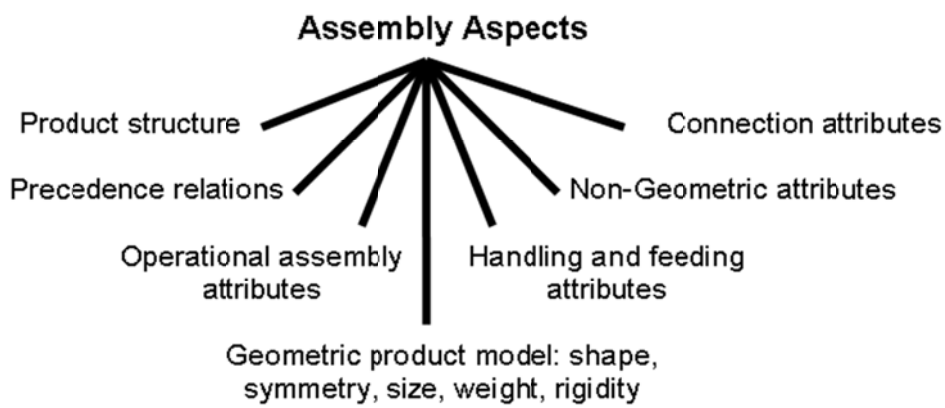



Figure 2. 13 Assembly representation (adapted from S.N. Samy and H. ElMaraghy, 2008)

### 2.2.2 Assembly technologies and systems

Most assembly machines and systems are designed for a particular product or a family of products. Basic components of assembly machines include assembly heads and devices, work holding fixtures, transfer and/or indexing mechanisms, feeders and orienting devices. In addition to their main functions, assembly machines and systems also include means for easy and rapid removal of jammed parts or defective assemblies. Safety, noise control, and environmental protection devices are also essential. Sufficient space is normally provided around the system for material handling and storage as well as for access by maintenance and repair personal.

There are three main assembly methods: manual, automatic and hybrid assembly as shown in Figure 2. 14.

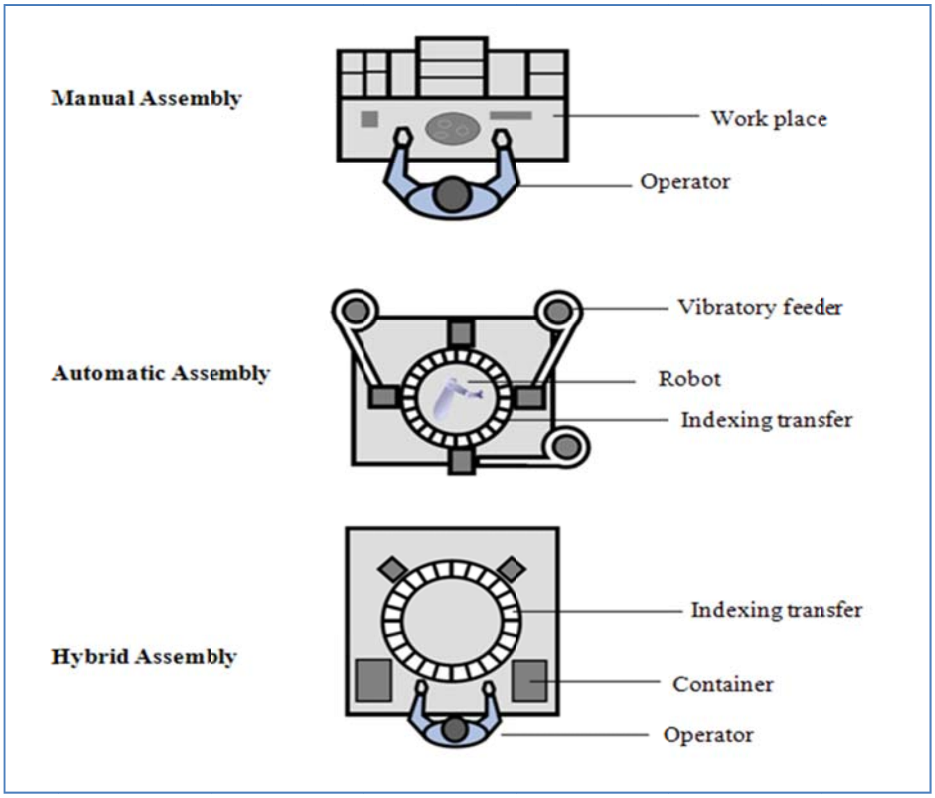



Figure 2. 14 Assembly systems by type of assemblers

2.2.2.1 Manual assembly

Manual assembly systems are often used within the area of fine mechanics and electrical engineering. They are suitable for the assembly of products with a large number of versions or products with high complexity. Human workers are located at the central point of manual assembly systems. They execute assembly operations by using their manual skill, senses, and their intelligence. They are supported by many tools and devices. The choice of the form of organization depends on the size of the product, the complexity of the product, the difficulty of assembly, and the number of units.

Workstations are used for small products or modules with limited complexity and a small number of units. High version and quantity flexibility are the most important advantages. Also, disturbances affect other workstations to only a small extent.

The components for the basic parts and the assembly parts are the substantial constituents of manual assembly systems. The assembly parts are often supplied in grab containers. The distances to be covered by the workers arms should be short and in the same direction. The intention is to shorten the cycle time and reduce the physical strain on the workers. This can be realized by arranging the grab containers in paternoster or on rotation plates. Further important criteria are glare-free lighting and adapted devices such as footrests or work chairs.

When assembly at a workstation is impossible for technological or economical reasons, the assembly can be carried out with several chained manual assembly stations. Manual assembly systems consist of a multiplicity of components. The stations are chained by double-belt conveyors or transport rollers. The modules rest on carriers with adapted devices for fixing the modules. The carriers form a defined interface between the module and the super ordinate flow of material. Identification systems separate the different versions and help to transport them to the correct assembly stations.

In manual assembly tasks, workers are confronted with multiple sources of information. Relevant information has to be selected, action planned and executed appropriately. Moreover, due to a growing demand for flexible and customized production, interfaces designed to optimally support workers in manufacturing become increasingly relevant (S. Stork and A. Schubo, 2010)

2.2.2.2 Automatic assembly

Automated assembly systems are used mainly for mass production. In the field of indexing machines, a distinction is made between rotary indexing turn tables and rectilinear transfer machines. The essential difference between the two systems is the spatial arrangement of the individual workstations. Rotary indexing turn tables are characterized by short transport distances. The disadvantage is the restricted number of assembly stations because of the limited place. Rectilinear transfer machines can be equipped with as many assembly stations as needed. However, the realizable cycle time deteriorates through the longer transport distances between the individual stations. Indexing machines are characterized by a rigid chain of stations. The construction design depends mostly on the complexity of the product to be mounted. The main transfer drives are electrical motor via an adapted ratchet mechanism or cam and lever gears or can be implemented pneumatically and/or hydraulically. Secondary movements (clamping of parts, etc.) can be carried out mechanically, electromechanically, or pneumatically. The handling and assembly stations are often driven synchronously over cam disks. The total availability of the assembly system is influenced by the availability of the individual feeding devices. The number of stations needed depends on the extent of the single working cycles that have to be carried out (e.g., feeding, joining, processing, testing, and adjusting) (G. Salvendy, 2001).

Automatic assembly often referred to as fixed or hard automation, use indexing tables and parts feeders. Soft automation incorporates the use of programmable assembly machines and robots in a single or a multi-station robotic assembly cell/system with all activities simultaneously controlled and coordinated by a programmable logic controller (PLC) or a computer (A. Mital *et al.*, 2008). Flexible automated assembly systems include the basic process elements and transfer modules. The hardware modules used to conduct operations are inserted into the automated stations manually using a loading platform, or automatically, whereas data and energy is transferred via plug-in connections (B. Lotter and H.-P. Wiendahl, 2009). The mobility of the process modules is advantageous since system modifications can usually be completed in less than an hour or sometimes few minutes. Capital cost investment can be incremental and grow or shrink with the varying demand during the product life span.

#### 2.2.2.3 Hybrid assembly

Hybrid assembly systems refer to combined automated and manual workstations. The cooperation between human operators and assembly equipment in such systems is motivated by the flexibility and changeability of assembly processes. Safety of the cooperation between human and machine should be managed. The efficiency of hybrid assembly systems depends on the intelligent feeding of workpieces to the cooperative workplace (J. Kruger *et al.*, 2009, M. Morioka and S. Sakakibara, 2010).

Hybrid assembly systems are characterized by production rates and product variations between those for the manual and automated assembly systems. One advantage is their flexibility regarding the number of pieces, which can be controlled by changing the number of assembly workers on the manual workstations. Additionally, the initial degree of automation can be adapted to changes in the production rate during the entire service life using a number of extension stages (B. Lotter and H.-P. Wiendahl, 2009). Hybrid assembly systems offers increased efficiency of the assembly line (T.K. Lien, 2001). Lien (2001) presented a theoretical model to predict the performance of the manual section in the assembly line. Parallel and sequential configurations were studied. The parallel configuration was approved as a better alternative because of the flexibility and the overall line efficiency. Assembly systems are complex technical structures consisting of a great number of individual units and integrating different technologies. It is complex at the micro level; it is complex at the macro level (D.E. Whitney, 2004). It is easy to see that, when individual components are manufactured with ease of assembly in mind, the result is a significant reduction in assembly lead limes. This leads to savings in resources (both equipment and human) (A. Mital *et al.*, 2008)

### 2.2.3 Complexity of Assembly

Measuring the complexity of assembly supports assembly-oriented product design and guides designers in creating a product with low assembly complexity. It also supports systems designers to rationalize the choice of various processes, sequences, equipment and system layouts. The economic importance of assembly has led to extensive efforts to improve the efficiency and cost effectiveness of assembly operations. One way of achieving this is by managing the complexity of assembly and its drivers or sources.

Researchers have attempted to measure the complexity of assembly. Boothroyd et al. (2002) proposed the Design for Assembly (*DFA*) method based on modelling assembly difficulty with data drawn from a large number of empirical observations of people and machines. This method does not include the actual assembly task complexity and is based on estimations of assembly time. Sturges and Kilani (1992) presented an index of difficulty to quantify the agility and time required to assemble a product but did not include the effect of a part's geometry in the calculation of the index of difficulty and it consumes time to compare different assembly systems and strategies. Braha and Maimon (1998) also gauged the complexity of a product assembly by the time required to perform the assembly. They introduced a time complexity measure as a linear function of the information content to estimate the total assembly time. Rodriguez-Toro (2003) presented the notion of complexity, in terms of the DFA methodology at two levels: 1) component complexity and 2) assembly complexity. Component complexity encompasses those aspects of design that relate directly to each component. It can be further divided into manufacturing complexity (such as geometric shape) and process complexity (such as handling and insertion). Assembly complexity accounts for most of the complexity of the product itself. It can be further divided into structural complexity (such as component interface and interactions) and assembly sequence complexity as shown in Figure 2. 15.

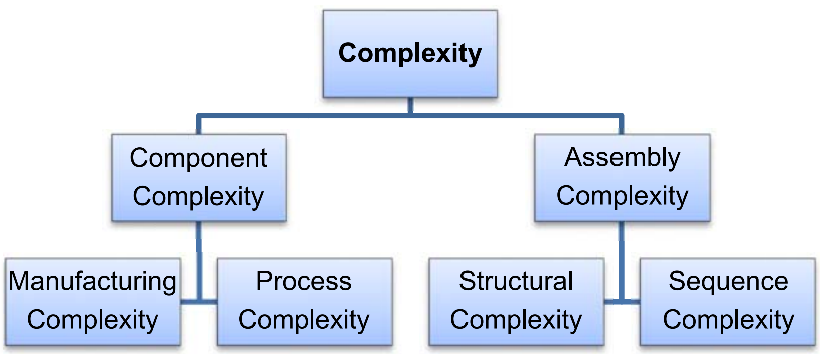



Figure 2. 15 Two levels of complexity (adapted from C. Rodriguez-Toro *et al.*, 2004)

A measure of complexity for the assembly and product configuration should be considered. Morse (2003) described the complexity of assembly in terms of the gaps or clearances between assembled components and used a GAPSPACE model to analyze assembly success in terms of non-interference of the components. The model was used to detect and analyze the fitting conditions in an assembly and to study the effect of tolerances on these fitting conditions. Zhu et al (2007, 2008) proposed a complexity measure called "operator choice complexity" (OCC) to quantify human performance in making choices at the station level in multi-stage mixed-model assembly systems. Their analytical model is an information-theoretic entropy measure of the average randomness in a selection process. later, Wang and Hu (2010) extend that complexity measure by considering system configuration and assembly cycle time in addition to operator choices.

Identifying global attributes that contribute to assembly difficulty will provide means for predicting assembly complexity more effectively. Zaeh et al. (2009) proposed a multi-dimensional measure for determining the complexity of manual assembly operations. They suggested that the exposure of the human worker resulting from a certain task shall be based upon three interrelated factors: temporal factor, cognitive factor, and knowledge-based factor. Their experimental results demonstrated an influence of task difficulty and communication mode on commissioning as well as on joining tasks. Su et al. (2010) investigated the problem of assembly defects caused by mistakes of operators by considering two complexity factors, namely, the design-based assembly complexity factor and the process-based assembly complexity factor, which are defined according to the structure and production characteristics of a copier machine.

## 2.3 Summary of the Literature Survey

The manufacturing environment becomes more complex and the significance and benefits of developing an appropriate complexity measure is obvious.

In this chapter a review of complexity definitions and measures issues especially for assembly was presented. From the review of different measures we observed that the most widely used metric is the entropic/information approach. Although this approach has difficulties in applying and getting data in order to calculate probability but it has the advantage of producing one number indicating the amount of complexity. This advantage facilitates the comparison between several systems options in terms of their level of complexity.

There is a need to describe and develop complexity measures capable of considering the impact of product (parts/sub-assemblies) assembly attributes on the product complexity. Design for Assembly-based complexity model is most appropriate.

The manufacturing environment consists of physical systems in which a series of sequential decisions need to be made in order to produce finished products. The sequence and nature of these decisions are not only dependent on the system capabilities but also on the products being manufactured in the system. Hence, developed measures of complexity should consider both the product and the related assembly system. The need is to map such a relation between product complexity and system complexity.

Developing such a model will help manufacturers to design and assemble products with least complexity and rationalize the various alternatives. Managing drivers or sources of complexity of assembly will help in reducing assembly cost and time; improve productivity and quality, and increase profitability and competitiveness.

# CHAPTER THREE

# MEASURING PRODUCTS ASSEMBLY COMPLEXITY

In this chapter product assembly complexity is defined as the degree to which the individual parts/subassemblies contain physical attributes that cause difficulties during the handling and insertion processes in manual or automatic assembly. A product complexity model has been developed by incorporating the information amount and content, as well as the Design for Assembly (DFA) principles for assembled products into an earlier model that was designed for measuring complexity of machined parts. The new model is used to assess the assembly complexity of individual parts using an index for measuring the complexity. Individual indices for parts are aggregated to obtain an overall measure for total product assembly complexity. The new measure accounts for the different parts' assembly attributes as well as their number and variety. An automobile piston and a family of three-pin electric power plugs are used to demonstrate the proposed approach for automatic and manual assembly respectively.

## 3.1 Product Assembly Complexity Model

A manufacturing part complexity model, introduced originally by W. ElMaraghy and Urbanic (2003) to measure complexity of machining processes, has been modified and further developed for assembly to account for the various parts handling and insertion attributes and to consider the effect of fasteners on the product assembly complexity. A method has also been introduced to aggregate the complexity indices of the various parts to obtain an overall index that represents the whole product assembly complexity. The earlier model (ElMaraghy and Urbanic, 2003) was created to measure the complexity of machined parts as a function of material, design and special specifications of each part. The basic elements of complexity were assumed to consist of three factors: the absolute quantity of information, the diversity of information and the information content. The information content was defined as a relative measure of effort to achieve the required result. A matrix was used to determine relative complexity factors and then capture the information content. The complexity model was originally expressed as:

$$C_{part} = \left(\frac{n}{N} + CI_{part}\right)[log_2(N+1)]$$

(3. 1)

where $C_{part}$ is part complexity, $N$ is the total quantity of information, $n$ is the quantity of unique information, and $CI_{part}$ is the part complexity index.

This model has been modified (S.N. Samy and H. ElMaraghy, 2010a, S.N. Samy and H. ElMaraghy, 2010c) for assembly as follows:

$$C_{product} = \left(\frac{n_p}{N_p} + CI_{product}\right)[log_2(N_p+1)] + \left(\frac{n_s}{N_s}\right)[log_2(N_s+1)]$$

(3. 2)

where $C_{product}$ is product assembly complexity, $N_p$, $N_s$ are the total numbers of parts and fasteners respectively, $n_p$, $n_s$ are the number of unique parts and fasteners respectively, and $CI_{product}$ is the product assembly complexity index.

The second term of Equation (3. 2) represents the diversity and quantity of information related to the used fasteners, $N_s$, $n_s \geq 1$

### 3.1.1 Complexity factor

Based on the DFA analysis, different assembly attributes can be classified into two groups: (1) assembly handling attributes and (2) assembly insertion attributes. In Table 3.1 and Table 3.2, average complexity factors have been calculated using the empirical values from the DFA data charts for both manual and automatic assemblies respectively.

Table 3. 1 Assembly attributes for manual assembly (S.N. Samy and H. ElMaraghy, 2010c)

| Group | Attribute | Description | Average complexity factor, $C_f$ |
|---|---|---|---|
| Handling attributes | Symmetry ($\alpha + \beta$) | $\alpha + \beta < 360$<br>$360 \leq \alpha + \beta < 540$<br>$540 \leq \alpha + \beta < 720$<br>$\alpha + \beta = 720$ | 0.70<br>0.84<br>0.94<br>1.00 |
| | Size | > 15 mm<br>6 mm < size ≤ 15 mm<br>< 6 mm | 0.74<br>0.81<br>1 |
| | Thickness | > 2 mm<br>0.25 mm< size ≤ 2 mm<br>≤ 0.25 mm | 0.27<br>0.5<br>1 |
| | Weight | < 10 lb (light)<br>> 10 lb | 0.5<br>1 |
| | Grasping and manipulation | Easy to grasp and manipulate<br>Not easy to grasp and manipulate | 0.91<br>1 |
| | Assistance | Using one hand<br>Using one hand with grasping aids<br>Using two hands<br>Using two hands with assistance | 0.34<br>1<br>0.75<br>0.57 |
| | Nesting and tangling | Parts do not severely nest or tangle and are not flexible.<br>Parts severely nest or tangle or are flexible. | 0.58<br>1 |
| | Optical magnification | Not necessary<br>Necessary | 0.8<br>1 |
| Insertion attributes | Holding down | Not required<br>Required | 0.54<br>1 |
| | alignment | Easy to align or position<br>Not easy to align or position | 0.86<br>1 |
| | Insertion resistance | No resistance<br>Resistance to insertion | 0.87<br>1 |
| | Accessibility and vision | No restrictions<br>Obstructed access or restricted vision<br>Obstructed access and restricted vision | 0.57<br>0.81<br>1 |
| | Mechanical Fastening processes | Bending<br>Riveting<br>Screw tightening<br>Bulk plastic deformation | 0.34<br>0.58<br>0.42<br>1 |
| | Non-Mech. fastening processes: | No additional material required<br>Soldering processes<br>chemical processes | 0.58<br>0.67<br>1 |
| | Non fastening processes: | Manipulation of parts or sub-assemblies(fitting or adjusting of parts, …)<br>Other processes (liquid insertion,..) | 0.75<br>1 |

Table 3. 2 Assembly attributes for automatic assembly (S.N. Samy and H. ElMaraghy, 2010c)

| Group | Attribute | Description | Average complexity factor, $C_f$ |
|---|---|---|---|
| Handling attributes | Symmetry | **Rotational part**<br>α symmetric and β symmetric<br>β symmetric only<br>α symmetric only<br>No symmetry<br><br>**Non-rotational part**<br>180° symmetry about three axes<br>180° symmetry about one axis only<br>No symmetry | <br>0.45<br>0.66<br>0.77<br>1<br><br><br>0.6<br>0.77<br>1 |
| | Size | > 15 mm<br>6 mm < size ≤ 15 mm<br>< 6 mm | 0.74<br>0.81<br>1 |
| | Flexibility | Non flexible<br>Flexible | 0.67<br>1 |
| | Delicateness | Non delicate<br>Delicate | 0.8<br>1 |
| | Stickiness | Not sticky<br>Sticky | 0.8<br>1 |
| | Tangling / nesting | Not tangle / nest<br>Tangle / nest | 0.8<br>1 |
| Insertion attributes | Securing assembly | Not required<br>Required | 0.75<br>1 |
| | Insertion resistance | Does not exist<br>Exists | 0.67<br>1 |
| | Alignment and positioning | Easy<br>Not easy | 0.67<br>1 |
| | Mechanical Fastening methods | Screwing or other processes<br>Riveting or similar processes<br>Bending or similar processes | 0.5<br>0.56<br>1 |
| | Non-mechanical fastening methods | Chemical processes<br>Additional material required<br>No addition of material (friction, …) | 0.67<br>0.92<br>1 |
| | Insertion direction | Straight line from above<br>Straight line not from above<br>Not straight line insertion | 0.5<br>0.54<br>1 |

Table 3.3 shows an example of calculating the average manual handling complexity factors for part *symmetry* attribute in manual handling assembly. The average of the estimated time (from DFA analysis charts) values is first calculated then normalized by its maximum value (2.91 for this attribute).

Table 3. 3 Average symmetry complexity factor, $C_f$, for manual handling (S.N. Samy and H. ElMaraghy, 2010c)

| | | Second digit | | | | | | | | | | Average | Normalized average complexity factor, $C_f$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | | |
| First digit | 0 | 1.13 | 1.43 | 1.88 | 1.69 | 2.18 | 1.84 | 2.17 | 2.65 | 2.45 | 2.98 | 2.04 | **0.70** |
| | 1 | 1.5 | 1.8 | 2.25 | 2.06 | 2.55 | 2.25 | 2.57 | 3.06 | 3 | 3.38 | 2.44 | **0.84** |
| | 2 | 1.8 | 2.1 | 2.55 | 2.36 | 2.85 | 2.57 | 2.9 | 3.38 | 3.18 | 3.7 | 2.74 | **0.94** |
| | 3 | 1.95 | 2.25 | 2.7 | 2.51 | 3 | 2.73 | 3.06 | 3.55 | 3.34 | 4 | 2.91 | **1** |

Assembly attributes affect the worker's effort to grasp, orient, insert, and fasten in manual assembly. In automatic assembly, they affect orientation efficiency and the cost of the equipment required. Figure 3. 1 is an example of a slightly symmetric part. This part would not present significant problems in manual handling and insertion whereas, for automatic handling, a vision system would be needed to recognize its correct orientation.


Figure 3. 1 Symmetry attribute (S.N. Samy and H. ElMaraghy, 2010c)

### 3.1.2 Complexity index

The proposed procedure to calculate product assembly complexity index is shown in Figure 3. 2 . Each part is examined separately to identify their different handling and insertion attributes. The overall product assembly complexity index is based on the individual assembly complexity indices of all parts. The evaluation procedure is described as follows:

- Construct a complexity matrix representing the average complexity factors for both handling and insertion attributes. Rows represent individual parts and columns represent their assembly attributes.
- Calculate the average handling complexity factor, $C_h$ ,

$$C_h = \frac{\sum_1^J C_{h,f}}{J} \tag{3. 3}$$

where $C_{h,f}$ is the relative handling complexity factor and *J* is the number of handling attributes of each part.

- Calculate the average insertion complexity factor, $C_i$,

$$C_i = \frac{\sum_1^k C_{i,f}}{k} \tag{3. 4}$$

where $C_{i,f}$ is the average insertion complexity factor and *K* is the number of insertion attributes of each part.

- Calculate the weighted average values of the part complexity factors, $\mathrm{C_{part}}$

$$C_{part} = \frac{C_h \sum_1^J C_{h,f} + C_i \sum_1^k C_{i,f}}{\sum_1^J C_{h,f} + \sum_1^k C_{i,f}} \tag{3. 5}$$

- Calculate the product complexity index, $\mathrm{CI_{product}}$

$$CI_{product} = \sum_{p=1}^{p=n} x_p C_{part} \tag{3. 6}$$

where $x_\mathrm{p}$ is the percentage of the $x^{\mathrm{th}}$ dissimilar parts, *n* is number of unique parts.

- Count the total and unique number of all parts.
- Count the total and unique number of all fasteners.
- Calculate the total product complexity using Equation (3. 2).

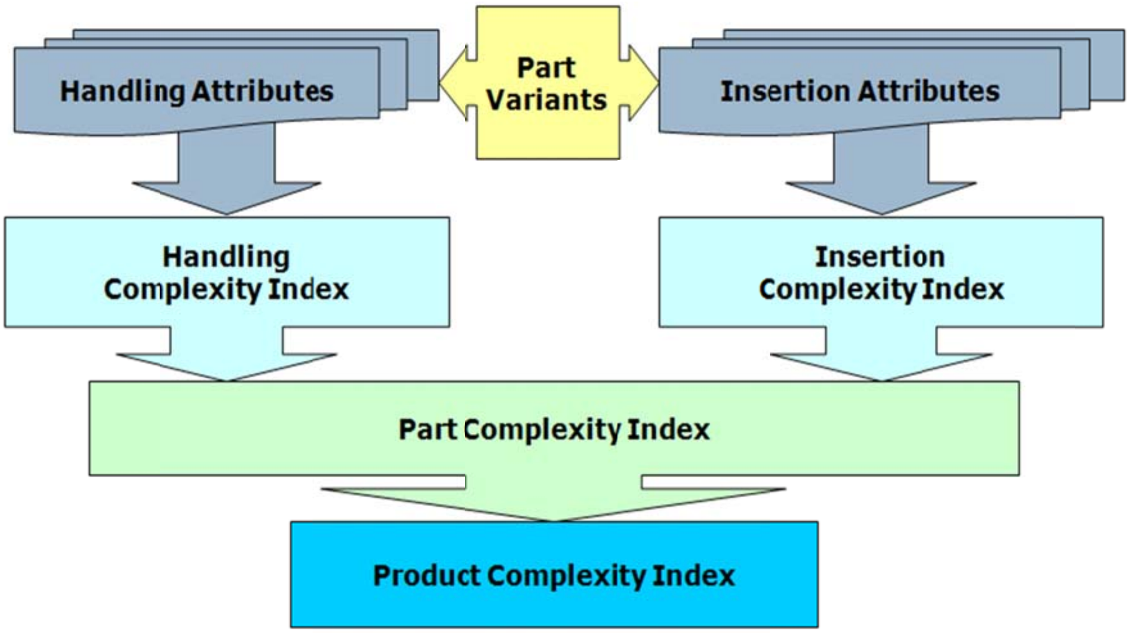



Figure 3. 2 Product complexity index

It is important to note that "product" in the original complexity metric (W. ElMaraghy and Urbanic, 2003) refers to individual parts to be machined, while in the new assembly complexity metric it refers to a product or sub-assembly that consists of more than one part. The effect of the number and variety of fasteners on the total product complexity is also considered by including the second part of Equation (3. 2).

## 3.2 Case study: Automatic assembly of an automobile engine piston

Figure 3. 3 shows an automobile piston assembly. It is a component of reciprocating engines and its purpose is to transfer force from expanding gas in the cylinder to the crankshaft via a piston rod and/or connecting rod. The individual components of the piston are analyzed for automatic assembly. The analysis results for handling and insertion attributes are shown in Table 3.4 and Table 3.5 respectively.

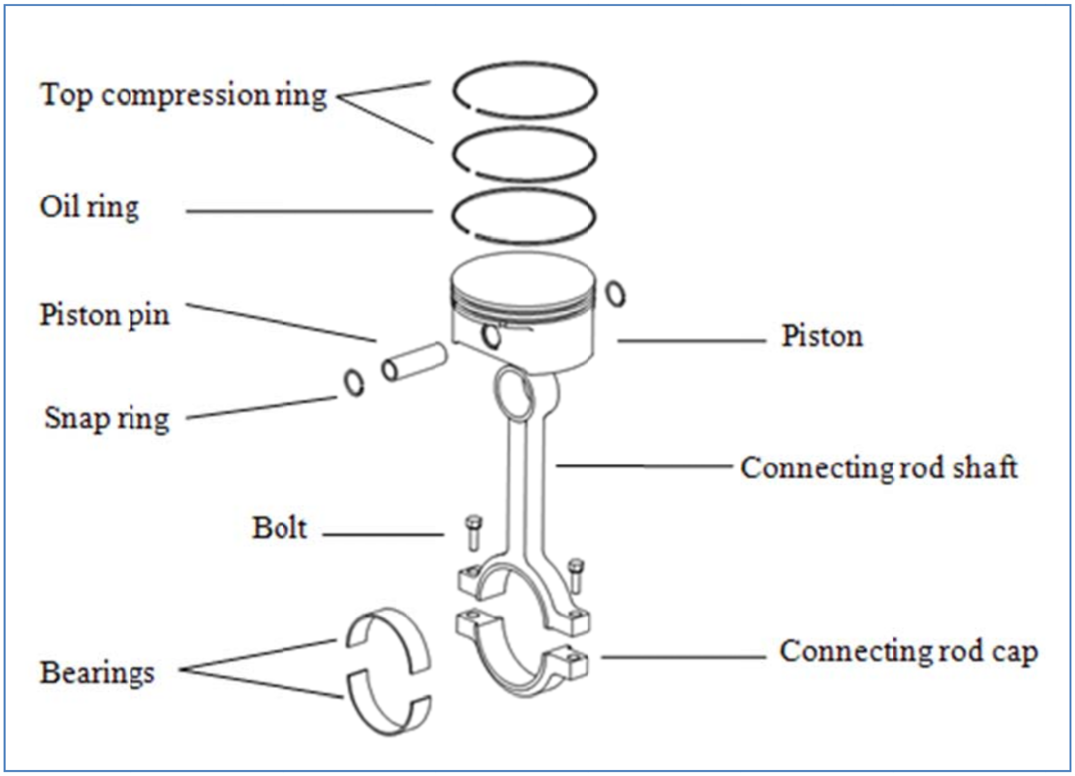



Figure 3. 3 Automobile engine piston assembly (S.N. Samy and H. ElMaraghy, 2010c)

Table 3. 4 Parts handling complexity attributes matrix, piston (S.N. Samy and H. ElMaraghy, 2010c)

| Part name | Handling complexity factor, $C_{h,f}$ | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number | Symmetry | Size | Flexibility | Delicateness | Stickiness | Nesting / tangling | J | SUM | $C_h$ | SUM* $C_h$ |
| **Compression ring** | 2 | 0.77 | 0.81 | 1 | 1 | 0.8 | 1 | 6 | 5.38 | 0.90 | 4.82 |
| **Oil ring** | 1 | 0.77 | 0.81 | 1 | 1 | 0.8 | 1 | 6 | 5.38 | 0.90 | 4.82 |
| **Piston** | 1 | 1 | 0.74 | 0.67 | 1.8 | 0.8 | 0.8 | 6 | 5.81 | 0.97 | 5.63 |
| **Piston pin** | 1 | 0.66 | 0.74 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.47 | 0.75 | 3.33 |
| **Snap ring** | 2 | 0.77 | 1 | 0.67 | 0.8 | 0.8 | 1 | 6 | 5.04 | 0.84 | 4.23 |
| **Connecting rod shaft** | 1 | 1 | 0.74 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.81 | 0.80 | 3.86 |
| **Connecting rod cap** | 1 | 1 | 0.74 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.81 | 0.80 | 3.86 |
| **Bearing** | 2 | 1 | 0.81 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.88 | 0.81 | 3.97 |

Table 3. 5 Parts insertion complexity attributes matrix, piston (S.N. Samy and H. ElMaraghy, 2010c)

| Part name | Insertion complexity factor, $C_{i,f}$ | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number | Secure assembly | Insertion resistance | Alignment | Mechanical Fastening | Non-mechanical fastening | Insertion direction | K | SUM | $C_i$ | SUM * $C_i$ |
| **Compression ring** | 2 | 0.75 | 1 | 1 | 0 | 0 | 0.5 | 4 | 3.25 | 0.81 | 2.64 |
| **Oil ring** | 1 | 0.75 | 1 | 1 | 0 | 0 | 0.5 | 4 | 3.25 | 0.81 | 2.64 |
| **Piston** | 1 | 0.75 | 0.67 | 0.67 | 0 | 0 | 0.5 | 4 | 2.59 | 0.65 | 1.68 |
| **Piston pin** | 1 | 0.75 | 1 | 1 | 0 | 0 | 0.54 | 4 | 3.29 | 0.82 | 2.71 |
| **Snap ring** | 2 | 0.75 | 1 | 1 | 0 | 0 | 0.54 | 4 | 3.29 | 0.82 | 2.71 |
| **Connecting rod shaft** | 1 | 1 | 0.67 | 1 | 0 | 0 | 0.5 | 4 | 3.17 | 0.79 | 2.51 |
| **Connecting rod cap** | 1 | 1 | 0.67 | 1 | 0.5 | 0 | 0.5 | 5 | 3.67 | 0.73 | 2.69 |
| **Bearing** | 2 | 1 | 1 | 1 | 0 | 0 | 0.5 | 4 | 3.5 | 0.88 | 3.06 |

Product complexity index is then calculated as shown in Table 3.6.

Table 3. 6 Calculation of product complexity index ($CI_{\text{product}}$), piston

| Part Name | $C_{part} = (SUM * C_h + SUM * C_i)/(C_h + C_i)$ | $x_p$ | $x_p C_{part}$ |
|---|---|---|---|
| **Compression ring** | 0.86 | 0.182 | 0.16 |
| **Oil ring** | 0.86 | 0.091 | 0.08 |
| **Piston** | 0.87 | 0.091 | 0.08 |
| **Piston pin** | 0.78 | 0.091 | 0.07 |
| **Snap ring** | 0.83 | 0.182 | 0.15 |
| **Connecting rod shaft** | 0.80 | 0.091 | 0.07 |
| **Connecting rod cap** | 0.77 | 0.091 | 0.07 |
| **Bearing** | 0.84 | 0.182 | 0.15 |
| $CI_{product} = \sum_{1}^{n_p} x_p C_{part}$ | | | 0.83 |

The parts count is: total number of parts ($N_p$) = 2 compression rings + 1 oil ring + 1 piston + 1 piston pin + 2 snap rings + 1 connecting rod shaft + 1 connecting rod cap + 2 bearings) =11, unique number of parts = ($n_p$) = 1 compression rings + 1 oil ring + 1 piston + 1 piston pin + 1 snap rings + 1 connecting rod shaft + 1 connecting rod cap + 1 bearings = 8. Fasteners count are $N_s = 2, n_s = 1$ . Thus the piston assembly complexity can be calculated using Equation (3. 2) as:

$$C_{piston} = \left(\frac{8}{11} + 0.83\right)[log_2(11+1)] + \left(\frac{1}{2}\right)[log_2(2+1)] = 6.38$$

### 3.3 Case study: Manual assembly of a three-pin electric power plug

A product family of a three-pin electric power plug (Figure 3. 4) is analyzed to illustrate the use of the assembly complexity model and show the impact of product variety on the product assembly complexity. The members of the power plug family show great similarity. The plug assortment consists of a number of common identical components, such as the cord grip, screws and pins, which reduces the diversity of system components in the assembly system. Also, the bases of the four plugs are similar; hence, the same fixture can be used for all product variants. The bases are having two blind holes on the bottom side that fit in the two nubs on the fixture. Plugs # 1 and # 2 have screws to assemble the cover and the base together. The screw is inserted from below in the first plug and from above in the second plug. Plugs # 3 and # 4 use snap fits to assemble the cover and the base.

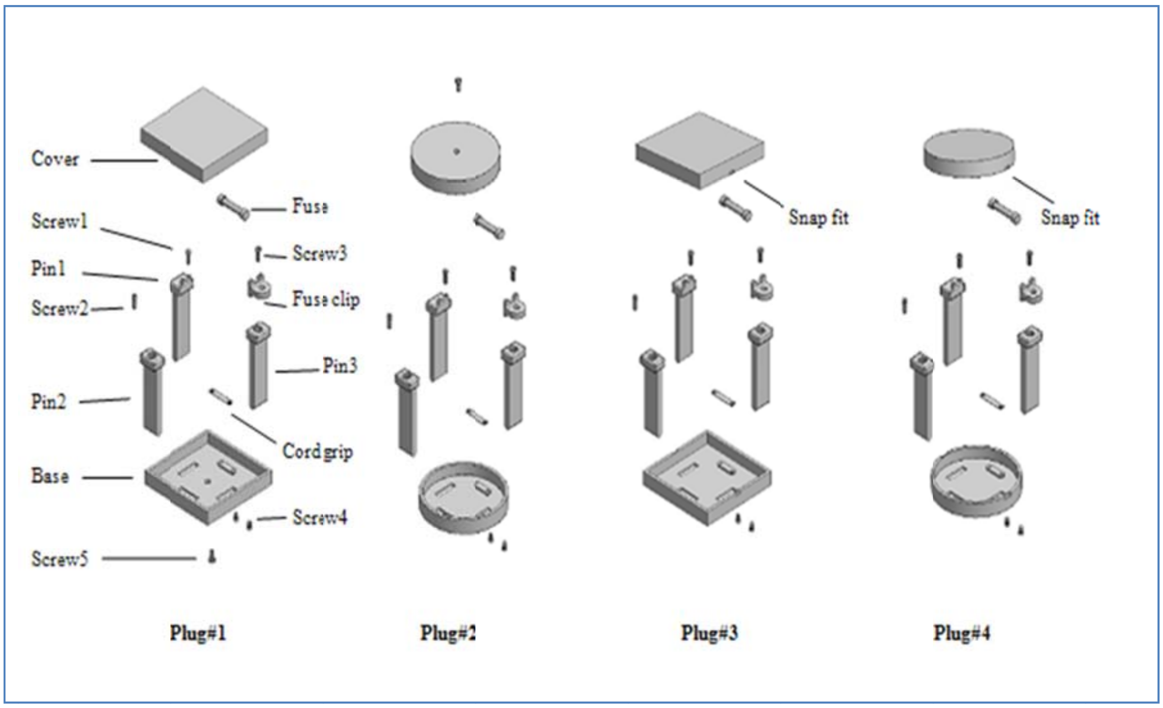



Figure 3. 4 Assortments of the three-pin electric power plug (S.N. Samy and H. ElMaraghy, 2010c)

The four power plugs are analyzed for manual assembly. Table 3.7 and Table 3. 8 show the results of complexity analysis for plug # 1. Analyses of plug #2, plug #3, and plug #4 are shown in Tables (A.1 - A.6) of Appendix (A). Table 3.7 shows that the highest handling complexity factors are associated with symmetry, grasping and manipulation attributes and the lowest values are associated with the part weight and attributes calling for assistance during assembly. Table 3. 8 shows that the highest insertion complexity factors are associated with the alignment attribute and the lowest values are associated with the accessibility attribute.

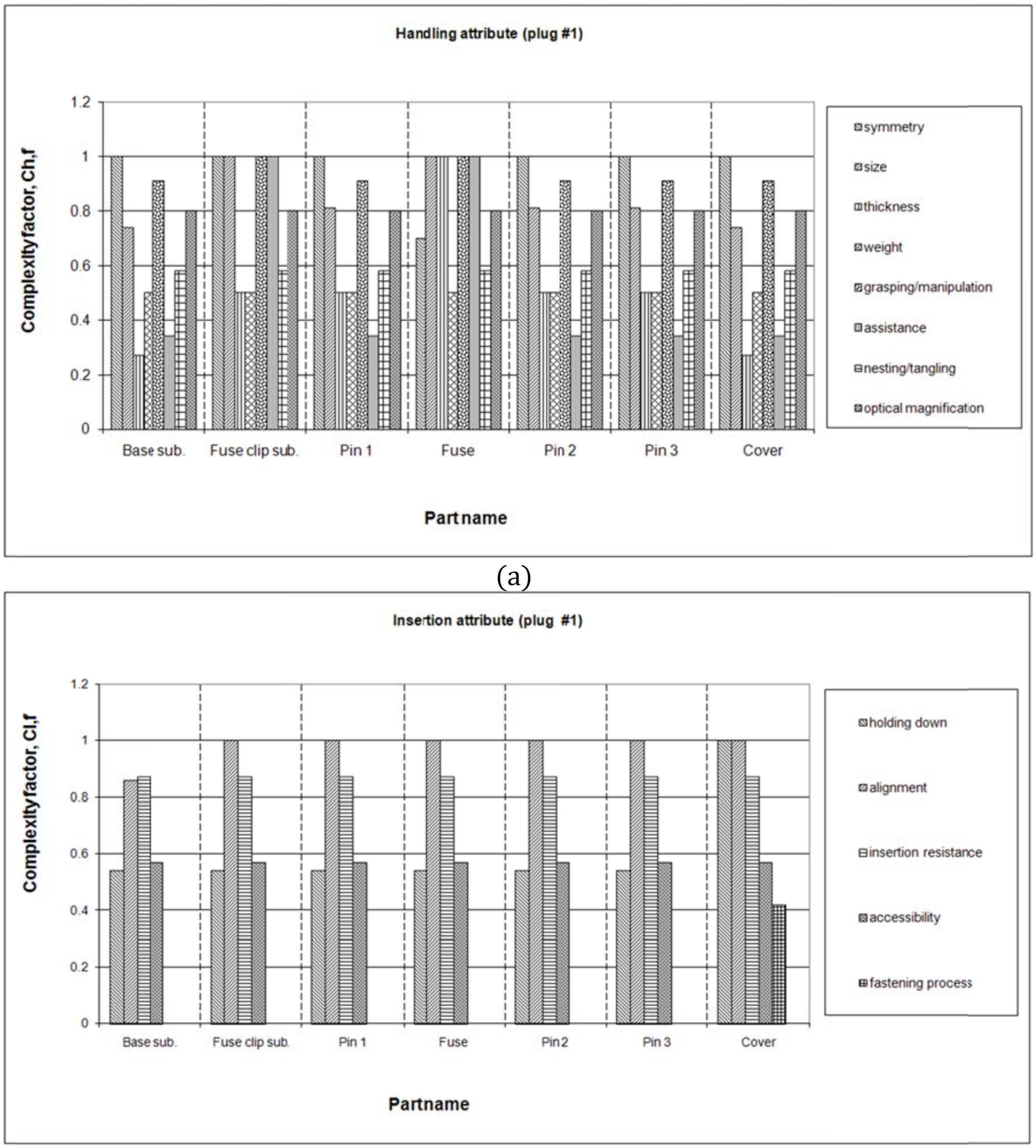
Table 3. 7 Parts handling complexity attributes matrix (plug #1) (S.N. Samy and H. ElMaraghy, 2010c)

| **Part name** | **Handling complexity factor, $C_{h,f}$** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Number** | **Symmetry** | **size** | **Thickness** | **weight** | **Grasping / manipulation** | **Assistance** | **Nesting / tangling** | **Optical magnification** | **J** | **SUM** | **$C_h$** | **SUM* $C_h$** |
| **Base sub.** | 1 | 1 | 0.74 | 0.27 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 5.14 | 0.64 | 3.30 |
| **Fuse sub.** | 1 | 1 | 1 | 0.5 | 0.5 | 1 | 1 | 0.58 | 0.8 | 8 | 6.38 | 0.80 | 5.09 |
| **Pin 1** | 1 | 1 | 0.81 | 0.5 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 5.44 | 0.68 | 3.70 |
| **Fuse** | 1 | 0.7 | 1 | 1 | 0.5 | 1 | 1 | 0.58 | 0.8 | 8 | 6.58 | 0.82 | 5.41 |
| **Pin 2** | 1 | 1 | 0.81 | 0.5 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 5.44 | 0.68 | 3.70 |
| **Pin 3** | 1 | 1 | 0.81 | 0.5 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 5.44 | 0.68 | 3.70 |
| **Cover** | 1 | 1 | 0.74 | 0.27 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 5.14 | 0.64 | 3.30 |

Table 3. 8 Parts insertion complexity attributes matrix (plug #1) (S.N. Samy and H. ElMaraghy, 2010c)

| **Part name** | **Insertion complexity factor, $C_{i,f}$** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Number** | **Holding down** | **Alignment** | **Insertion resistance** | **Accessibility** | **Fastening process** | **Non-mechanical** | **Non-fastening process** | **K** | **SUM** | **$C_i$** | **SUM * $C_i$** |
| **Base sub.** | 1 | 0.54 | 0.86 | 0.87 | 0.57 | - | - | - | 4 | 2.84 | 0.71 | 2.02 |
| **Fuse sub.** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Pin 1** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Fuse** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Pin 2** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Pin 3** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Cover** | 1 | 1 | 1 | 0.87 | 0.57 | 0.42 | - | - | 5 | 3.86 | 0.77 | 2.98 |

Figure 3. 5 is a column chart of the analyzed part handling and insertion attributes for manual assembly. Figure 3. 6 is a column chart of the total complexity index of the individual parts of the four plugs.




(b)

Figure 3. 5 (a) Part handling attributes, and (b) Part insertion attributes of plug # 1 (S.N. Samy and H. ElMaraghy, 2010c)

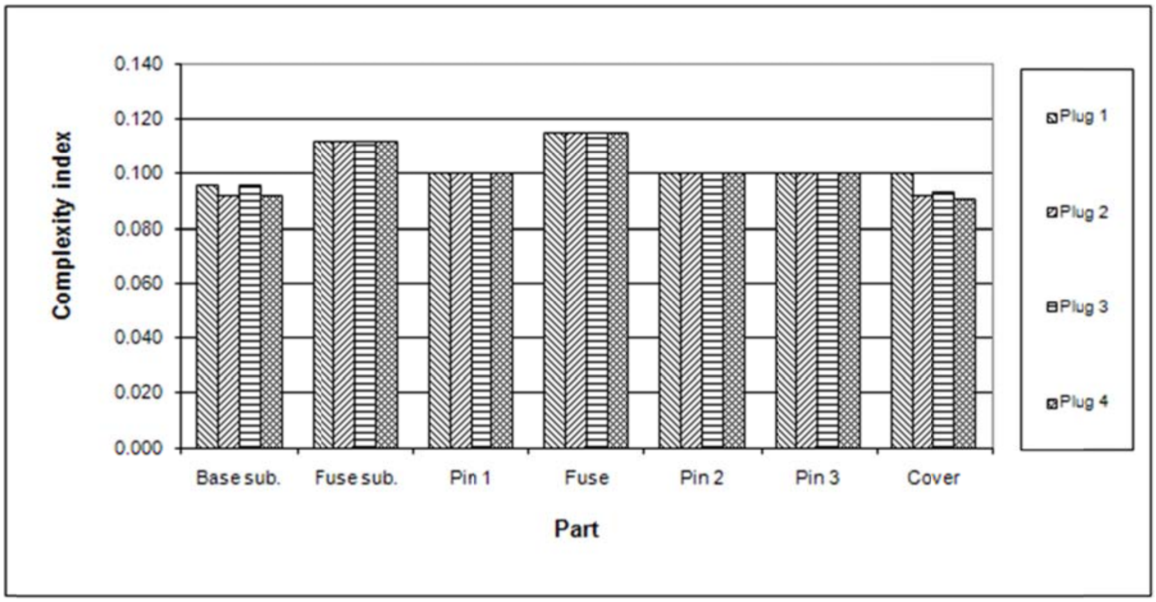


Figure 3. 6 Parts assembly complexity index (S.N. Samy and H. ElMaraghy, 2010c)

All parts and fasteners of the four plugs are counted and recorded in Table 3. 9. Based on the analysis results of the four plugs, the total product complexity index can be calculated as shown in Table 3.10.

Therefore, the total product assembly complexity is calculated for the four plugs using Equation (3. 2).

For plug # 1 as an example:

$$C_{plug\#1} = \left(\frac{6}{7} + 0.72\right)[log_2(7+1)] + \left(\frac{1}{1}\right)[log_2(1+1)] = 5.74$$

A summary of the results of the calculation of product complexity of the four plugs is shown in Table 3. 11. Table 3. 11 shows that plug # 1 has a higher product complexity (5.74) than the other three plugs, with plug # 4 having the lowest product complexity. Although the differences between the values of the four complexity indices are small, the reason for these differences can be tracked. The total product assembly complexity of Plug # 1 is high due to the asymmetry of its base and cover, the need to hold down the cover till the next assembly step, and using screws for fastening. The base and cover of plug #4 are more symmetric, and there is no need to hold down the cover due to the use of snap fits instead of screws. These redesigned features affect the handling and insertion attributes of these components lead to a less complex product (4.70).

Table 3. 9 Parts and fasteners counts for all plugs (S.N. Samy and H. ElMaraghy, 2010c)

| **# of Parts** | | | | | | | | **# of Fasteners** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Plug#1** | | **Plug#2** | | **Plug#3** | | **Plug#4** | | **Plug#1** | | **Plug#2** | | **Plug#3** | | **Plug#4** | |
| n | N | n | N | n | N | n | N | n | N | n | N | n | N | n | N |
| 6 | 7 | 6 | 7 | 6 | 7 | 6 | 7 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |

Table 3. 10 Calculation of product complexity index ($CI_{product}$) for all plugs (S.N. Samy and H. ElMaraghy, 2010c)

| **Part Name** | **$C_{part}$ = (SUM* $C_p$ + SUM * $C_a$) / ($C_p$+ $C_a$)** | | | | **$x_p$** | | | | **Part complexity index = $x_p$ * $C_{part}$** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Plug #1 | Plug #2 | Plug #3 | Plug #4 | Plug #1 | Plug #2 | Plug #3 | Plug #4 | Plug #1 | Plug #2 | Plug #3 | Plug #4 |
| **Base sub.** | 0.67 | 0.64 | 0.67 | 0.64 | 0.143 | 0.143 | 0.143 | 0.143 | 0.096 | 0.092 | 0.096 | 0.092 |
| **Fuse sub.** | 0.78 | 0.78 | 0.78 | 0.78 | 0.143 | 0.143 | 0.143 | 0.143 | 0.112 | 0.112 | 0.112 | 0.112 |
| **Pin 1** | 0.70 | 0.70 | 0.70 | 0.70 | 0.143 | 0.143 | 0.143 | 0.143 | 0.100 | 0.100 | 0.100 | 0.100 |
| **Fuse** | 0.80 | 0.80 | 0.80 | 0.80 | 0.143 | 0.143 | 0.143 | 0.143 | 0.114 | 0.114 | 0.114 | 0.114 |
| **Pin 2** | 0.70 | 0.70 | 0.70 | 0.70 | 0.143 | 0.143 | 0.143 | 0.143 | 0.100 | 0.100 | 0.100 | 0.100 |
| **Pin 3** | 0.70 | 0.70 | 0.70 | 0.70 | 0.143 | 0.143 | 0.143 | 0.143 | 0.100 | 0.100 | 0.100 | 0.100 |
| **Cover** | 0.70 | 0.64 | 0.65 | 0.63 | 0.143 | 0.143 | 0.143 | 0.143 | 0.100 | 0.092 | 0.093 | 0.090 |
| **$CI_{product}$ = SUM ($x_p$ * $C_{part}$)** | | | | | | | | | 0.722 | 0.709 | 0.715 | 0.708 |

Table 3. 11 Product assembly complexity of the power plug assortment (S.N. Samy and H. ElMaraghy, 2010c)

| **Product** | **Product complexity** | **Total assembly time from *DFA* analysis (sec)** |
|---|---|---|
| Plug # 1 | 5.74 | 38.66 |
| Plug # 2 | 5.70 | 37.02 |
| Plug # 3 | 4.72 | 31.16 |
| Plug # 4 | 4.70 | 29.52 |

Design for Assembly (*DFA*) has been done for the four plugs as shown in Tables (C.1 – C.4) of Appendix (C). The calculated complexities are also compared with the manual assembly time estimated by the analysis as shown in Table 3. 11. The results show that plug #1 (with highest complexity) requires longer assembly time compared with other plugs which having lower complexity. Higher complexity leads to longer assembly time and increases cost of assembly equipment.

Table 3. 12 shows the effect of changing assembly attributes on the product assembly complexity for the four plugs. Using snap fit fastening (plug # 3) instead of screws (plug # 1) will cause an assembly complexity reduction of 21.6 %. Not having to hold down plug # 4 during assembly reduced the assembly complexity, compared with plug # 2 where holding down is needed by 17.6 %. The symmetry of plug # 4 reduced the assembly complexity compared with plug # 3 (asymmetric) by 0.42%.

Table 3. 12 Effect of redesign change on product assembly complexity (S.N. Samy and H. ElMaraghy, 2010c)

| Product | Plugs # 1 & 3 | Plugs # 2 & 4 | Plugs # 3 & 4 |
|---|---|---|---|
| **Redesigned attribute** | **Fastening method** | **Holding down** | **Symmetry** |
| **Complexity ratio** | $C_{plug\#3} / C_{plug\#1} = 0.822$ | $C_{plug\#4} / C_{plug\#2} = 0.824$ | $C_{plug\#4} / C_{plug\#3} = 0.995$ |
| **Complexity reduction** | 21.6 % | 17.54 % | 00.42 % |

The differences between the total product assembly complexities of the four electric power plugs variants were small due to their similarity. The analysis, however, highlights the significant impact of the fasteners on assembly complexity and the need for holding parts due to lack of stability during assembly on manual product assembly complexity. The same is true in automated assembly where fixtures are used to secure and stabilize the parts. Hence, the proposed metric can be used at early design stages to guide designers in selecting parts features to reduce the total product assembly complexity.

# CHAPTER FOUR

# MEASURING ASSEMBLY SYSTEM COMPLEXITY

In this chapter, a static system complexity model is developed. A structural classification coding system is extended to capture the relevant characteristics of various entities within an assembly system. The structural classification coding is then used to measure assembly system complexity.

## 4.1 Coding and Classification

Coding and classification were originally used for controlling design versions and material storage and retrieval. However, with the development of work statistics and group technology, the use of coding and classification has spread into production planning and control and the selection of components for group machining. Also, advances in the application of computers have extended the use of coding and classification especially for information storage and retrieval. Coding and classification is a method of organizing knowledge by sorting and analyzing information and grouping similar features, facts and elements. Coding refers to the process of assigning symbols to entities. The symbols in the code could be all numeric, all alphabetic or a combination of both types. For parts coding, the symbols represent the attributes of parts which may later be used to form families of parts with similar attributes. Classification refers to categorization of parts into part families (N. Singh, 1993). The process of coding is preceded by classification for each critical attribute. There are three basic code structures used in classification and coding schemes (M. Agarwali *et al.*, 1994, H. ElMaraghy, 2005).

Hierarchical code structure (mono-code); where interpretation of each successive digit depends on the value of the preceding digit in the code string. The advantage of this approach is the relatively small number of digits of the code string. However this type of coding is very complicated and difficult to implement. Chain-type code structure (poly-code); where the meaning of each digit is constant regardless of any other digit within the code string. This type of coding is simple to implement, however, a large number of digits may be required for representation depending on the amount of information to be captured. Hybrid code structure is a combination of hierarchical and chain-type structures, taking advantage of both the mono-code and the poly-code systems. The basic requirements to get a good classification and coding scheme are (C.T. Mosier and R.E. Janaro, 1990):

- Comprehensive to include all existing items within a class.
- Flexible to allow for expansion to include new items.
- Using clear format and definition.
- Having a consistent point of view.
- Balanced distribution between the code classes.
- Each digit should have a unique meaning within a group.

Most of the available coding systems are implemented using a Hybrid structure. An example of this coding type is the OPITZ coding (Figure 4. 1). It consists of nine basic digits which can be extended by adding four more digits.

| DIGIT 1 | | DIGIT 2 | | DIGIT 3 | | DIGIT 4 | | DIGIT 5 | |
|---|---|---|---|---|---|---|---|---|---|
| 0 | Part class | 0 | External shape element | 0 | Internal shape element | 0 | Plane surface machining | 0 | Auxiliary holes and gear teeth |
| 1 | | 1 | | 1 | | 1 | | 1 | |
| 2 | | 2 | | 2 | | 2 | | 2 | |
| 3 | | 3 | | 3 | | 3 | | 3 | |
| 4 | | 4 | | 4 | | 4 | | 4 | |
| 5 | | 5 | | 5 | | 5 | | 5 | |
| 6 | | 6 | | 6 | | 6 | | 6 | |
| 7 | | 7 | | 7 | | 7 | | 7 | |
| 8 | | 8 | | 8 | | 8 | | 8 | |
| 9 | | 9 | | 9 | | 9 | | 9 | |

Figure 4. 1 Basic Structure of Opitz System (adapted fromM.P. Groover, 2008)

### 4.1.1 Automated coding and classification

Group Technology (GT) codes have been used in manufacturing and design applications for the retrieval of existing parts data and using it in downstream applications such as grouping and planning. Traditionally coding systems used manual methods. Development coding and classification systems automated this process to eliminate human errors and reduce coding time (M. Agarwali *et al.*, 1994, J. Barton and

D. Love, 2005, C.T. Mosier and R.E. Janaro, 1990). Classification and coding systems were originally developed for manufactured parts. However, equivalent coding and classification systems for manufacturing systems did not exist until the development of the structural classification and coding system (SCC) by H. ElMaraghy (2006). The original classification system is described briefly in the following section followed by description of new extensions to include various entities typically found in assembly systems.

### 4.1.2 Manufacturing systems structural classification code

A manufacturing system consists of the following major classes of entities: 1) Machines to carry out the manufacturing processes, 2) buffers to ensure the continuous supply of parts, 3) material handling equipment to transfer parts between machines, and 4) operators for complementary manual tasks, system operations, and supervisory tasks. There can be a large variation in the type of system entities to respond to changing production requirements (H. ElMaraghy, 2005). H. ElMaraghy (2006) developed a new manufacturing Systems Structural Classification Code (SCC) to classify the various types of equipment in a manufacturing system as well as their layout. The code represents equipment, such as machines, buffers and transporters, as well as their layout as shown in Figure 4. 2. The equipment Classification code (ECC) consists of three fields: (1) machines, (2) buffers, and (3) transporters. Fields representing their type and general structure, controls, programming, and operation are included in the code.

Each field contains a string of digits; the value of each digit depends on the degree of complexity of the structure, control, programming and operation of these entities. The generated code string is similar to a biological DNA identifier for the system characteristics (H. ElMaraghy, 2005). The potential implications and applications of this novel code for manufacturing systems parallel those of Group Technology codes for products and cellular manufacturing. Kuzgunkaya and H. ElMaraghy (2006) illustrated the use of this classification code in assessing the structural complexity of manufacturing system configurations as one of the candidate code applications.

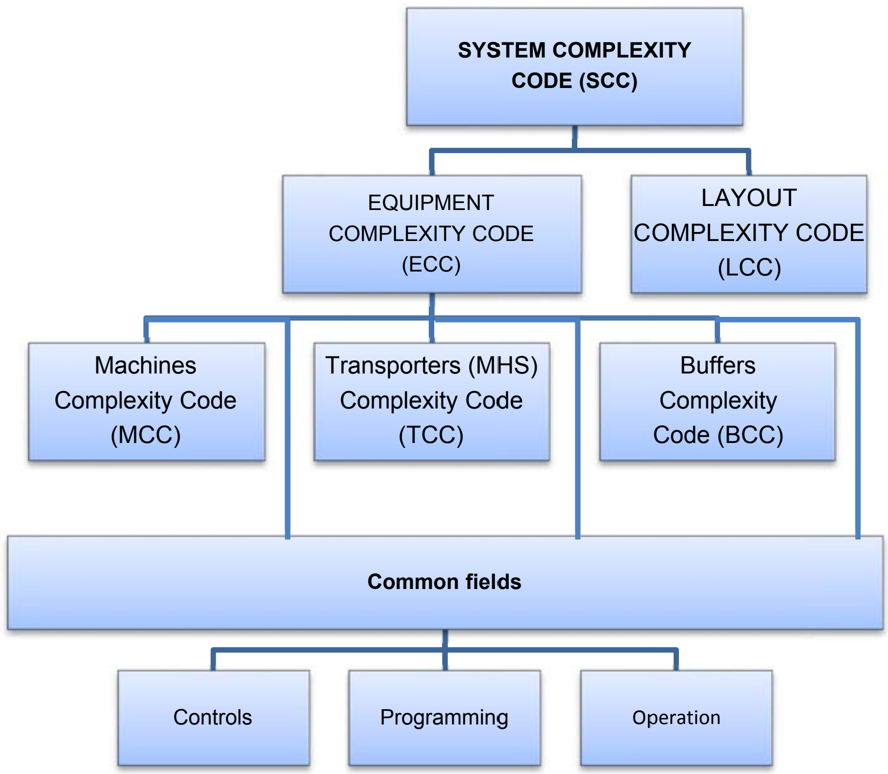



Figure 4. 2 Manufacturing systems characteristics and components (adapted from H. ElMaraghy, 2006)

## 4.2 Assembly Systems Classification Code

The original equipment structural classification code by H. ElMaraghy (2006) is extended to include the assembly-specific structural features of various pieces of equipment. Some code digits have been re-grouped and extended. The layout classification system remains unchanged. The Equipment Classification code (ECC) consists of three fields: (1) machines, (2) handling equipment, and (3) buffers. Each field has digits representing their type and general structure. The controls, programming, and operation fields are common for all equipment. A resulting digits code string is generated for each field to represent the inherent system complicatedness as shown in Figure 4. 3. The coding scheme is a chain-type structure which allows future extension of the code. It consists of 7 digits for describing machine type, 7 digits for describing handling equipment, and 4 digits for describing buffers. An additional 9 digits are common for all equipment. Thus, the maximum number of the equipment digits is 16 digits.

<table>
<tr><th colspan="7">Field #1</th><th colspan="4">Field #2</th><th colspan="2">Field #3</th><th colspan="3">Field #4</th></tr>
<tr><td colspan="7">Machine Type CC</td><td colspan="4">Controls CC</td><td colspan="2">Programming CC</td><td colspan="3">Operation CC</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td></tr>
</table>

(a)

<table>
<tr><th colspan="7">Field #1</th><th colspan="4">Field #2</th><th colspan="2">Field #3</th><th colspan="3">Field #4</th></tr>
<tr><td colspan="7">Handling Equipment CC</td><td colspan="4">Controls CC</td><td colspan="2">Programming CC</td><td colspan="3">Operation CC</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td></tr>
</table>

(b)

<table>
<tr><th colspan="4">Field #1</th><th colspan="4">Field #2</th><th colspan="2">Field #3</th><th colspan="3">Field #4</th></tr>
<tr><td colspan="4">Buffer Equipment CC</td><td colspan="4">Controls CC</td><td colspan="2">Programming CC</td><td colspan="3">Operation CC</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td></tr>
</table>

(c)

Figure 4. 3 Equipment code string: (a) Machine, (b) Handling Equipment (c) Buffers (adapted from H. ElMaraghy *et al.*, 2010)

The various digits are described in Tables 4.1- 4.3 and annotated in Tables D.1 – D.6 of Appendix (D). The bolded digits refer to new digits while the underlined digits refer to modified digits. Each digit position in each field represents a specific characteristic.

Table 4. 1 Machine classification code

| # | Machine CC | Description | Value | Maximum value | Normalized value |
|---|---|---|---|---|---|
| 1 | Structure | Fixed | 1 | 3 | 1/3 |
| | | Modular | 2 | | 2/3 |
| | | Changeable | 3 | | 3/3 |
| 2 | Axes of motion | N | N | 6 | N/6 |
| 3 | Work heads | N | N | 2* | N/2 |
| 4 | Spindles | N | N | 2** | N/2 |
| 5 | Tools | Fixed | 1 | 2 | 1/2 |
| | | **Changeable** | **2** | | 2/2 |
| 6 | Tool magazine | None | 1 | 3 | 1/3 |
| | | Fixed | 2 | | 2/3 |
| | | Changeable | 3 | | 3/3 |
| 7 | Pin fixtures | Fixed | 1 | 2 | 1/2 |
| | | Moving | 2 | | 2/2 |
| **#** | **Controls CC** | **Description** | **Value** | **Maximum value** | **Normalized value** |
| 8 | **Mode** | Manual | 1 | 2 | 1/2 |
| | | **Programmable** | 2 | | 2/2 |
| 9 | **Type** | **Non-adaptive** | 1 | 2 | 1/2 |
| | | **Adaptive** | 2 | | 2/2 |
| 10 | Access | Open | 1 | 3 | 1/3 |
| | | Limited | 2 | | 2/3 |
| | | Closed | 3 | | 3/3 |
| 11 | **Structure** | **Fixed** | 1 | 3 | 1/3 |
| | | **Modular** | 2 | | 2/3 |
| | | **Reconfigurable** | 3 | | 3/3 |
| **#** | **Programming CC** | **Description** | **Value** | **Maximum value** | **Normalized value** |
| 12 | Mode | Manual | 1 | 2 | 1/2 |
| | | Programmable | 2 | | 2/2 |
| 13 | Difficulty | Low | 1 | 3 | 1/3 |
| | | Medium | 2 | | 2/3 |
| | | High | 3 | | 3/3 |
| **#** | **Operation CC** | **Description** | **Value** | **Maximum value** | **Normalized value** |
| 14 | Mode | Manual | 1 | 3 | 1/3 |
| | | Semi-automated | 2 | | 2/3 |
| | | Fully automated | 3 | | 3/3 |
| 15 | **Power** | **Un-powered** | 1 | 2 | 1/2 |
| | | **Powered** | 2 | | 2/2 |
| 16 | **Fault detection** | **Manual** | 1 | 2 | 1/2 |
| | | **Automated** | 2 | | 2/2 |

* The maximum number of N is assumed as 2 workheads
** The maximum number of N is assumed as 2 spindles

Table 4. 2 Handling equipment classification code

| # | MHS CC | Description | Value | Maximum value | Normalized value |
|---|---|---|---|---|---|
| 1 | Type | Conveyor | 1 | 7 | 1/7 |
| | | Monorail | 2 | | 2/7 |
| | | Forklift trucks | 3 | | 3/7 |
| | | AGV | 4 | | 4/7 |
| | | Cranes and Gantries | 5 | | 5/7 |
| | | Robot | 6 | | 6/7 |
| | | **Feeder** | **7** | | 7/7 |
| 2 | **Structure** | **Fixed** | **1** | 2 | 1/2 |
| | | **Reconfigurable** | **2** | | 2/2 |
| 3 | **Motion** | **Uni-directional, synchronized** | **1** | 4 | 1/4 |
| | | **Uni-directional, asynchronized** | **2** | | 2/4 |
| | | **Bi-directional, synchronized** | **3** | | 3/4 |
| | | **Bi-directional, asynchronized** | **4** | | 4/4 |
| 4 | **Path** | **Fixed** | **1** | 2 | 1/2 |
| | | **Variable** | **2** | | 2/2 |
| 5 | **Parts holders** | **None** | **1** | 4 | 1/4 |
| | | **Pallet** | **2** | | 2/4 |
| | | **Fixture** | **3** | | 3/4 |
| | | **Gripper** | **4** | | 3/4 |
| 6 | **Part types** | **Single** | **1** | 2 | 1/2 |
| | | **Multiple** | **2** | | 2/2 |
| 7 | **Parts orientation** | **Passive** | 1 | 2 | 1/2 |
| | | **Active** | 2 | | 1/3 |
| **#** | **Controls CC** | **Description** | **Value** | **Maximum value** | **Normalized value** |
| 8 | **Mode** | Manual | 1 | 2 | 1/2 |
| | | **Programmable** | 2 | | 2/2 |
| 9 | **Type** | **Non-adaptive** | 1 | 2 | 1/2 |
| | | **Adaptive** | 2 | | 2/2 |
| 10 | Access | Open | 1 | 3 | 1/3 |
| | | Limited | 2 | | 2/3 |
| | | Closed | 3 | | 3/3 |
| 11 | **Structure** | **Fixed** | 1 | 3 | 1/3 |
| | | **Modular** | 2 | | 2/3 |
| | | **Reconfigurable** | 3 | | 3/3 |
| **#** | **Programming CC** | **Description** | **Value** | **Maximum value** | **Normalized value** |
| 12 | Mode | Manual | 1 | 2 | 1/2 |
| | | Programmable | 2 | | 2/2 |

Table 4.2 Handling equipment classification code (cont.)

| | | | | | |
|---|---|---|---|---|---|
| 13 | Difficulty | Low | 1 | 3 | 1/3 |
| | | Medium | 2 | | 2/3 |
| | | High | 3 | | 3/3 |
| **#** | **Operation CC** | **Description** | **Value** | **Maximum value** | **Normalized value** |
| 14 | Mode | Manual | 1 | 3 | 1/3 |
| | | Semi-automated | 2 | | 2/3 |
| | | Fully automated | 3 | | 3/3 |
| 15 | **Power** | **Un-powered** | 1 | 2 | 1/2 |
| | | **Powered** | 2 | | 2/2 |
| 16 | **Fault detection** | **Manual** | 1 | 2 | 1/2 |
| | | **Automated** | 2 | | 2/2 |

Table 4. 3 Buffer classification code

| # | Buffers CC | Description | Value | Maximum value | Normalized value |
|---|---|---|---|---|---|
| 1 | Type | Magazines | 1 | 4 | 1/4 |
| | | Indexing tables | 2 | | 2/4 |
| | | Carousels | 3 | | 3/4 |
| | | AS/RS | 4 | | 4/4 |
| 2 | **Part types** | **Single** | 1 | 2 | 1/2 |
| | | **Multiple** | 2 | | 2/2 |
| 3 | Access | FIFO | 1 | 3 | 1/3 |
| | | LIFO | 2 | | 2/3 |
| | | Random access | 3 | | 3/3 |
| 4 | **Location** | **With machine** | 1 | 3 | 1/3 |
| | | **Separate** | 2 | | 2/3 |
| | | **Central** | 3 | | 3/3 |
| **#** | **Controls CC** | **Description** | **Value** | **Maximum value** | **Normalized value** |
| 5 | **Mode** | Manual | 1 | 2 | 1/2 |
| | | **Programmable** | 2 | | 2/2 |
| 6 | **Type** | **Non-adaptive** | 1 | 2 | 1/2 |
| | | **Adaptive** | 2 | | 2/2 |
| 7 | Access | Open | 1 | 3 | 1/3 |
| | | Limited | 2 | | 2/3 |
| | | Closed | 3 | | 3/3 |
| 8 | **Structure** | **Fixed** | 1 | 3 | 1/3 |
| | | **Modular** | 2 | | 2/3 |
| | | **Reconfigurable** | 3 | | 3/3 |
| **#** | **Programming CC** | **Description** | **Value** | **Maximum value** | **Normalized value** |
| 9 | Mode | Manual | 1 | 2 | 1/2 |
| | | Programmable | 2 | | 2/2 |

Table 4.3 Buffer classification code (cont.)

| | | | | | |
|---|---|---|---|---|---|
| 10 | Difficulty | Low | 1 | 3 | 1/3 |
| | | Medium | 2 | | 2/3 |
| | | High | 3 | | 3/3 |
| **#** | **Operation CC** | **Description** | **Value** | **Maximum value** | **Normalized value** |
| 11 | Mode | Manual | 1 | 3 | 1/3 |
| | | Semi-automated | 2 | | 2/3 |
| | | Fully automated | 3 | | 3/3 |
| 12 | **Power** | **Un-powered** | 1 | 2 | 1/2 |
| | | **Powered** | 2 | | 2/2 |
| 13 | **Fault detection** | **Manual** | 1 | 2 | 1/2 |
| | | **Automated** | 2 | | 2/2 |

### 4.2.1 Illustrative example

The use of the classification code is illustrated using the examples of equipment typically used in assembly systems. Each piece of equipment is analyzed and the detailed code representation of an assembly machine, a material handling equipment, and a buffer equipment is shown in Table 4.4, Table 4.5 and Table 4.6 respectively.

Table 4. 4 Assembly machine code representation

| **Characteristics** | **Control** | **Robotic Work Cell** |
|---|---|---|
| 1. Structure: Fixed<br>2. N Axes of motion: 6<br>3. N Work heads: 1<br>4. N Spindles: 1<br>5. Tools: Changeable<br>6. Tool magazine: Fixed<br>7. Pin fixtures: Fixed | 8. Mode: Programmable<br>9. Type: Adaptive<br>10. Access: Open<br>11. Structure: Fixed |  |
| **Programming**<br>12. Mode: Programmable<br>13. Difficulty: High | **Operation**<br>14. Mode: Fully-automated<br>15. Power: Powered<br>16. Fault detection: Auto. | |

**CODE STRING**

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 6 | 1 | 1 | 2 | 2 | 1 | 2 | 2 | 1 | 1 | 2 | 3 | 3 | 2 | 2 |

Table 4. 5 Handling equipment code representation

<table>
<tr><td colspan="5">Characteristics<br>1. Type: Feeder<br>2. Structure: Fixed<br>3. Motion: Uni-dir, Synch.<br>4. Path: Fixed<br>5. Parts Holders: None<br>6. Part Types: Single<br>7. Parts Orientation: Active</td><td colspan="6">Control<br>8. Mode: Programmable<br>9. Type: Adaptive<br>10. Access: Open<br>11. Structure: Fixed</td><td colspan="5" rowspan="2">Bowl Feeder<br></td></tr>
<tr><td colspan="5">Programming<br>12. Mode: Programmable<br>13. Difficulty: High</td><td colspan="6">Operation<br>14. Mode: Fully-automated<br>15. Power: Powered<br>16. Fault detection: Auto.</td></tr>
<tr><td colspan="16">CODE STRING</td></tr>
<tr><td>7</td><td>1</td><td>2</td><td>1</td><td>1</td><td>1</td><td>2</td><td>2</td><td>2</td><td>1</td><td>1</td><td>2</td><td>3</td><td>3</td><td>2</td><td>2</td></tr>
</table>

Table 4. 6 Buffer equipment code representation

<table>
<tr><td colspan="4">Characteristics<br>1. Type: AS/RS<br>2. Part Types: Multiple<br>3. Access: Random<br>4. Location: Central</td><td colspan="5">Control<br>5. Mode: Programmable<br>6. Type: Open Loop<br>7. Access: Closed<br>8. Structure: Modular</td><td colspan="4" rowspan="2">AS/RS<br></td></tr>
<tr><td colspan="4">Programming<br>9. Mode: Programmable<br>10. Difficulty: Medium</td><td colspan="5">Operation<br>11. Mode: automated<br>12. Power: Powered<br>13. Fault detection: Auto.</td></tr>
<tr><td colspan="13">CODE STRING</td></tr>
<tr><td>4</td><td>2</td><td>3</td><td>3</td><td>2</td><td>1</td><td>3</td><td>2</td><td>2</td><td>2</td><td>3</td><td>2</td><td>2</td></tr>
</table>

In addition to grouping, standardizing and information retrieval, the classification code has other applications such as measuring system complexity as explained in the following sections.

## 4.3 System Complexity Model

### 4.3.1 Complexity Index for Assembly System Modules

The presented code is indicative of the inherent structural equipment, programming, operation and control complexity. However, an index is proposed for each class to incorporate more factors than those included in the SCC code. *First*, the SCC code string of digits for each piece of equipment in the assembly system is reduced to a single number. The conversion of the various code digits into a single number indicates the information content of an equipment can be done by many methods such as the arithmetic mean, median. Such methods are easy to apply but they are greatly affected by the data outliers. A more robust method is to represent the code digits values graphically on a radar plot as follows, taking into consideration the fixed positions of the code digits due to the design of the code structure.

The various code digits, normalized by the corresponding maximum value of each digit, are plotted in a radar plot, for each piece of equipment in each of the three equipment classes, as shown in Figure 4. 4.

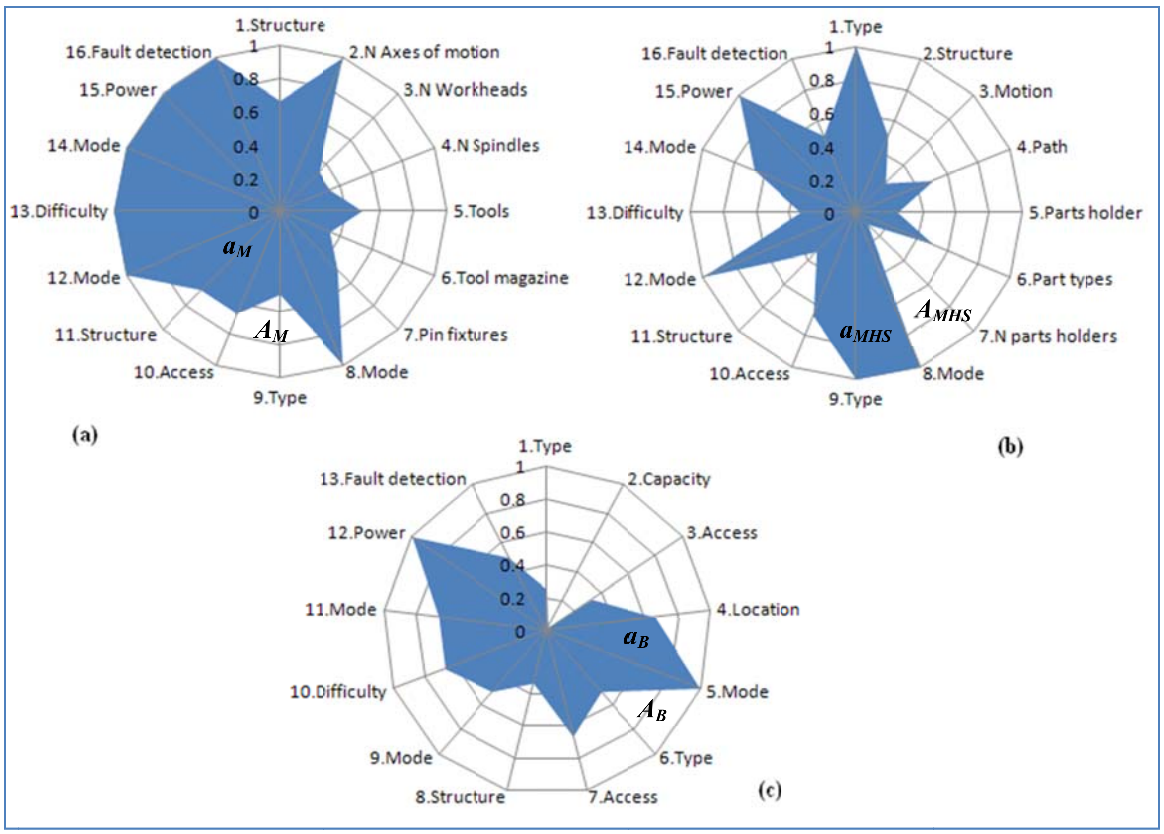



Figure 4. 4 Radar plot SCC Code representation (a) Machine, (b) MHS, (c) Buffer (S.N. Samy and H. ElMaraghy, 2010b)

A complexity index is defined as the ratio between shaded area and the total plot area. Larger shaded area refers to higher complexity index. The shaded area of each radar plot is the summation of individual triangles as:

$$a_M \quad = \frac{1}{2}\left[(C_1 * C_{16}) + \sum_{i=1}^{i=15}(C_i * C_{i+1})\right] sin\left(\frac{360}{16}\right)$$

$$a_{MHS} = \frac{1}{2}\left[(C_1 * C_{16}) + \sum_{i=1}^{i=15}(C_i.* C_{i+1})\right] sin\left(\frac{360}{16}\right)$$

$$a_B \quad = \frac{1}{2}\left[(C_1 * C_{13}) + \sum_{i=1}^{i=12}(C_i * C_{i+1})\right] sin\left(\frac{360}{13}\right)$$

(4. 1)

where $a_M$, $a_{MHS}$ , $a_B$ are the shaded radar plot areas of machine, material handling, and buffer equipment respectively. $C_i$ is the normalized code value on the radial axis of digit *i* for each radar plot, e.g., in Figure 4. 4(a) for $i = 2$, $C_2 = 1$.

The total radar plot area are given by:

$$A_M \quad = (16/2)sin(360/16)$$

$$A_{MHS} = (16/2)sin(360/16)$$

$$A_B \quad = (13/2)sin(360/13)$$

(4. 2)

where $A_M$, $A_{MHS}$, $A_B$ are the total radar plot areas for machine, material handling, buffer equipment respectively.

Then, the complexity index, *I*, for each class is calculated by dividing both shaded and radar plot areas. For example, for an assembly machine represented by a 16 digit code string:

$$I_M = \frac{a_M}{A_M} = \frac{1}{16}\left[(C_1 * C_{16}) + \sum_{i=1}^{i=15}(C_i * C_{i+1})\right]$$

(4. 3)

Similarly, for material handling and buffer devices represented by a 16 and 13 digit code strings respectively:

$$I_{MHS} = \frac{a_{MHS}}{A_{MHS}} = \frac{1}{16}\left[(C_1 * C_{16}) + \sum_{i=1}^{i=15}(C_i * C_{i+1})\right]$$

$$I_B = \frac{a_B}{A_B} = \frac{1}{13}\left[(C_1 * C_{13}) + \sum_{i=1}^{i=12}(C_i * C_{i+1})\right]$$

(4. 4)

The calculated individual Complexity Index, $I$, represents the information content defined by its type, controls, programming, and operation fields and it is calculated for each piece of equipment within the assembly system.

4.3.1.1 Illustrative example

Figure 4. 5 shows a machine typically used in assembly systems. The machine is used to assemble the washer and screw together automatically. The Machine is equipped with safety movement and detective sensors, to protect the operator and machine from damage. The feeding and assembling points are equipped with sensors. The machine stops automatically if it runs out of the parts. This example illustrates the use of the code to calculate the machine complexity index $I_M$. The code digit values for this machine are shown in Table 4. 7. Digits values normalized by their maximum possible values are then plotted as shown in Figure 4. 6. The radar plot shaded and maximum areas are then calculated as 1.228 and 3.061 respectively.

The Complexity Index of this machine, $I_M = \frac{a_M}{A_M} = \frac{1.228}{3.061} = 0.401$. The calculated index represents the information content defined by the type, controls, programming, and operation fields. This index will be used together with the diversity and amount of information to obtain a metric for the whole assembly system complexity as described in next sections.

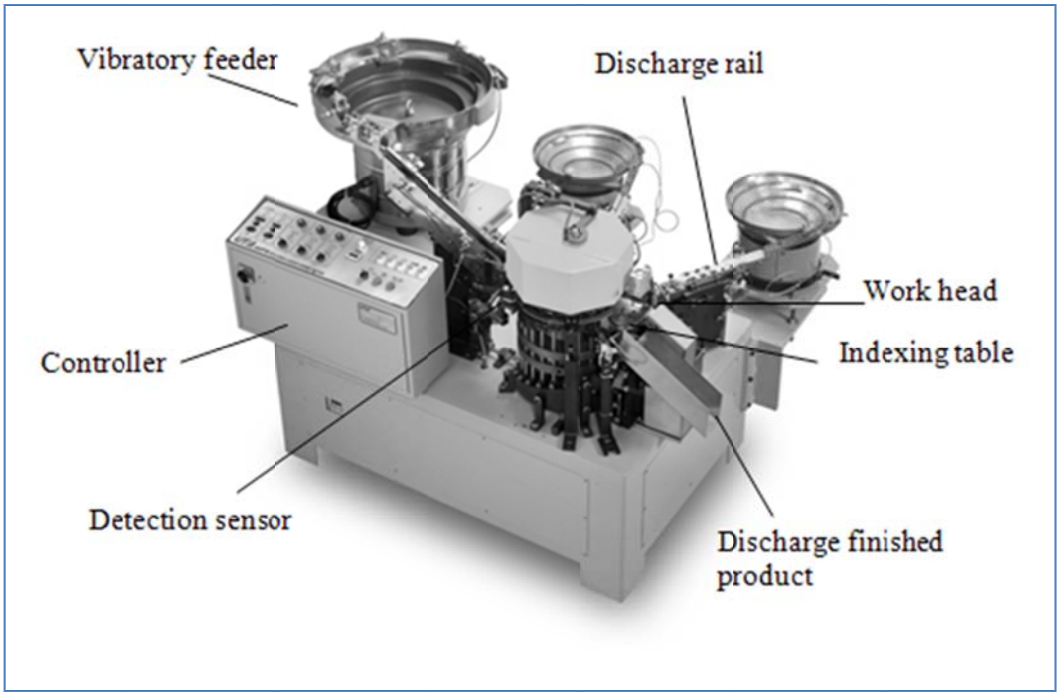



Figure 4. 5 M-type Washer assembly machine

Table 4. 7 Classification Coding for the M-type Washer assembly machine

| Machine CC | Description | Digit value | Maximum value | Normalized value |
|---|---|---|---|---|
| Structure | Modular | 2 | 3 | 0.667 |
| N Axes of motion | N | 1 | 6 | 0.167 |
| N Workheads | N | 1 | 2 | 0.500 |
| N Spindles | N | 1 | 2 | 0.500 |
| Tools | Fixed | 1 | 2 | 0.500 |
| Tool magazine | None | 1 | 3 | 0.333 |
| Pin fixtures | Fixed | 1 | 2 | 0.500 |
| **Controls CC** | **Description** | **Digit value** | **Maximum value** | **Normalized value** |
| Mode | Programmable | 2 | 2 | 1.000 |
| Type | Open loop | 1 | 2 | 0.500 |
| Access | Limited | 2 | 3 | 0.667 |
| Structure | Fixed | 1 | 3 | 0.333 |
| **Programming CC** | **Description** | **Digit value** | **Maximum value** | **Normalized value** |
| Mode | Manual | 1 | 2 | 0.500 |
| Difficulty | Low | 2 | 3 | 0.667 |
| **Operation CC** | **Description** | **Digit value** | **Maximum value** | **Normalized value** |
| Mode | Fully-auto. | 3 | 3 | 1.000 |
| Power | Powered | 2 | 2 | 1.000 |
| Fault detection | Automated | 2 | 2 | 1.000 |

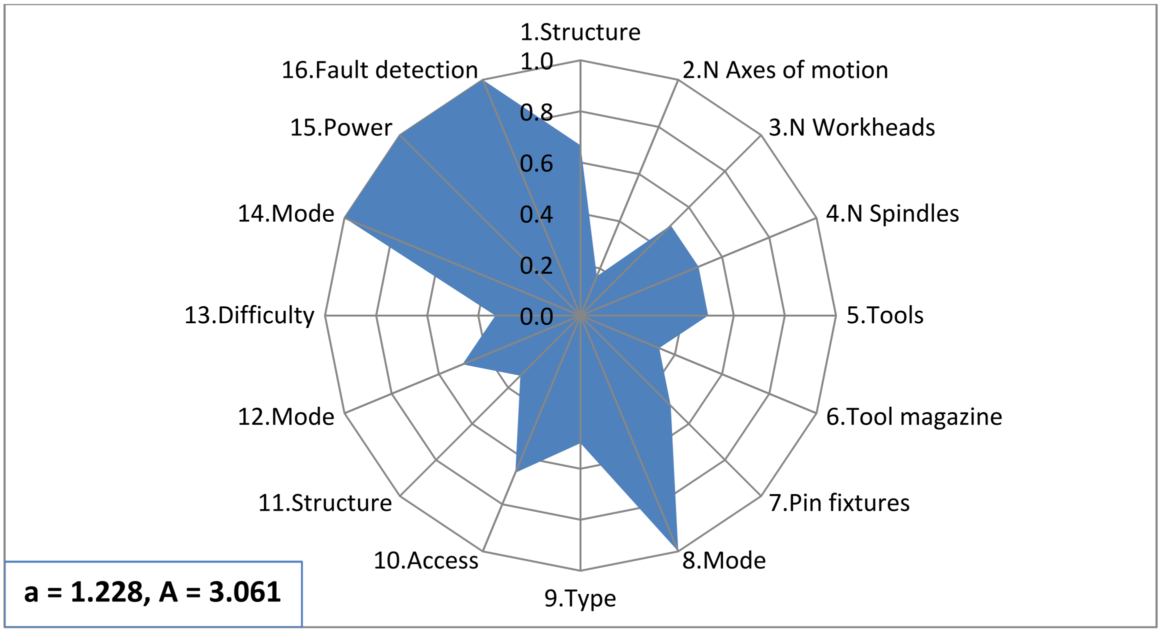



Figure 4. 6 Radar plot of M-type Washer assembly machine

### 4.3.2 Assembly System Complexity Metric

Individual pieces of equipment, in all three classes, are analyzed to generate the corresponding SCC codes and a complexity index for each is calculated. The resulting indices are then used to calculate the complexity of each assembly equipment class. The resulting complexity values of the assembly equipment classes are then used to calculate total system complexity.

In addition to the information content defined in the previous section and represented by the three complexity indices “$I_M, I_{MHS}, I_B$”, the diversity of information and amount of information are considered to calculate equipment complexity by adapting the complexity model proposed by W. ElMaraghy and Urbanic (2003).

#### 4.3.2.1 Assembly machine complexity metric

The assembly machine complexity is represented by:

$$C_M = \left(\frac{n_M}{N_M} + \bar{I}_M\right)[log_2(N_M + 1)]$$

(4. 5)

where $C_M$ is the machine complexity, $N_M$ is the total number of assembly machines, $n_M$ is the number of unique assembly machines (an indicator of diversity within a class of equipment), and $\bar{I}_M$ is the average complexity index of the $N_M$ assembly machines.

#### 4.3.2.2 Material handling complexity metric

Similarly, the material handling equipment complexity is represented by:

$$C_{MHS} = \left(\frac{n_{MHS}}{N_{MHS}} + \bar{I}_{MHS}\right)[log_2(N_{MHS} + 1)]$$

(4. 6)

where $C_{MHS}$ is the material handling complexity, $N_{MHS}$ is the total number of material handling equipment, $n_{MHS}$ is the number of unique material handling equipment, and $\bar{I}_{MHS}$ is the average complexity index of the $N_{MHS}$ material handling equipment.

#### 4.3.2.3 Buffer complexity metric

Similarly, the buffer equipment complexity is represented by:

$$C_B = \left(\frac{n_B}{N_B} + \bar{I}_B\right)[log_2(N_B + 1)]$$

(4. 7)

where $C_B$ is the buffer equipment complexity, $N_B$ is the total number of buffer equipment, $n_B$ is the number of unique buffer equipment, and $\bar{I}_B$ is the average complexity index of the $N_B$ buffer equipment.

The first terms of the right hand side of Equations (4. 5), (4. 6), and (4. 7): $\left(\frac{n_M}{N_M}\right)$, $\left(\frac{n_{MHS}}{N_{MHS}}\right)$, and $\left(\frac{n_B}{N_B}\right)$ account for the diversity of information of machines, handling equipment, and buffers respectively. The second terms: $(\bar{I}_M)$, $(\bar{I}_{MHS})$, and $(\bar{I}_B)$ represent the information content of machines, handling equipment, and buffers respectively. The terms: $[log_2(N_M + 1)]$, $[log_2(N_{MHS} + 1)]$, and $[log_2(N_B + 1)]$

represent the quantity of information of machines, handling equipment, and buffers respectively. The proposed metric for assembly systems complexity is different from the one developed by W. ElMaraghy and Urbanic (2003) in the method of calculating the information content index, and the aggregation of individual system component complexity indices to obtain an overall measure of assembly system complexity.

#### 4.3.2.4 Total system complexity

After calculating the complexities of the assembly machines, material handling systems, and buffers equipment, the assembly system complexity is represented by:

$$C_{system} = w_1 C_M + w_2 C_{MHS} + w_3 C_B \tag{4. 8}$$

where $C_{system}$ is the assembly system complexity, $C_M$, $C_{MHS}$, $C_B$ are machine, material handling equipment, and buffer equipment complexities respectively. The $w_1$, $w_2$, $w_3$ are weights representing the relative importance of the complexity of the three classes. These weights would be determined based on the users experience and desire to emphasize certain components of the system. They are set at 1 in the remainder of this work as an indication of equal importance of all three classes of equipment in the system.

**The methodology to calculate the assembly system complexity is described below:**

1. Decompose the system equipment into three classes: machines, handling equipment, and buffers equipment.
2. Specify the characteristics of each piece of equipment in each class as described in Tables 4.1 - 4.3.
3. Generate the code string of each piece of equipment.
4. Calculate the complexity index of each piece of equipment as defined by Equation (4.3), i.e. $I_M$, $I_{MHS}$, $I_{B.}$
5. Calculate the average complexity index of the three classes of equipment, i.e. $\bar{I}_M, \bar{I}_{MHS}, \bar{I}_B$.

6. Count the total number of equipment within each class, i.e. $N_M$, $N_{MHS}$, $N_{B.}$
7. Count the unique number of equipment within each class, i.e. $n_M$, $n_{MHS}$, $n_{B..}$
8. Calculate the complexity of each class of equipment as defined by Equations 4.5 – 4.7, i.e. $C_M$, $C_{MHS}$, $C_{B.}$ respectively.
9. Define the relative importance of each class , i.e. $w_1$, $w_2$, $w_3$
10. Calculate the assembly system complexity as defined by Equation (4.8).

## 4.4 Case Study: Assembly of Domestic Appliance Drive

This case study demonstrates the use of the proposed approach to determine the complexity of assembly systems. Figure 4. 7 shows the layout of the actual assembly equipment used for assembling the domestic appliance drive shown in Figure 4.8.

A SCARA robot is placed in the centre of the assembly equipment for the completion of the automatic operations. Gripping points G1 to G9 are positioned within the working range of the robot. The cylindrical pins and spring nuts are passively oriented by small vibratory bowl feeders and delivered to the gripping points via discharge rails. A large bowl feeder with active orientation devices is used for the gearwheels. The bearing ring and thrust washer are drawn from chute magazines and then also fed to the gripping points. The drive shaft, drive, stepped shaft and fan wheel are placed manually on feed rails or double-belt systems and transported to the gripping points. A circular table with 18 work piece carriers is positioned upstream of the assembly robot. The arrangement makes 18 similar operations possible so that the gripper change times are distributed over 18 similar operations. The operator has the task of removing the housing manually from a compartmentalized crate and placing it in the assembly fixture. The different gripper systems required are placed in the immediate vicinity of the gripping point in order to achieve the shortest possible distances between gripper change actions and gripping (B. Lotter, 1989).

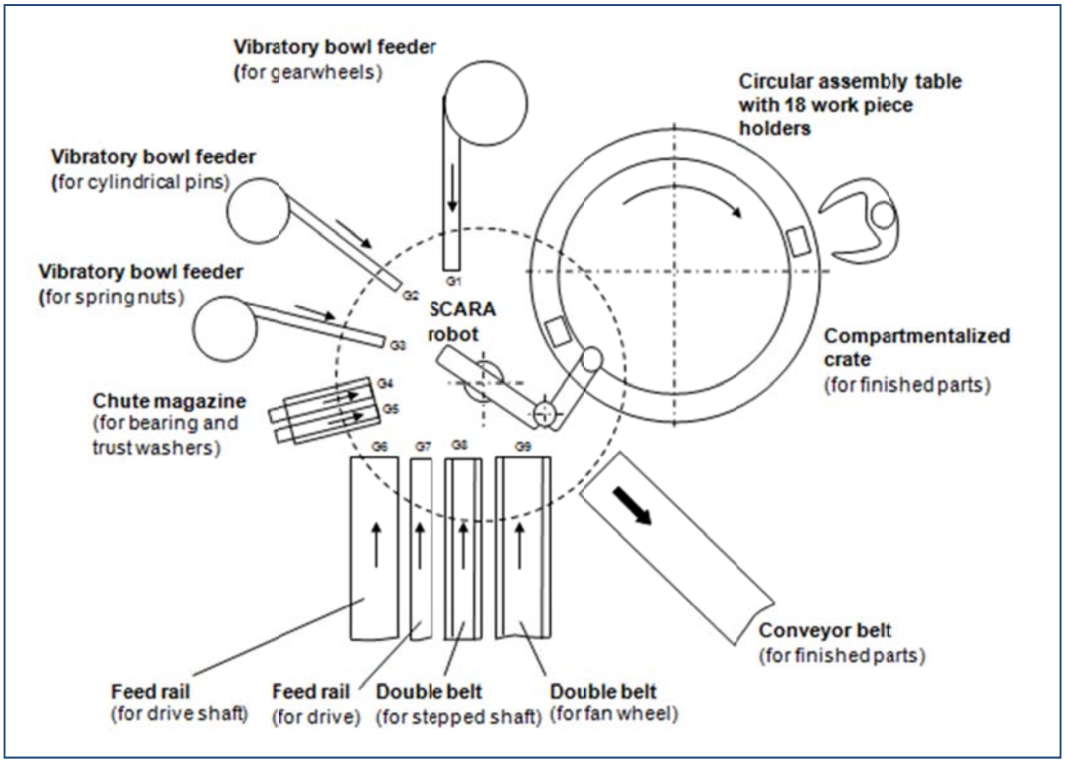



Figure 4. 7 Domestic appliance drives assembly system (G1…G9 are gripping points) (adapted from B. Lotter, 1989)

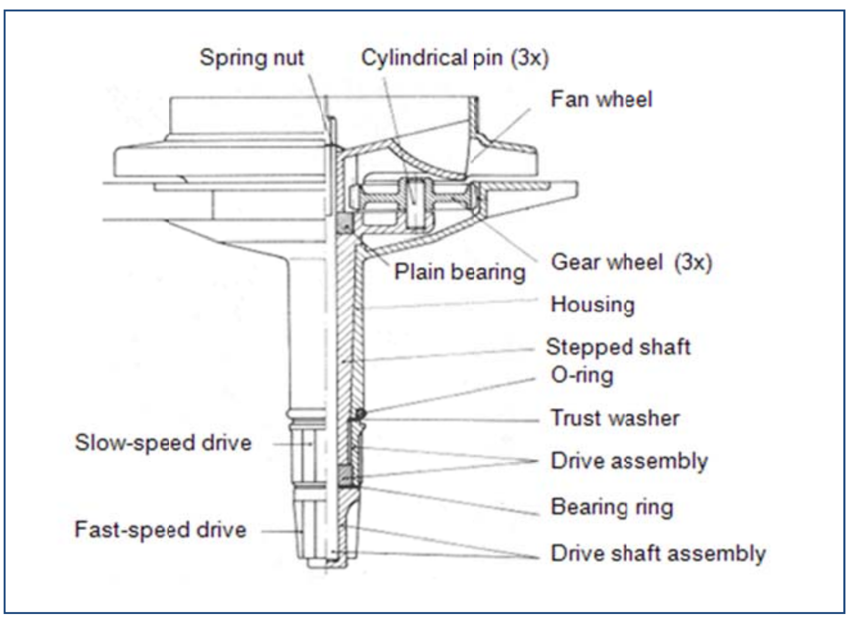



Figure 4.8 Domestic appliance drive (adapted from B. Lotter, 1989)

**The following assembly operations sequence is used for this drive assembly:**

- Place pre-assembled drive shaft unit in the assembly fixture by SCARA robot.
- Fit bearing ring over the drive shaft by SCARA robot.
- Fit drive assembly over the drive shaft using SCARA robot.
- Place thrust washer on drive by SCARA robot.
- Place pre-assembled housing manually over the drive shaft in the assembly fixture.
- Place stepped shaft, pre-assembled with plain bearings, over the drive shaft and fit in the housing by the SCARA robot.
- Fit three cylindrical pins into stepped shaft by SCARA robot.
- Fit three gear wheels onto cylindrical pins and, at the same time, engage the gearwheel teeth in the housing teeth by SCARA robot.
- Fit fan wheel to drive shaft by SCARA robot.
- Fit spring nut over drive shaft by SCARA robot.
- Remove fully assembled units from assembly fixture and place to one side manually.

**Description of equipment in the hybrid manual/automated assembly cell**

- A SCARA robot is placed in the centre of the cell. Robot Gripping points G1 to G9 are positioned within the working area of the robot. The robot is used for both material handling and assembly.
- The gearwheels, cylindrical pins and spring nuts are oriented by three vibratory bowl feeders and fed to the gripping points via discharge rails.
- The bearing ring and thrust washer are picked from chute magazines and then placed by the robot at gripping points G4 and G5.
- The drive shaft, drive, stepped shaft and fan wheel are placed and arranged manually on feed rails or double-belt conveyors and transported to the gripping points G6, G7, G8, and G9 respectively.

- A circular table with 18 work piece holders is positioned upstream of the SCARA robot. This arrangement makes 18 successive similar assembly operations possible to minimize the gripper change time.
- The worker is in charge of placing the housing in the assembly fixture and observing the automatic feeding equipment and assembly operations and, if necessary, fix any faults or malfunction.
- The different grippers required are placed in the immediate vicinity of the gripping points in order to minimize the robot travel distances between positions of gripper change and gripping.

All equipment in the assembly system are analyzed and the classification code is generated for each piece of equipment. The various digit values and description of each field of the system equipment are listed in Table 4.8 – Table 4.13. The two feed rails used for feeding the drive and the drive shaft are assumed to have same characteristics hence they are having same complexity index. The two double belt feeders are similar to the two feed rails except that they do not have parts holders (digit#5) and they are having active orientation devices (digit#5). Their complexity index is calculated as $I_{MHS} = 0.396$. The conveyor belt is similar to the feed rails except it has pallets to hold parts (digit#5). It's complexity index is calculated as $I_{MHS} = 0.365$.

Two of the three vibratory bowl feeders are similar (N = 3, n = 2), the two feed rails are similar (N = 2, n = 1), the two double belts are similar (N = 2, n = 1), plus one conveyor belt (N = 1, n=1). Therefore, the total number of the MHS equipment is N = 3 + 2 + 2 + 1 = 8. The unique number of the MHS equipment is n = 2 + 1 + 1 + 1 = 5.

Equation (4. 5), Equation (4. 6) and Equation (4. 7) are then used to calculate machine, material handling, and buffer equipment respectively. The calculated values and the number of pieces of equipment are listed in Table 4.14.

Considering the amount and diversity of information and assuming that all three equipment classes contribute equally to total system complexity (i.e. $w_1 = w_2 = w_3 =$

1), then the complexity of the domestic appliance drive assembly cell/system can be calculated using Equation (4. 8) as:

$$C_{system} = 1.536 + 3.255 + 2.069 = 6.860$$

Table 4. 8 Chute magazine (Buffer Equipment)

| # | Buffer CC | Description | Digit value | Maximum Value | Normalized value |
|---|---|---|---|---|---|
| 1 | Type | Magazine | 1 | 4 | 0.250 |
| 2 | Part types | Single | 1 | 2 | 0.500 |
| 3 | Access | FIFO | 1 | 3 | 0.333 |
| 4 | Location | Separate | 2 | 3 | 0.667 |
| 5 | Mode | Manual | 1 | 2 | 0.500 |
| 6 | Type | Non-adaptive | 1 | 2 | 0.500 |
| 7 | Access | Open | 1 | 3 | 0.333 |
| 8 | Structure | Fixed | 1 | 3 | 0.333 |
| 9 | Mode | Manual | 1 | 2 | 0.500 |
| 10 | Difficulty | Low | 1 | 3 | 0.333 |
| 11 | Mode | Semi- | 2 | 3 | 0.667 |
| 12 | Power | Powered | 2 | 2 | 1.000 |
| 13 | Fault detection | Manual | 1 | 2 | 0.500 |
| **$I_B$ = 0.248** | | | | | |

Table 4. 9 SCARA robot (Machine Equipment)

| # | Machine CC | Description | Digit value | Digit value | Normalized value |
|---|---|---|---|---|---|
| 1 | Structure | Fixed* | 1 | 3 | 0.333 |
| 2 | N Axes of motion | N | 4** | 6 | 0.667 |
| 3 | N Workheads | N | 1 | 2 | 0.500 |
| 4 | N Spindles | N | 1 | 2 | 0.500 |
| 5 | Tools (Gripper) | Changeable | 2 | 2 | 1.000 |
| 6 | Tool magazine | None | 1 | 3 | 0.333 |
| 7 | Pin fixtures | Fixed | 1 | 2 | 0.500 |
| 8 | Mode | Programmable | 2 | 2 | 1.000 |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 |
| 10 | Access | Limited | 2 | 3 | 0.667 |
| 11 | Structure | Modular | 2 | 3 | 0.667 |
| 12 | Mode | Programmable | 2 | 2 | 1.000 |
| 13 | Difficulty | High | 3 | 3 | 1.000 |
| 14 | Mode | Fully-automated | 3 | 3 | 1.000 |
| 15 | Power | Powered | 2 | 2 | 1.000 |
| 16 | Fault detection | Auto | 2 | 2 | 1.000 |
| **$I_M$ = 0.536** | | | | | |

* SCARA robot generally has fixed structure, modular SCARA robots are also available (G. Yang, 1999)
** SCARA robot generally has 4-DOF. However, higher DOF SCARA robots are also available (U. Claudio et al., 2011)

Table 4. 10 Circular table (Buffer Equipment)

| # | Buffer CC | Description | Digit value | Maximum Value | Normalized value |
|---|---|---|---|---|---|
| 1 | Type | Indexing tables | 2 | 4 | 0.500 |
| 2 | Part types | Multiple | 2 | 2 | 1 |
| 3 | Access | FIFO | 1 | 3 | 0.333 |
| 4 | Location | Separate | 2 | 3 | 0.667 |
| 5 | Mode | Programmable | 2 | 2 | 1.000 |
| 6 | Type | Non-adaptive | 1 | 2 | 0.500 |
| 7 | Access | Limited | 2 | 3 | 0.667 |
| 8 | Structure | Fixed | 1 | 3 | 0.333 |
| 9 | Mode | Manual | 1 | 2 | 0.500 |
| 10 | Difficulty | Medium | 2 | 3 | 0.667 |
| 11 | Mode | Semi- | 2 | 3 | 0.667 |
| 12 | Power | Powered | 2 | 2 | 1.000 |
| 13 | Fault detection | Manual | 1 | 2 | 0.500 |
| **$I_B$ = 0.363** | | | | | |

Table 4. 11 Vib. bowl feeder (MHS Equipment) for cylindrical pins and spring nuts

| # | MHS CC | Description | Digit value | Maximum value | Normalized value |
|---|---|---|---|---|---|
| 1 | Type | Feeder | 7 | 7 | 1.000 |
| 2 | Structure | Fixed | 1 | 2 | 0.500 |
| 3 | Motion | Uni-dir, synch. | 1 | 4 | 0.250 |
| 4 | Path | Fixed | 1 | 2 | 0.500 |
| 5 | Parts holder | None | 1 | 4 | 0.250 |
| 6 | Part types | Single | 1 | 2 | 0.500 |
| 7 | Parts orientation | Passive | 1 | 2 | 0.500 |
| 8 | Mode | Programmable | 2 | 2 | 1.000 |
| 9 | Type | Non-Adaptive | 2 | 2 | 1.000 |
| 10 | Access | Limited | 2 | 3 | 0.667 |
| 11 | Structure | Fixed | 1 | 3 | 0.333 |
| 12 | Mode | Programmable | 2 | 2 | 1.000 |
| 13 | Difficulty | Low | 1 | 3 | 0.333 |
| 14 | Mode | Semi- | 2 | 3 | 0.667 |
| 15 | Power | Powered | 2 | 2 | 1.000 |
| 16 | Fault detection | Manual | 1 | 2 | 0.500 |
| **$I_{MHS}$ = 0.387** | | | | | |

Table 4. 12 Vib. bowl feeder (MHS Equipment) for gear wheels

| # | MHS CC | Description | Digit value | Maximum value | Normalized value |
|---|---|---|---|---|---|
| 1 | Type | Feeder | 7 | 7 | 1.000 |
| 2 | Structure | Fixed | 1 | 2 | 0.500 |
| 3 | Motion | Uni-dir, synch. | 1 | 4 | 0.250 |
| 4 | Path | Fixed | 1 | 2 | 0.500 |
| 5 | Parts holder | None | 1 | 4 | 0.250 |
| 6 | Part types | Single | 1 | 2 | 0.500 |
| 7 | Parts orientation | Active | 2 | 2 | 1.000 |
| 8 | Mode | Programmable | 2 | 2 | 1.000 |
| 9 | Type | Non-Adaptive | 2 | 2 | 1.000 |
| 10 | Access | Limited | 2 | 3 | 0.667 |
| 11 | Structure | Fixed | 1 | 3 | 0.333 |
| 12 | Mode | Programmable | 2 | 2 | 1.000 |
| 13 | Difficulty | Low | 1 | 3 | 0.333 |
| 14 | Mode | Semi- | 2 | 3 | 0.667 |
| 15 | Power | Powered | 2 | 2 | 1.000 |
| 16 | Fault detection | Manual | 1 | 2 | 0.500 |
| $I_{MHS}$ = 0.434 | | | | | |

Table 4. 13 Feed rail (MHS Equipment) for drive and drive shaft

| # | MHS CC | Description | Digit value | Maximum value | Normalized value |
|---|---|---|---|---|---|
| 1 | Type | Monorail | 2 | 7 | 0.286 |
| 2 | Structure | Fixed | 1 | 2 | 0.500 |
| 3 | Motion | Uni-dir, asynch. | 2 | 4 | 0.500 |
| 4 | Path | Fixed | 1 | 2 | 0.500 |
| 5 | Parts holder | Fixture | 3 | 4 | 0.75 |
| 6 | Part types | Single | 1 | 2 | 0.500 |
| 7 | Parts Orientation | Passive | 1 | 2 | 0.500 |
| 8 | Mode | Programmable | 2 | 2 | 1.000 |
| 9 | Type | Non-Adaptive | 2 | 2 | 1.000 |
| 10 | Access | Open | 1 | 3 | 0.333 |
| 11 | Structure | Modular | 2 | 3 | 0.667 |
| 12 | Mode | Programmable | 2 | 2 | 1.000 |
| 13 | Difficulty | Medium | 2 | 3 | 0.667 |
| 14 | Mode | Semi- | 2 | 3 | 0.667 |
| 15 | Power | Powered | 2 | 2 | 1.000 |
| 16 | Fault detection | Manual | 1 | 2 | 0.500 |
| $I_{MHS}$ = 0.424 | | | | | |

In this specific example, some equipment of the same type and characteristics (e.g. the two vibratory feeders, the two feed rails and the two double belt feeders) have the same complexity index. Sometimes different pieces of equipment in a class can end up having the same or very similar value of complexity index, although they have different collection of characteristics and are not interchangeable.

Equipment of the same type/class, but with different characteristics, will result in different complexity code digit values, and these pieces of equipment will be considered as a unique variant within the class and hence adding to the complexity due to increased variety and information content. This will add to the total number of unique pieces of equipment. For example, if all pieces of equipment in the Table 4.13 were different (even if they were of the same type) this will result in n = 8 and the MHS complexity becomes 4.443 which is higher than the earlier values of 3.255. The following two case studies further illustrate some similar type equipment with different complexity values due to their different characteristics.

Table 4. 14 Domestic appliance drives assembly system

| Class | Equipment | $I$ | $\bar{I}$ | $n$ | $N$ | $C$ |
|---|---|---|---|---|---|---|
| **Machine** | SCARA | 0.536 | 0.536 | 1 | 1 | 1.536 |
| **MHS** | Vibratory feeder | 0.387 | 0.402 | 5 | 8 | 3.255 |
| | Vibratory feeder | 0.387 | | | | |
| | Vibratory feeder | 0.434 | | | | |
| | Feed rail | 0.424 | | | | |
| | Feed rail | 0.424 | | | | |
| | Double belt | 0.396 | | | | |
| | Double belt | 0.396 | | | | |
| | Conveyor Belt | 0.365 | | | | |
| **Buffer** | Chute magazine | 0.248 | 0.306 | 2 | 2 | 2.069 |
| | Circular table | 0.363 | | | | |
| **System complexity =** | | | | | | 6.860 |

## 4.5 Case Study: Assembly of a Three-Pin Electric Power Plug

This case study illustrates not only the use of the proposed complexity metric to measure the assembly system complexity, but also to compare assembly system alternatives in the context of complexity.

Two assembly system configurations are used for the assembly of a three–pin electric power plug (Figure 4.9) are analyzed. The first and the second system structures are shown in Figure 4. 10 and Figure 4.11 respectively.

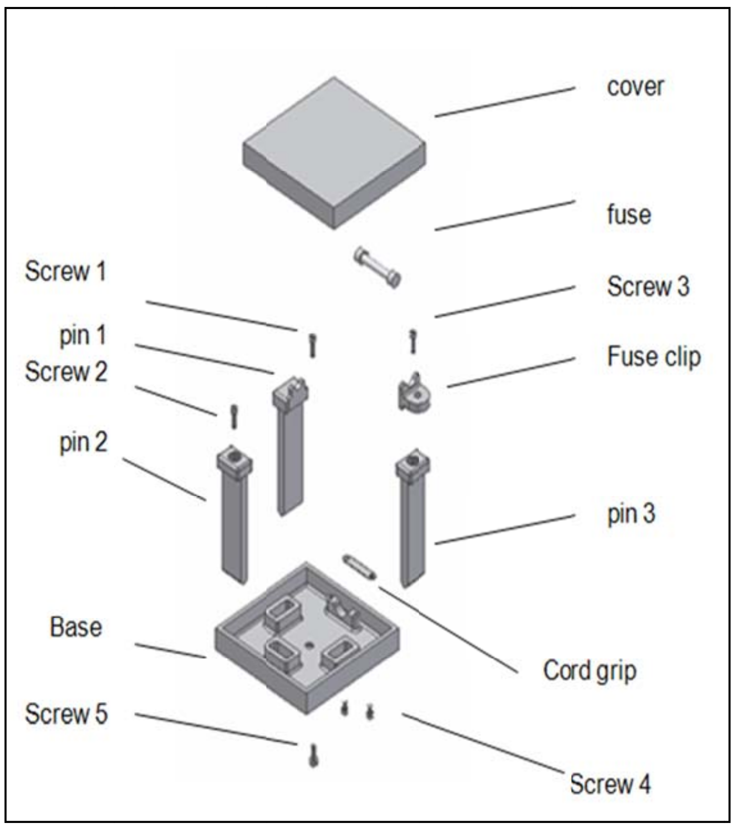



Figure 4.9 Three–pin electric power plug (S.N. Samy and H. ElMaraghy, 2010b)

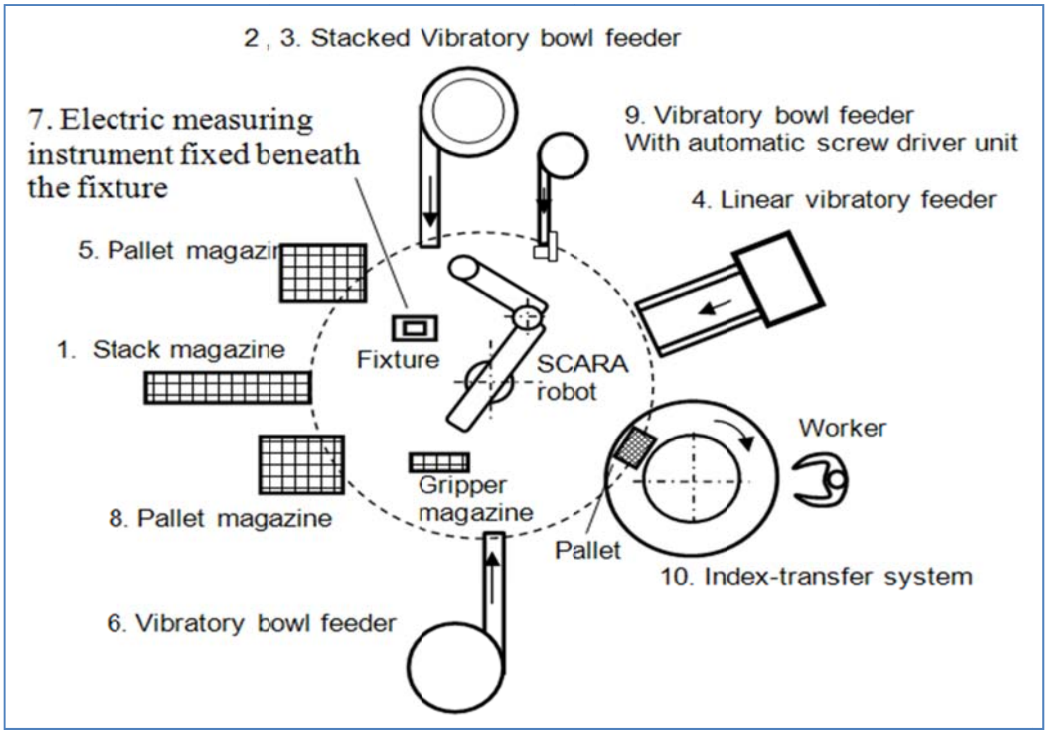


Figure 4. 10 First system structure (adapted from H.K. Rampersad, 1994)

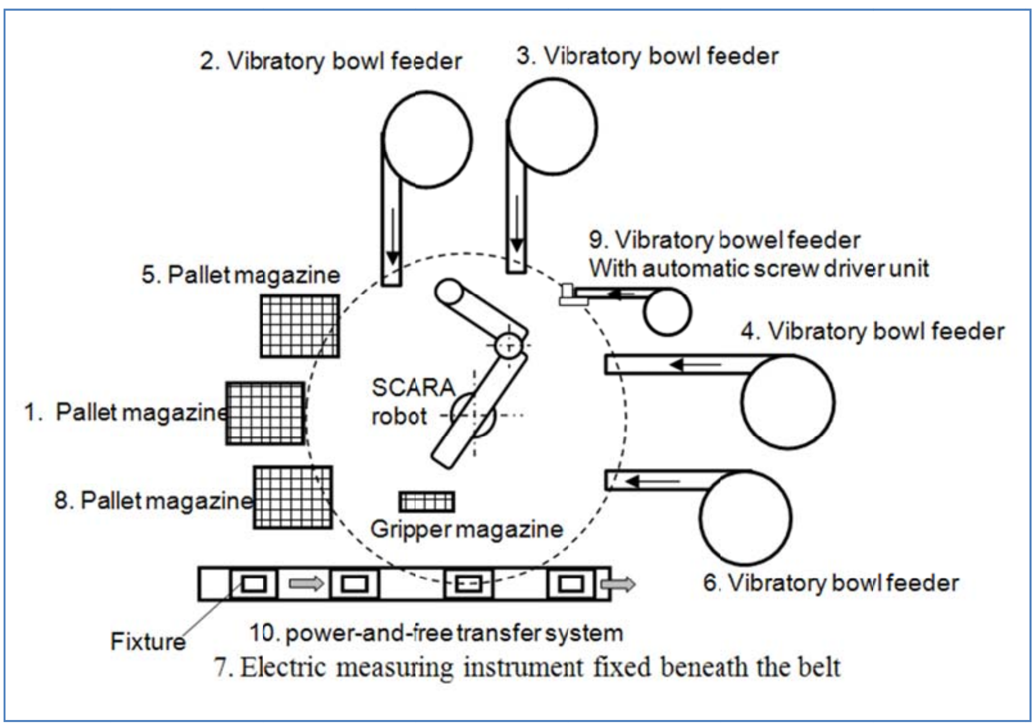


Figure 4.11 Second system structure (adapted from H.K. Rampersad, 1994)

**The first system consists of the following equipment:**

- Two vibratory bowl feeders stacked one on top of the other, making use of a vision-system to feed pin 2 and pin 3.
- A linear vibratory feeder for feeding pin 1.
- A pallet magazine to feed the fuse clip subassembly and the cover.
- A vibratory bowl feeder for feeding the fuse.
- An automatic screwdriver positioned under the fixture to assemble screw 5.
- An index-transfer provided with pallets to remove the acceptable assemblies.
- A SCARA robot provided with a gripper exchange system with grippers positioned in the work area of the robot.
- The worker role in this assembly system includes the feeding and removal of the fixture, material supply (such as filling the parts magazines), removal of assemblies, repairing jams, system setup, and adjusting system components as needed. Hence, this is treated as an automatic assembly cell/system.

**The second system consists of the following equipment:**

The following operations correspond with the second assembly system components:

- Three pallet magazines to feed base subassembly and the fuse clip, as well as the cover.
- Four circular vibratory feeders to feed pin 1, pin 2, pin 3 and the fuse.
- A screwdriver unit to be handled by the robot to assemble screw 5.
- Power-and-free transport system for the automatic feeding and removing of fixtures.
- The operator tasks consist of supplying material, remedying jams, system set-up, and if necessary the adjustment of system components.
- The remaining system components are consistent with the first system structure described above.

The numbers in Figure 4.9 and Figure 4.10 correspond to the numbering of the following assembly operations:

(1) Feed the subassembly base by a stack magazine (first system) or by a pallet magazine (second system).

(2) Feed pin 2 by a vibratory bowl feeder.

(3) Feed pin 3 by a vibratory bowl feeder.

(4) Feed pin 1 by a linear vibratory feeder (first system) or by a vibratory bowl feeder (second system).

(5) & (8) Feed fuse clip by a pallet magazine.

(6) Feed cover by a vibratory bowl feeder.

(7) Check the quality of the assembly with electrical measuring instrument.

(9) Assemble screw 5 with automatic screw driver unit.

(10) Remove acceptable assemblies by index-transfer system (first system) or by power and free transfer system (second system).

All system components are analyzed and the classification code is generated for each field. The detailed code descriptions of the different pieces of equipment of the two systems are detailed in Tables (B.1 – B.9) of Appendix (B). Table 4.15 compares the equipment and complexity indices of the first and second systems.

Table 4. 15 Equipment and complexity indices comparison (S.N. Samy and H. ElMaraghy, 2010b)

<table>
<tr><th>Part name</th><th>Process #</th><th>Equipment<br>(first system)</th><th>Equipment<br>(second system)</th></tr>
<tr><td>Base subassembly</td><td>1</td><td>Stack magazine</td><td>Pallet magazine</td></tr>
<tr><td>Pin 2</td><td>2</td><td rowspan="2">Stacked Vibratory Bowl feeder</td><td>Vibratory bowl feeder</td></tr>
<tr><td>Pin 3</td><td>3</td><td>Vibratory bowl feeder</td></tr>
<tr><td>Pin1</td><td>4</td><td>Linear vibratory feeder</td><td>Vibratory bowl feeder</td></tr>
<tr><td>Fuse subassembly</td><td>5</td><td colspan="2">Pallet magazine</td></tr>
<tr><td>Fuse</td><td>6</td><td colspan="2">Vibratory bowl feeder</td></tr>
<tr><td>-</td><td>7</td><td colspan="2">Electric measuring instrument</td></tr>
<tr><td>Cover</td><td>8</td><td colspan="2">Pallet magazine</td></tr>
<tr><td>Screw</td><td>9</td><td colspan="2">Automatic screw driver</td></tr>
<tr><td>Finished product</td><td>10</td><td>Index-transfer table</td><td>Power and free transfer conveyor</td></tr>
<tr><td>-</td><td>-</td><td>SCARA robot</td><td>SCARA robot</td></tr>
</table>

Complexity indices, number and complexity measures of all equipment in the three class types of first system and second systems are shown in Table 4.16 and Table 4.17 respectively. Assuming all three class types (Machines, MHS, and Buffers) contribute equally to the total system complexity (i.e. the weights values are 1), then both system complexities can be calculated using Equation (4. 8) as:

**First system:**

$$\mathrm{C}_{\mathrm{system1}} = 1.460 + 2.549 + 2.340 = 6.349$$

**Second system:**

$$C_{system2} = 1.460 + 2.378 + 1.030 = 4.868$$

The second system complexity is 4.868 compared to 6.349 of the first system. Assembly machines are the same for both systems which gives same values of machine complexity "$C_M$". Although the second system has a higher number of material handling equipment "$N_{MHS}$", it has less diversity "$n_{MHS}/N_{MHS}$" and less complexity index "$I_{MHS}$" which results in less material handling equipment complexity "$C_{MHS}$". Similarly, buffer equipment analysis of the second system shows lower complexity index "$I_B$", lower diversity "$n_B/N_B$", and a lower number of equipment "$N_B$" than the first system. This results in less Buffer complexity "$C_B$".

Table 4. 16 Complexity indices, number and complexity of the first system

| Class | Equipment | $I$ | $\bar{I}$ | $n$ | $N$ | $C$ |
|---|---|---|---|---|---|---|
| **Machine** | SCARA robot | 0.460 | 0.460 | 1 | 1 | 1.460 |
| **MHS** | Stacked vibratory feeder | 0.438 | 0.348 | 3 | 4 | 2.549 |
| | Vibratory bowl feeder | 0.318 | | | | |
| | Vibratory bowl feeder | 0.318 | | | | |
| | Linear vibratory feeder | 0.318 | | | | |
| **Buffer** | Stack magazine | 0.247 | 0.258 | 3 | 4 | 2.340 |
| | Pallet magazine | 0.182 | | | | |
| | Pallet magazine | 0.182 | | | | |
| | Indexing table | 0.421 | | | | |

Table 4. 17 Complexity indices, number and complexity of the second system

| Class | Equipment | $I$ | $\bar{I}$ | $n$ | $N$ | $C$ |
|---|---|---|---|---|---|---|
| **Machine** | SCARA robot | 0.460 | 0.460 | 1 | 1 | 1.460 |
| **MHS** | Vibratory bowl feeder | 0.434 | 0.347 | 3 | 6 | 2.378 |
| | Vibrator bowl feeder | 0.434 | | | | |
| | Vibratory bowl feeder | 0.434 | | | | |
| | Vibrator bowl feeder | 0.434 | | | | |
| | Vibratory bowl feeder with screw driver unit | 0.531 | | | | |
| | Power-and free transfer | 0.458 | | | | |
| **Buffer** | Pallet magazine | 0.182 | 0.182 | 1 | 3 | 1.030 |
| | Pallet magazine | 0.182 | | | | |
| | pallet magazine | 0.182 | | | | |

# CHAPTER FIVE

# PRODUCT AND ASSEMBLY EQUIPMENT COMPLEXITY MAPPING

Individual parts handling and insertion attributes, described in chapter three, are used in this chapter to map the relationship between part assembly complexity and its related equipment complexity. A dependency matrix is developed to represent the interactions between individual part attributes and the related assembly equipment functions. The dependency matrix is then used to predict the relevant equipment complexity for a certain product before its assembly system and its equipment are known. Using regression analysis, the relationship between part complexity and equipment complexity is developed and used to predict the assembly equipment complexity.

## 5.1 Dependency Matrix

As described in chapter three, assembly attributes for automatic assembly are classified into handling attributes (symmetry, size, flexibility, delicateness, stickiness, tangling/nesting) and insertion attributes (securing assembly, insertion resistance, alignment/positioning, joining method, insertion direction). On the other hand, Assembly equipment functions are classified into feeding, handling, joining, and transportation (G. Boothroyd *et al.*, 2002, H.K. Rampersad, 1994, G. Salvendy, 2001). The various assembly functions are defined as:

- Feeding: includes the separation, sorting, positioning, and orienting of parts for the handling equipment.
- Handling: includes pick and place from the feeding position to the joining position and the insertion action.
- Joining: is combining together more than one part by fastening, riveting, welding,
- Transportation: is the moving process from one location to another

The methodology of using qualitative interactions in a "dependency matrix" is rather common in engineering. In this section, a symbolic representation similar to that used in QFD "Quality Function Deployment", is used to indicate: strong, medium, weak (or non-existing) interactions. Interactions between part assembly attributes and assembly equipment functions can be expressed qualitatively as shown in Figure 5.1.

◉ STRONG
◎ MEDIUM
X NOTHING

| *System Functions* | *Part Attributes* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Symmetry** | **Size** | **Flexibility** | **Delicateness** | **Stickiness** | **Tangling/nesting** | **Securing assembly** | **Insertion resistance** | **Alignment/positioning** | **Joining method** | **Insertion direction** |
| **Feeding** | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | X | X | X | X | X |
| **Handling** | ◎ | ◉ | ◉ | ◎ | ◉ | X | ◎ | ◉ | ◉ | X | ◉ |
| **Joining** | X | X | X | ◎ | X | X | ◉ | X | X | ◉ | X |
| **Transportation** | X | ◎ | ◎ | ◎ | X | X | X | X | X | X | X |

Figure 5. 1 Part attributes and system functions interactions

In order to make use of this type of qualitative interactions representation, a three-point scale: 1, 0.5 and 0 is used to represent the degree of interaction between part assembly attributes and system functions as shown in Figure 5. 2.

"1" refers to a significant interaction, "0.5" refers to a medium interaction, and "0" refers to no interaction. The quantitative form of the interactions is represented in a matrix named Dependency Matrix (DM). Although the numbers 1, 0.5, and 0 respectively have been chosen in this research, a finer scale may be used as more analysis, experiments and knowledge becomes available. The presented association methodology and dependency matrix can use finer scales (such as 1, 0.75, 0.5, 0.25, 0) if desired to represent the interactions between part attributes and assembly system functions.

| | | *Part Attributes* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Symmetry | Size | Flexibility | Delicateness | Stickiness | Tangling/nesting | Securing assembly | Insertion resistance | Alignment/positioning | Joining method | Insertion direction |
| *System Functions* | **Feeding** | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| | **Handling** | 0.5 | 1 | 1 | 0.5 | 1 | 0 | 0.5 | 1 | 1 | 0 | 1 |
| | **Joining** | 0 | 0 | 0 | 0.5 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| | **Transportation** | 0 | 0.5 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Figure 5. 2 Dependency matrix

Firstly, the interactions between each part attribute and the assembly functions are subjectively determined. For example, symmetry greatly affects the feeder type of orienting devices (passive or active). Symmetry also affects the type of feeding being manual or automatic. Therefore, the interaction between the symmetry attribute and feeding function is set as “1”. After feeding, parts are usually ready or need little effort by the handling equipment to present them correctly. Hence, the interaction between the symmetry attribute and the handling function is set at “0.5”. There are no interactions between the symmetry attribute and the joining or transportation functions, hence, the values are set as “0”.

Then, for each attribute of the eleven columns of the dependency matrix, the total interactions of assembly equipment functions represented by the four rows of the dependency matrix are summed up and normalized (divided by four) to represent the degree to which each part attribute interacts with the corresponding four system functions. The normalized total interactions between “symmetry” and the four assembly functions, is $(1 + 0.5 + 0 + 0)/4 = 0.375$. Other attributes are treated similarly to give:

$$[\mathrm{DM}] = [\ 0.375 \ \ 0.625 \ \ 0.625 \ \ 0.625 \ \ 0.500 \ \ 0.250 \ \ 0.375 \ \ 0.250 \ \ 0.250 \ \ 0.250 \ \ 0.250\ ]$$

The [DM] is then used to predict the assembly equipment complexity as follows:

## 5.2 Parts Complexity Attributes Matrix (PCAM)

Based on design for assembly (DFA) analysis, there are two matrices. The first one is the parts handling complexity attributes matrix. The second one is the parts insertion complexity attributes matrix. The two matrices are combined together here to give one single matrix named Parts Complexity Attributes Matrix (*PCAM*).

$[\boldsymbol{PCAM}] =$

| | Part#1 | Part#2 | Part#3 | …….. | Part#n |
|---|---|---|---|---|---|
| **Symmetry** | | | | | |
| **Size** | | | | | |
| **Flexibility** | | | $C_{h,f}$ | | |
| **Delicateness** | | | | | |
| **Stickiness** | | | | | |
| **Nesting** | | | | | |
| **Secure assembly** | | | | | |
| **Insertion resistance** | | | | | |
| **Alignment** | | | $C_{i,f}$ | | |
| **Joining** | | | | | |
| **Insertion direction** | | | | | |

where $C_{h,f}$ and $C_{i,f}$ are the complexity factors for handling and insertion respectively.

## 5.3 Assembly Equipment Complexity Matrix (AECM)

The above parts complexity attributes matrix (PCAM) is then multiplied by the dependency matrix (DM). The result is a new matrix named Assembly Equipment Complexity Matrix (AECM) as:

$$[AECM] = [DM][PCAM] \tag{5. 1}$$

The [AECM] represents an estimation of the average assembly equipment complexity. The following example explains the generation and use of the described complexity mapping approach.

5.3.1 Illustrative example

Figure 5. 3 shows the exploded view of an automobile engine piston.

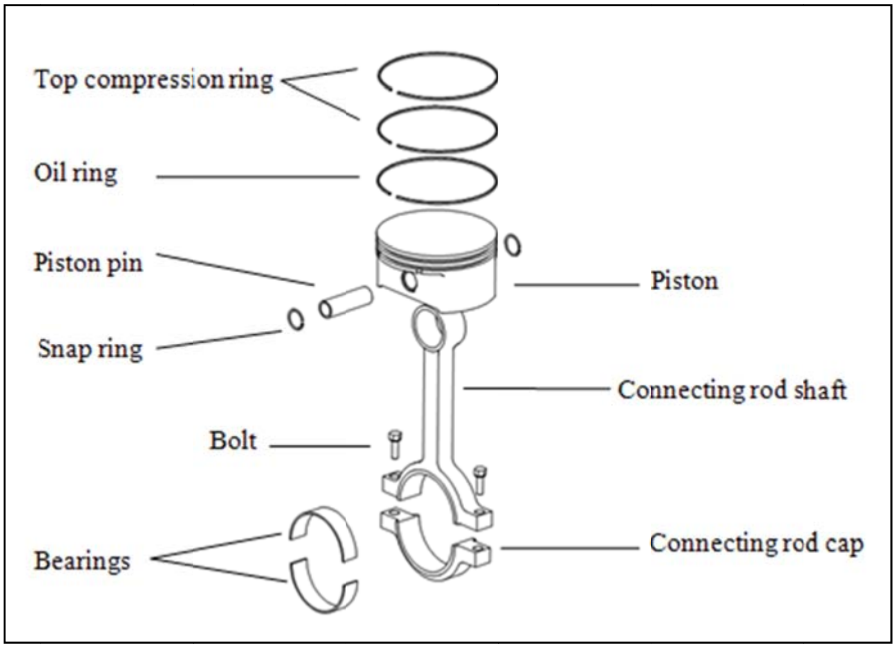



Figure 5. 3 Automobile engine piston decomposition

Individual parts of piston are analyzed and the parts complexity attributes matrix [*PCAM*] is generated as:

**[PCAM] =**

| | **Compression ring** | **Oil ring** | **Piston** | **Piston pin** | **Snap ring** | **Connecting rod shaft** | **Connecting rod cap** | **Bearing** |
|---|---|---|---|---|---|---|---|---|
| **Symmetry** | 0.77 | 0.77 | 1 | 0.66 | 0.77 | 1 | 1 | 1 |
| **Size** | 0.81 | 0.81 | 0.74 | 0.74 | 1 | 0.74 | 0.74 | 0.81 |
| **Flexibility** | 1 | 1 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 |
| **Delicateness** | 1 | 1 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| **Stickiness** | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| **Nesting** | 1 | 1 | 0.8 | 0.8 | 1 | 0.8 | 0.8 | 0.8 |
| **Secure assembly** | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 1 | 1 | 1 |
| **Insertion resistance** | 1 | 1 | 0.67 | 1 | 1 | 0.67 | 0.67 | 1 |
| **Alignment** | 1 | 1 | 0.67 | 1 | 1 | 1 | 1 | 1 |
| **Joining** | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 |
| **Insertion direction** | 0.5 | 0.5 | 0.5 | 0.54 | 0.54 | 0.5 | 0.5 | 0.5 |

Using both [DM] and [PCAM] matrices would give the average assembly equipment complexity matrix [AECM] as:

| | Compression ring | Oil ring | Piston | Piston pin | Snap ring | Connecting rod shaft | Connecting rod cap | Bearing |
|---|---|---|---|---|---|---|---|---|
| $[AECM]$ = | 3.601 | 3.601 | 3.098 | 3.145 | 3.399 | 3.274 | 3.399 | 3.400 |

These values represent the average complexity of the assembly equipment used during the assembly process of each part.

## 5.4 Normalization

To normalize the calculated average assembly equipment complexity matrix [AECM], another [PCAM] matrix with maximum part assembly attributes values is generated as:

$[PCAM]_{max}$ =

| | Compression ring | Oil ring | Piston | Piston pin | Snap ring | Connecting rod shaft | Connecting rod cap | Bearing |
|---|---|---|---|---|---|---|---|---|
| **Symmetry** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Size** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Flexibility** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Delicateness** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Stickiness** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Nesting** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Secure assembly** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Insertion resistance** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Alignment** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Joining** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| **Insertion direction** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

Multiplying $[\mathrm{PCAM}]_{\mathrm{max}}$ by [DM] would give the corresponding maximum $[\mathrm{AECM}]_{\mathrm{max}}$. In case of the automobile engine piston assembly the $[\mathrm{AECM}]_{\mathrm{max}}$ is:

$$[AECM]_{max} = [DM][PCAM]_{max}$$

(5. 2)

i.e.,

| | Compression ring | Oil ring | Piston | Piston pin | Snap ring | Connecting rod shaft | Connecting rod cap | Bearing |
|---|---|---|---|---|---|---|---|---|
| $[\boldsymbol{AECM}]_{\mathbf{max}}$ = | 4.125 | 4.125 | 4.125 | 4.125 | 4.125 | 4.125 | 4.375 | 4.125 |

Dividing[AECM] by $[\mathrm{AECM}]_{\mathrm{max}}$ would give the normalized average assembly equipment complexity $[\mathrm{AECM}]_{\mathrm{norm}}$ as:

$$[AECM]_{norm} = [AECM][AECM]_{max}^{-1}$$

(5. 3)

i.e.,

| | Compression ring | Oil ring | Piston | Piston pin | Snap ring | Connecting rod shaft | Connecting rod cap | Bearing |
|---|---|---|---|---|---|---|---|---|
| $[\boldsymbol{AECM}]_{\mathbf{norm}}$ = | 0.873 | 0.873 | 0.751 | 0.762 | 0.824 | 0.794 | 0.777 | 0.824 |

The following section presents the use of regression analysis to drive a general relationship between part complexity and assembly equipment.

## 5.5 Regression Analysis

In addition to the automobile piston, three other different mechanical products (Figure 5. 4) are considered. The products are: car fan motor, domestic appliance drive, electric power plug, in addition to the automotive piston. The four products have 33 parts. Part complexity and the normalized average equipment complexity$[\mathrm{AECM}]_{\max}$ are listed in Table 5.1. Detailed analyses of the selected products are shown in Appendix (A). The procedure of calculating part complexity was described in chapter three.

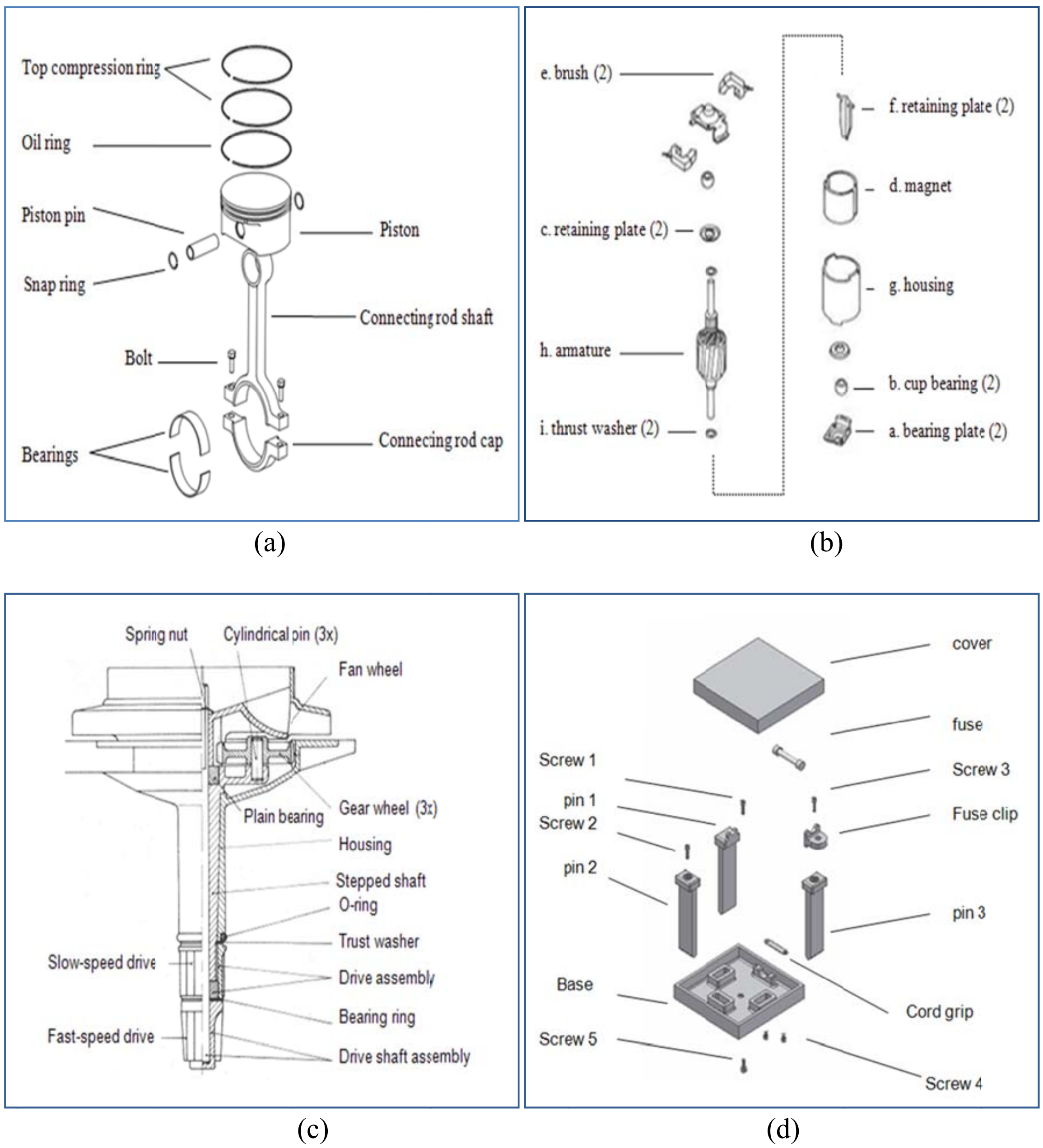
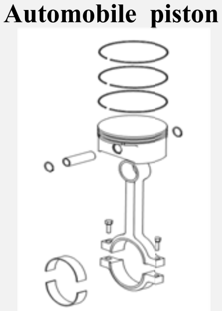
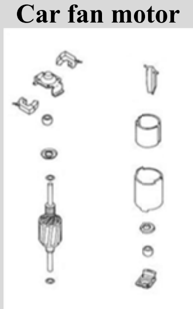
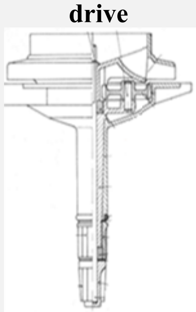
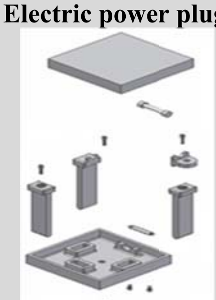


Figure 5. 4 Product (a) automobile engine piston (b) Car fan motor (c) Domestic appliance drive (d) Electric power plug

Table 5. 1 Parts complexity versus mapping-based equipment complexity

| Product name | Part name | Part complexity* | Mapping-based equipment complexity $[AECM]_{norm}$ |
|---|---|---|---|
| **Automobile piston**  | Compression ring | 0.804 | 0.873 |
| | Oil ring | 0.865 | 0.873 |
| | Piston | 0.748 | 0.751 |
| | Piston pin | 0.778 | 0.762 |
| | Snap ring | 0.833 | 0.824 |
| | Connecting rod shaft | 0.798 | 0.794 |
| | Connecting rod cap | 0.852 | 0.777 |
| | Bearing | 0.839 | 0.824 |
| **Car fan motor**  | Bearing plates | 0.764 | 0.769 |
| | Cup bearings | 0.769 | 0.783 |
| | Retaining plates | 0.789 | 0.795 |
| | Magnets | 0.765 | 0.763 |
| | Brushes | 0.847 | 0.847 |
| | Retaining springs | 0.782 | 0.782 |
| | Housing | 0.765 | 0.763 |
| | Armature | 0.765 | 0.763 |
| | Thrust washers | 0.769 | 0.783 |
| **Domestic appliance drive**  | Gear wheels | 0.752 | 0.754 |
| | Cylindrical pin | 0.778 | 0.780 |
| | Spring nuts | 0.765 | 0.775 |
| | Drive shaft | 0.765 | 0.763 |
| | Drive | 0.765 | 0.763 |
| | Stepped shaft | 0.765 | 0.763 |
| | Fan wheel | 0.740 | 0.748 |
| | Bearing | 0.790 | 0.774 |
| | Thrust washer | 0.789 | 0.795 |
| **Electric power plug**  | Base subassembly | 0.747 | 0.758 |
| | Fuse clip | 0.803 | 0.810 |
| | Pin 1 | 0.782 | 0.782 |
| | Fuse | 0.744 | 0.760 |
| | Pin 2 | 0.758 | 0.761 |
| | Pin 3 | 0.758 | 0.761 |
| | Cover | 0.768 | 0.774 |

* Calculations are based on procedure described in chapter 3

In addition to the 33 parts of the four products, two hypothetical parts are considered to represent two extreme points. The two extreme points define the limits of part complexity. One part has all minimum values of handling and insertion attributes, the other part has all maximum values of handling and insertion attributes. The procedure of generating the two extreme points is the same as the one described in the illustrative example (5.3.1). The only difference is the substitution of minimum values of handling and insertion attributes into the [PCAM] matrix to give the first extreme point. The substitution of maximum values of handling and insertion attributes into the [PCAM] matrix gives the second extreme point. These minimum and maximum attributes values yield 0.671 and 1 as minimum and maximum part complexities respectively. The corresponding minimum and maximum values of the [AECM]norm are 0.689 and 1 respectively.

Figure 5. 5 shows part complexity of all parts of the four products and the two hypothetical parts versus the predicted equipment complexity. Regression analysis is used to formulate the relationship between part complexity and assembly equipment complexity as follows:

A relationship between part complexity and the mapped assembly equipment complexity would be a second degree polynomial regression model as given in Equation 5.4 with 95% confidence and a coefficient of determination of 0.8708.

$$C_{equip.} = 0.5622\ C_{part}^2 - 0.0311 C_{part} + 0.4633 \tag{5. 4}$$

where $C_{equip.}$ is the average complexity of assembly equipment required to assemble individual part, $C_{part}$ is part complexity.

The average assembly equipment complexity predicted by the proposed association mapping approach increases as part complexity increases.

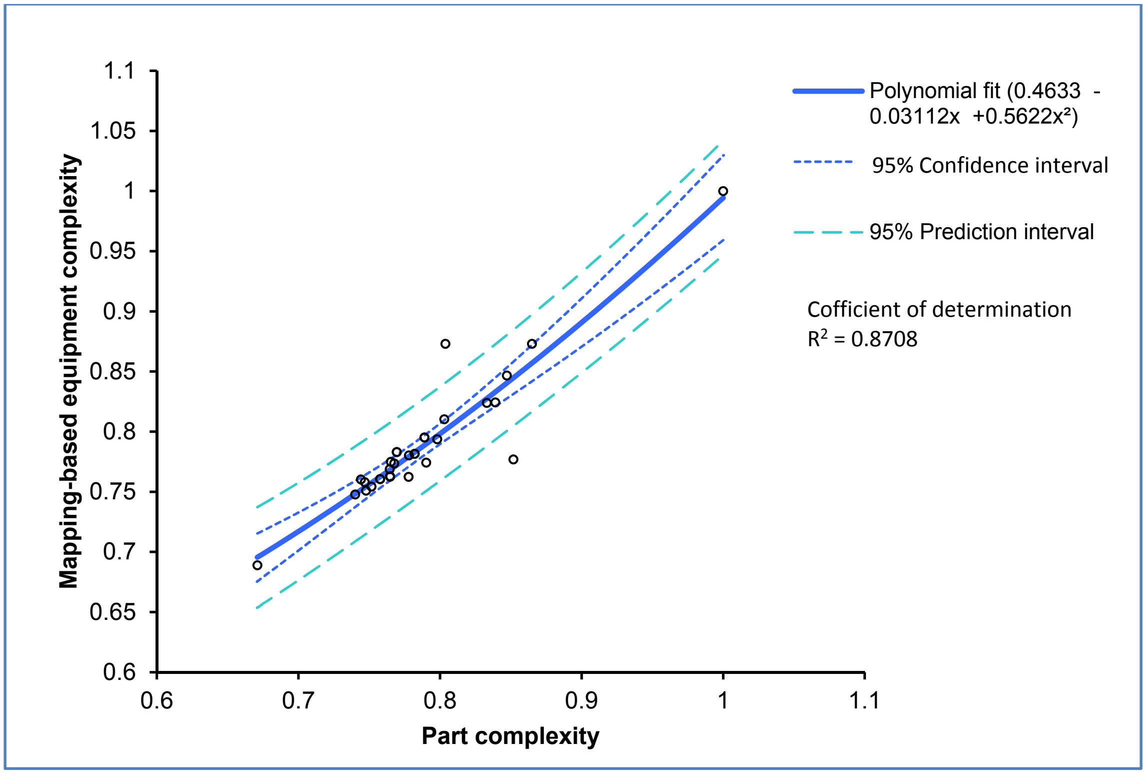



Figure 5. 5 Part complexity versus mapping-based equipment complexity

The above analysis gives the average complexity of the necessary assembly equipment knowing the complexity of the part to be assembled. Figure 5. 6 show the followed mapping procedure to predict the assembly equipment complexity starting with the assembled parts and ending with the assembly equipment complexity.

The figure shows the procedure of predicting the assembly equipment complexity of new products or design variants. Thus, the proposed method of analysis and mapping would help product designers in analyzing products with respect to parts assembly complexity and predict the complexity of the required assembly equipment in the early design stages (stage I of Figure 5. 7 ) before detailing the whole system and determining its exact structure. At this stage, the only available data represent product and individual parts. Data about system structure and equipment characteristics are not available yet.

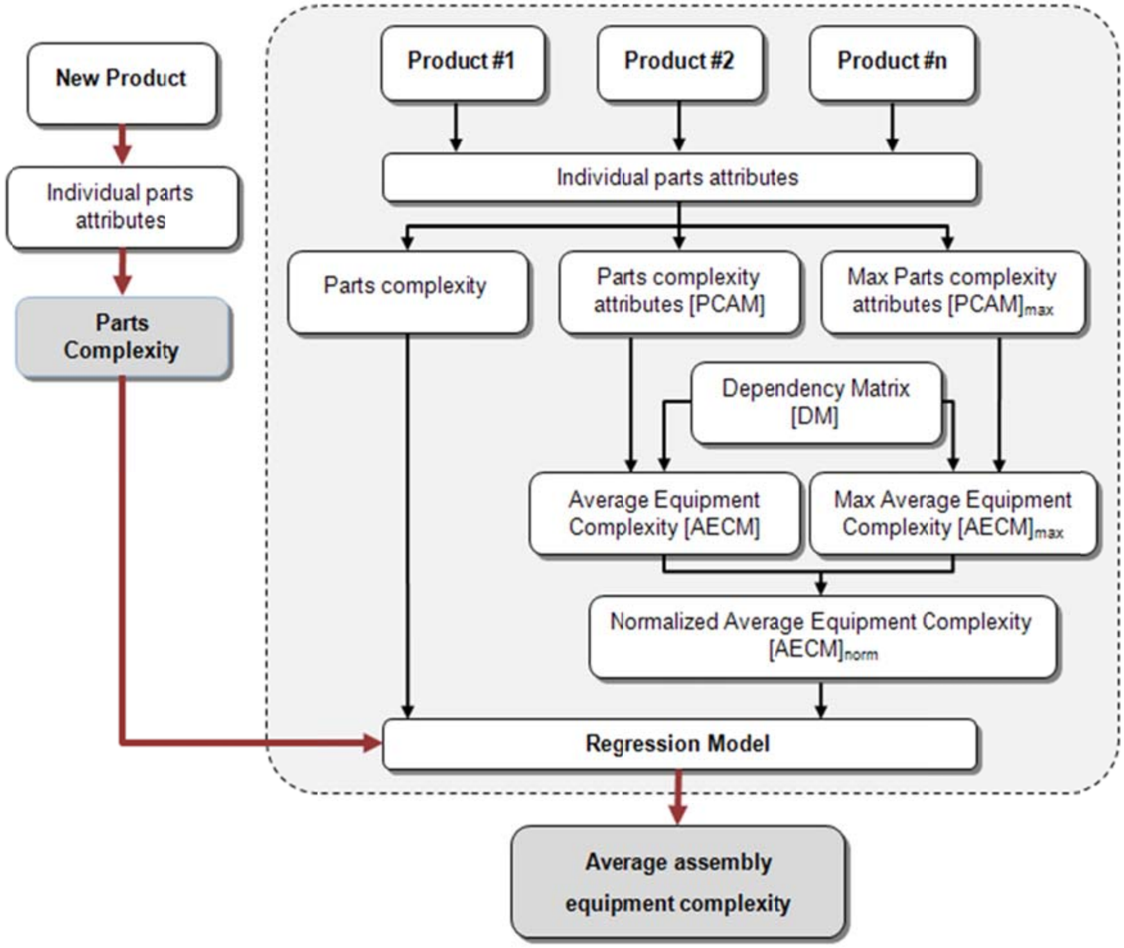



Figure 5. 6 Mapping part complexity into equipment complexity

Once the exact system structure and equipment characteristics are determined (stage II of Figure 5. 7 ), The SCC code can then help system designers in calculating system complexity and compare the various alternatives and select the least complex one. The impact of product complexity on system complexity can then be determined as follows:

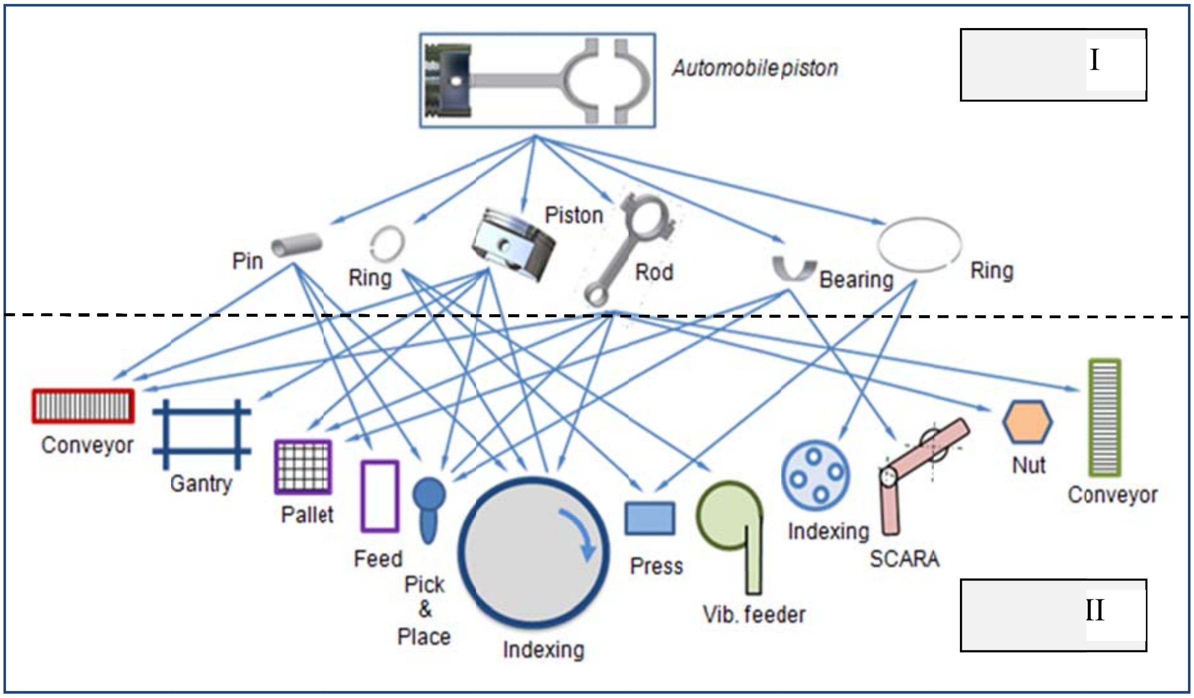



Figure 5. 7 Product and system decomposition

## 5.6 Code – based analysis

Four different assembly systems corresponding to the automotive engine piston, car fan motor, domestic appliance drive, and electric power plug are described below:

### 5.6.1 Automobile Engine Piston Assembly System

Figure 5. 8 shows the automobile engine piston assembly system and its equipment (the data has been adapted from a real system of a car assembly plant in Windsor, Ontario, Canada).

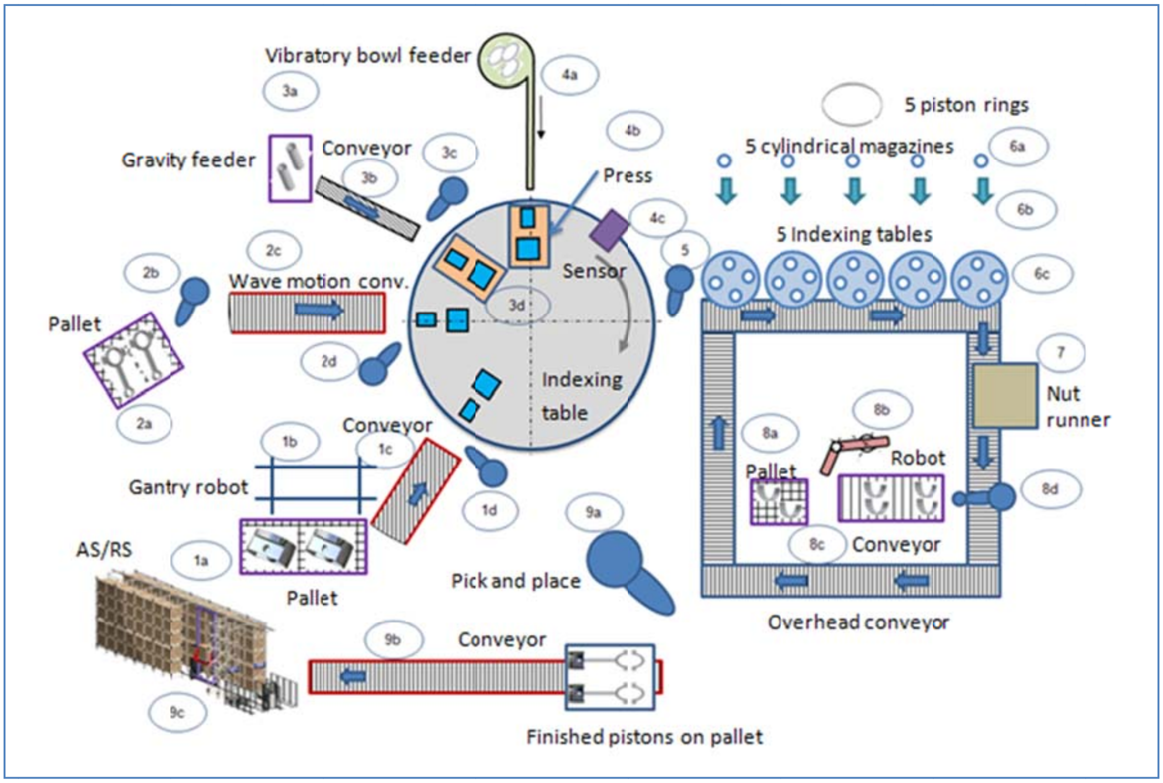



Figure 5. 8 Automobile engine piston assembly system

The company assembles engines for midsize vehicles. There are two identical assembly systems each producing half of the production simultaneously. One robotic gantry suction head is common at the beginning and serves both lines. The pace of assembly operations is different from a station to another, since different types of material handling systems are incorporated. These MHSs use different pallets and with different number of products per pallet. The plant looks like a one big dedicated assembly machine with very limited possibility for flexibility and changeability. Number of workers is small; they are mainly used for loading and unloading material boxes and feeders, and for monitoring and supervising. Following is a description of the system operations and equipment. Figure 5. 9 shows the assembly sequence of the automobile engine piston. The numbers in the figure correspond to the following assembly operations:

1a. Load piston head on pallet.

1b. a gantry robot Handles piston head to pallets on a belt conveyor by suction.

1c. Conveyor feeds piston head pallets to a pick and place.

1d. Pick and place piston head pallets to an indexing table.

2a. Connecting rod comes pre-stacked horizontally as a rack of 10 in a pallet.

2b. Pick and place connecting rods to a wave motion (cam) conveyor.

2c. Wave motion conveyor Feeds connecting rod to a pick & place.

2d. Pick and place connecting rod to the indexing table.

3a. Piston pin is pre-stacked in a vertical gravity feeder (chute box).

3b. A conveyor feeds pins from the gravity feeder to a pick and place.

3c. Pick and place pins to the indexing table.

3d. A press inserts the pins into the piston head with connecting rod.

4a. Feeding snap rings by a vibratory bowel feeder.

4b. A press Inserts the snap rings into the piston head.

4c. Checking (inspection) the existence of the snap rings.

5. Picking the finished subassembly and placing it on an overhead asynchronous conveyor.

6a. Piston rings in vertical cylindrical magazine.

6b. Handling the magazine manually to five indexing tables.

6c. Inserting the piston rings into the piston head.

7. A nut runner disassembles the connecting rod cap.

8a. Putting Bearing on pallets.

8b. A robot handles bearings by grippers to a wave motion conveyor.

8c. The wave motion conveyor feeds the bearings to a pick and place device.

8d. Pick the bearing and placing in position and pressing them.

9a. Pick the finished assembly and placing them on a pallet on a belt conveyor.

9b. A conveyor handles the filled pallets to AS/RS.

9C. An AS/RS is used for storage (FIFO)

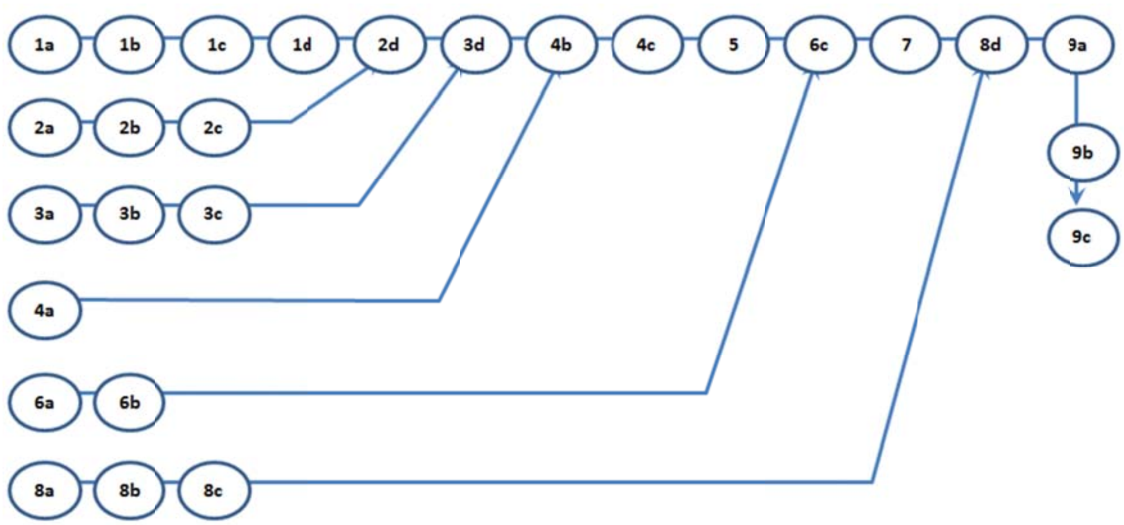



Figure 5. 9 Automobile engine piston assembly sequence

5.6.2 Car fan motor assembly system

Figure 5. 10 shows the car fan motor assembly system and its equipment. The system is consisting of individual equipment connected together by a double belt transfer system.

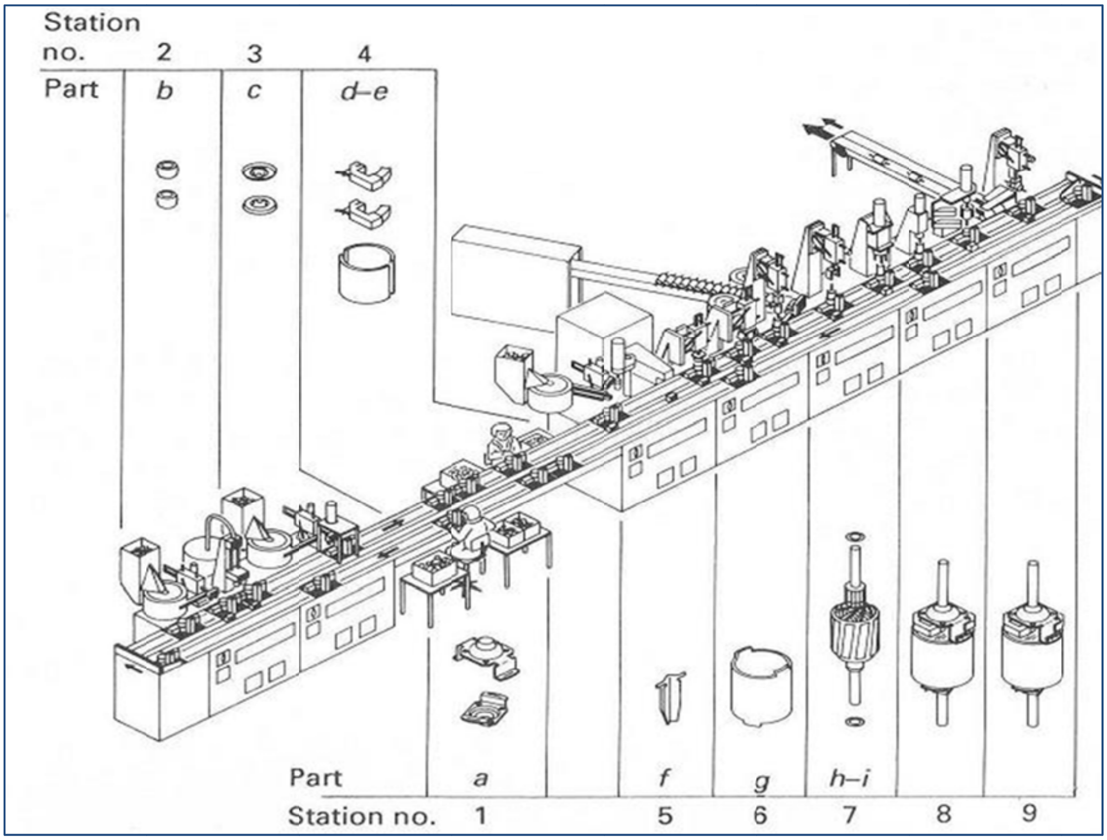



Figure 5. 10 Car fan motor assembly system (B. Lotter, 1989)

The operational sequence is as follows ((B. Lotter, 1989)):

- Station 1: is a manual work point for positioning the bearing plates in the pre-assembly fixture of the work piece carrier. The remaining parts are removed by the same operator.
- Station 2: is designed as a double station so that the work piece carrier can be stopped and positioned at two different positions. The cup bearings are arranged in pairs, fed and separated in the first position and fitted into the bearing shells by

a handling unit equipped with a double gripper. Both cup bearings are automatically lubricated with grease in this position.

- Station 3: is constructed with as a double station. The work piece carriers are also stopped and positioned. The retaining plates are arranged by a vibratory feeder, fed to the separating station via a discharge rail, grasped in pairs by a positioning unit and placed in bearing shells by a pneumatic press at the second station.
- Station 4: is a manual work point for the fitting of the magnets in pairs in the work piece holder and placing brushes in a bearing plate.
- Station 5: is also designed as a double station so that the work piece carriers can also be stopped and positioned at two points. The retaining spring is arranged by a vibratory feeder at the first feeder, fed to the separating station by a discharge rail and placed in the work piece holder by a handling unit. At the second position, the housing is placed on the work piece carrier by a conveyor and magnetized.
- Station 6: the first pre-assembled bearing plate is transferred from the pre-assembly fixture into the final assembly fixture; the housing is positioned on the bearing plate.
- Station 7: the armature is removed from a column magazine by a conveyor belt and fed to a stopping station. The trust plate are then fed by a vibratory feeder and transported to a separating station by discharge rails and fitted to the armature spindle ends. Then, pre-assembled with the trust plates, the armature is fitted into the housing and the second bearings plate positioned.
- Station 8: the form-locking connection of the bearing plates with the housing is made at the first stop point by a pneumatically operated preening tool.
- Station 9: a test run is undertaken and the insulation strength of the motor tested. The finally assembled fan motors are placed in a slide by a positioning unit. Depending on the test results, bad motors are rejected and good motors are transported by a belt system to the packing station. The empty work piece carriers are transferred on to the return belt for transport to the first station.

5.6.3 Domestic appliance drive assembly system

Figure 5. 11 shows the car fan motor assembly system and its equipment. System structure, individual equipment and assembly operations were previously described in section (4.4) of chapter 4.

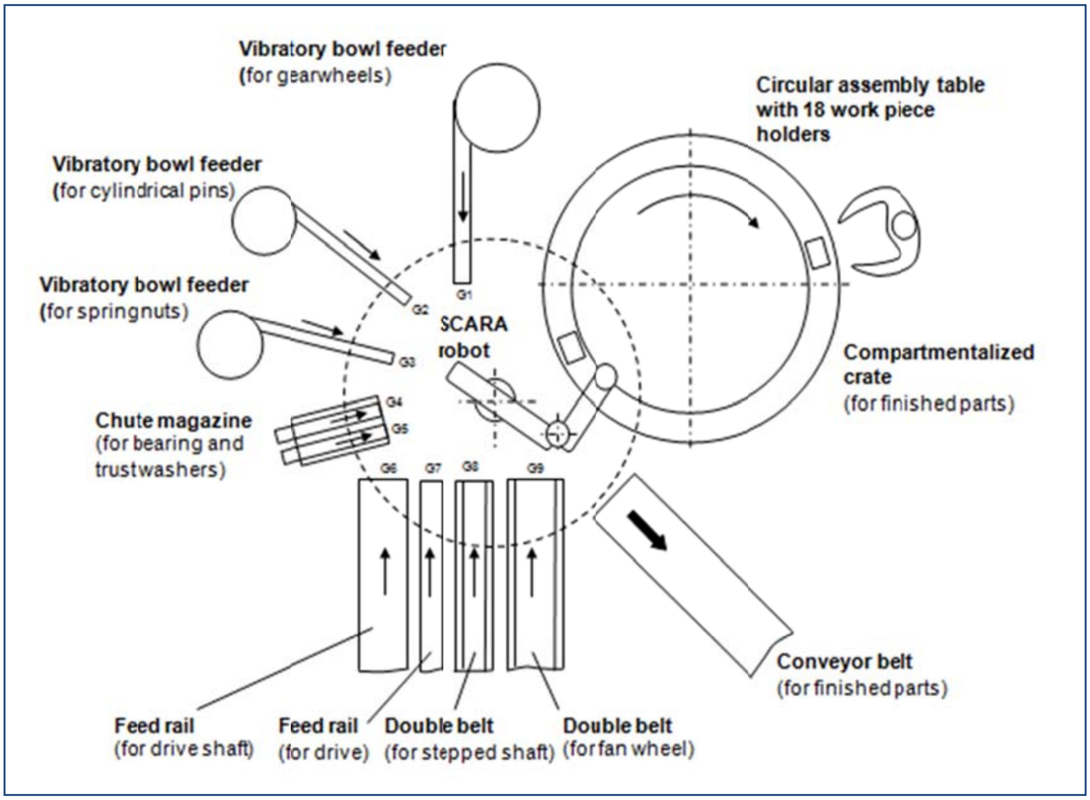



Figure 5. 11 Domestic appliance drive assembly system (adapted from B. Lotter, 1989)

5.6.4 Three-pin electric power plug

Figure 5. 12 shows the three-pin electric power plug assembly system and its equipment. System structure, individual equipment and assembly operations are previously described in section (4.5) of chapter 4.

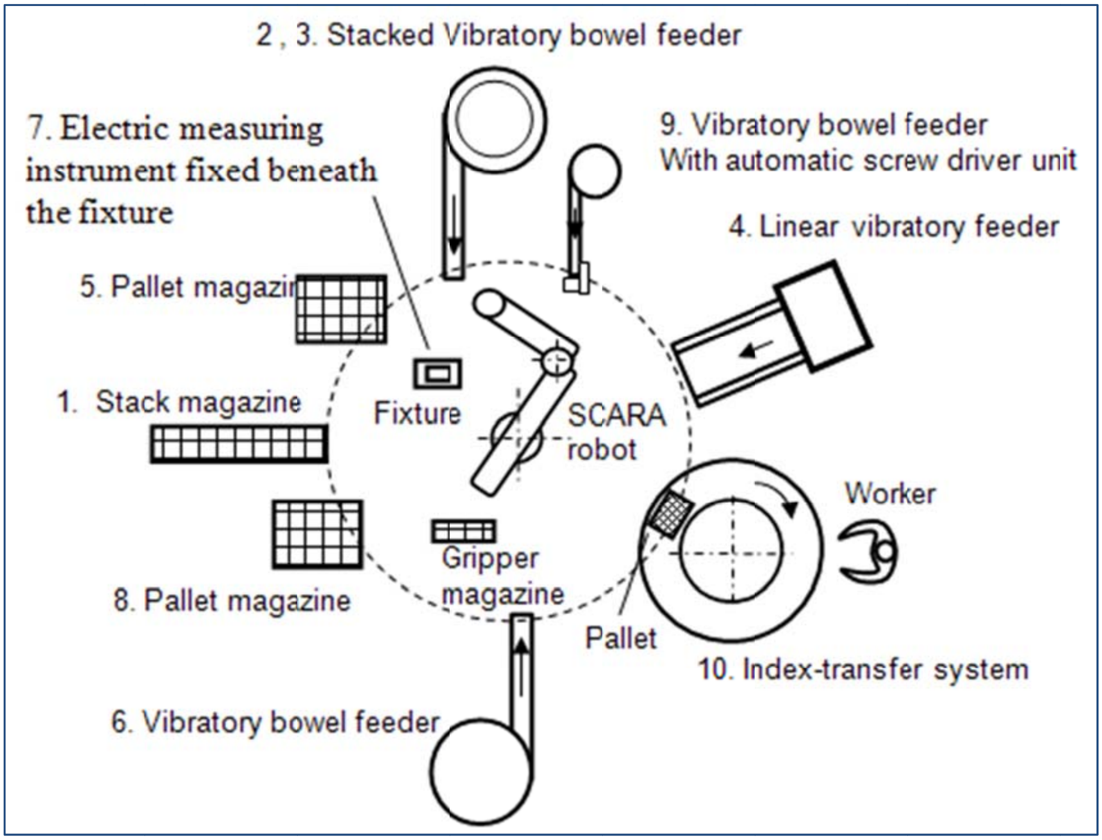


Figure 5. 12 Electric power plug (adapted from H.K. Rampersad, 1994)

### 5.6.5 Product complexity versus system complexity

The classification and coding of the individual assembly equipment is shown in Appendix (B). Table 5. 2 summarizes the results of the calculated system complexity.

For each case, both product complexity and code-based system complexity have been calculated. Figure 5. 13 shows product complexity versus system complexity. System complexity increases as product complexity increases. This is in agreement with Equation 5.4. Higher part complexity leads to higher equipment complexity, number and diversity of parts also affect the number and diversity of assembly equipment. The result is an increase in system complexity as product complexity increases too. The calculated product and code-based system complexity values could be used to guide systems designers in the mature design stages to compare and select system design alternatives.

Table 5. 2 Product complexity vs. code-based system complexity

| Product complexity* | System | Class | Equipment | I | $\bar{I}$ | N | n | C | System complexity |
|---|---|---|---|---|---|---|---|---|---|
| 6.38 | Automobile engine piston assembly system | Machine | Press | 0.262 | 0.266 | 2 | 2 | 2.007 | 8.949 |
| | | | Nut runner | 0.271 | | | | | |
| | | MHS | Vibratory feeder | 0.547 | 0.495 | 6 | 6 | 4.198 | |
| | | | Handling robot | 0.657 | | | | | |
| | | | Conveyor belt | 0.396 | | | | | |
| | | | Conveyor | 0.440 | | | | | |
| | | | Gantry robot | 0.518 | | | | | |
| | | | Conveyor | 0.420 | | | | | |
| | | | Pick and place | 0.491 | | | | | |
| | | Buffer | Magazine | 0.182 | 0.372 | 3 | 3 | 2.744 | |
| | | | indexing table | 0.530 | | | | | |
| | | | indexing table | 0.404 | | | | | |
| 5.76 | Car fan motor assembly system | Machine | Peening unit | 0.417 | 0.404 | 2 | 2 | 2.225 | **6.658** |
| | | | Pneumatic press | 0.481 | | | | | |
| | | MHS | Vibratory feeder | 0.589 | 0.564 | 3 | 4 | 3.051 | |
| | | | Vibratory feeder | 0.589 | | | | | |
| | | | Positioning unit | 0.596 | | | | | |
| | | | Conveyor | 0.483 | | | | | |
| | | Buffer | Magazine | 0.311 | 0.311 | 1 | 1 | 1.311 | |
| 5.85 | Domestic appliance drive assembly system | Machine | SCARA robot | 0.536 | 0.536 | 1 | 1 | 1.536 | **6.860** |
| | | MHS | Vibratory feeder | 0.387 | 0.402 | 8 | 5 | 3.255 | |
| | | | Vibratory feeder | 0.387 | | | | | |
| | | | Vibratory feeder | 0.434 | | | | | |
| | | | Feed rail | 0.424 | | | | | |
| | | | Feed rail | 0.424 | | | | | |
| | | | Double belt | 0.396 | | | | | |
| | | | Double belt | 0.396 | | | | | |
| | | | Conveyor Belt | 0.365 | | | | | |
| | | Buffer | Magazine | 0.248 | 0.306 | 2 | 2 | 2.069 | |
| 5.59 | Three-pin electric power plug assembly system | Machine | SCARA robot | 0.460 | 0.460 | 1 | 1 | 1.460 | **6.349** |
| | | MHS | Vibratory feeder | 0.438 | 0.348 | 3 | 4 | 2.549 | |
| | | | Vibratory feeder | 0.318 | | | | | |
| | | | Vibratory feeder | 0.318 | | | | | |
| | | | vibratory feeder | 0.318 | | | | | |
| | | Buffer | Stack magazine | 0.247 | 0.258 | 3 | 4 | 2.340 | |
| | | | Pallet magazine | 0.182 | | | | | |
| | | | Pallet magazine | 0.182 | | | | | |
| | | | Indexing table | 0.421 | | | | | |

* Calculations are based on procedure described in chapter 3

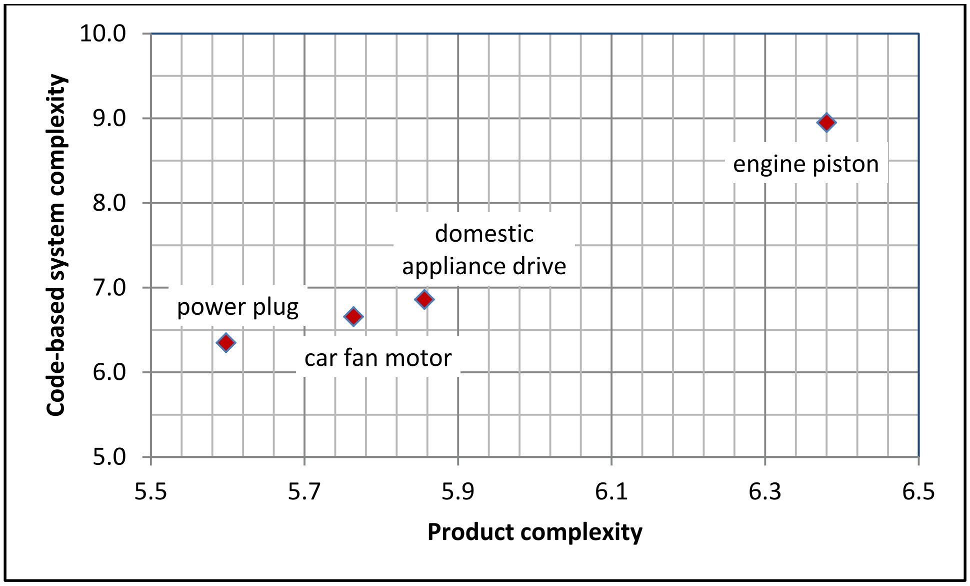



Figure 5. 13 Product complexity versus code-based system complexity

CHAPTER SIX

# CONCLUSIONS

In designing any assembly system a number of trade-offs are made considering function, cost as well as complexity, which is known to affect performance, quality and reliability. Complex assembly systems are costly to implement, run, control and maintain. Complexity of assembly is an important characteristic worth exploring and modelling for evaluating manufacturing systems at the early design stage. Attention should be paid to the assembly system complexity resulting from the complexity of products and their variants. The objective of this research was to manage the complexity of assembly. The complexity of assembly is managed through defining complexity, developing proper complexity measures, and considering both the complexity of products and their assembly systems in an integrated form. To achieve the research objective the following contributions has been made:

## 6.1 Research Contributions

### 6.1.1 Mathematical model of product assembly complexity

A mathematical model of product complexity was developed. The model considers the information content defined by the assembly attributes of individual parts, the diversity of information defined by the diversity of parts and fasteners, and the amount of information defined by the total number of parts and fasteners. A DFA-based product assembly complexity index has been developed to represent the information content of individual parts. The model calculates complexity indices of the assembled individual parts. The individual indices were then aggregated in the product assembly complexity model.

The developed product assembly complexity model is applicable to manual and automatic mechanical assembly of medium size products.

### 6.1.2 Mathematical model of assembly system complexity

- A manufacturing system structural classification code has been extended to classify and code the various equipment typically found in assembly systems. The code characterizes the complexity of the various types of assembly equipment within the system.
- A Code-based assembly system complexity model has been developed to measure the individual assembly equipment static complexity and the overall system static complexity as well.
- In addition to the information content captured by the generated complexity indices, the equipment number and diversity were considered to measure the total assembly system static complexity.

### 6.1.3 Mapping complexity of products and assembly systems

- A dependency matrix has been developed to represent the relationship between parts attributes and system functions. The dependency matrix has been used to predict the average complexity of equipment required for the assembly of a certain product.
- Regression analysis has been used to model the relationship between part complexity and assembly equipment complexity and predict the equipment complexity for new products or design variants.

## 6.2 Conclusions

- Integrating and aggregating individual complexities into an overall product or system complexity makes it easier to compare design alternatives.
- The products complexity of a three-pin electric power plug product family assembled manually were calculated and compared. The high similarity between the product family variants resulted in small differences between the total product assembly complexities of the four variants. Using snap fit fastening instead of screws reduced assembly complexity by 21.6 %. Not having to hold down parts

during assembly reduced the assembly complexity by 17.6 %. The symmetry of parts reduced the assembly complexity by 0.42%.

- The assembly of an automobile engine piston as a case study demonstrated the use of the proposed product complexity metric to measure the complexity of product automatic assembly.
- Guidelines such as reducing the number and diversity of parts, reducing number of fasteners, reducing part diversity, increasing symmetry of parts, avoiding flexible parts, avoiding nesting and tangling of parts,…etc., used to make assembly easier are also recommended to reduce product complexity.
- The results show that higher product complexity are proportional to longer assembly time calculated by DFA analysis in case of manual assembly
- The developed SCC structural classification code helped in measuring the static complexity of the various assembly system entities as well as the whole assembly system.
- The developed assembly system complexity model was demonstrated by measuring the static complexity of two alternate assembly systems. The complexity metric was able to identify the complexity of each class of equipment within the system and the total assembly system complexity as well. Reducing the complexity of material handling equipment by 6.71%, reducing the buffer equipment complexity by 55.98% and reducing diversity resulted in a reduction of the total assembly system complexity by 23.33%.
- A methodology has been developed to predict the average complexity of the required assembly equipment complexity in the early design stages before detailing the exact system structure. Knowledge and experience affect the selection of values in the dependency matrix. However the methodology is sound and reasonable for extension and refinement.
- The assembly equipment complexity increases as part complexity increases according to the developed nonlinear relationship between part complexity and equipment complexity.
- After detailing the assembly system and its equipment, the SCC code would help designers to investigate the impact of product complexity on system complexity.

Compare alternatives and configurations based on their complexity and select the least complex one.

- Analysis of four products and the corresponding assembly systems show an increase in system complexity as product complexity increases too.

## 6.3 Future work

- The developed product complexity metric is easy to apply for medium size products but it could be time consuming for products with large number of parts. This can be avoided in the future by automating the analysis process and linking the proposed model evaluation procedure with feature based CAD systems.
- Extending the product complexity model to consider the precedence order of the various assembly processes. One suggestion is to use features of liaison graph (nodes and arcs) to consider the structural connectivity between parts. Furthermore, selecting the optimal assembly sequence that lead to least complexity should be considered.
- Extending the scope of the research work to include other types of assembly such printed circuit board and welding processes. Parameters such as welding type, shape of joint, required heat and pressure, energy source could be considered as addition information of welding specific parameters and could affect the complexity of the process.
- Using the system complexity model together with data base of available prices of assembly equipment to translate complexity into cost
- Investigating the impact of complexity of both product and system on the performance of the assembly system (productivity, lead time, bottlenecks, ..) using simulation models.
- Considering the inherent complexity of multi-disciplinarity and coupling of design objects. This will help to track the impact of design changes not only on the total complexity but also on the complexity of other entities within the system.
- The values in the dependency matrix were subjectively chosen. Methods such as utility functions or fuzzy logic could be used to accurately estimate these values. Making use of agents maximizing/minimizing utility and the use of linguistic

variables and associative matrices would lead to better analysis and improve the [DM] matrix.

- Additional case studies can be analyzed in order to refine the assembly complexity mapping model.

## 6.4 Summary

Product complexity model, a static system complexity model, and a mapping model have been developed. The developed models can be used as decision support tools to manage sources of complexity and rationalize the design alternatives and select the least complex one that meets the requirements. This will help in reducing assembly cost and time, improving productivity and quality, and increasing profitability and competitiveness. Two methods of design for reduced complexity were considered; (1) mapping-based, (2) code-based as shown in Figure 6. 1. The mapping –based method uses assembly attributes of individual parts for a certain product to predict the complexity of the required assembly equipment before the exact system exists. Design changes can be made to reduce complexity at the early design stage. The code-based method is used to compare known design alternative and configuration based on their complexity and selecting the least complex one the meets the requirements. The two methods can be used together by designers to design for reduced complexity, making design changes, and avoid risky level of high complexity beyond which a system could fail.

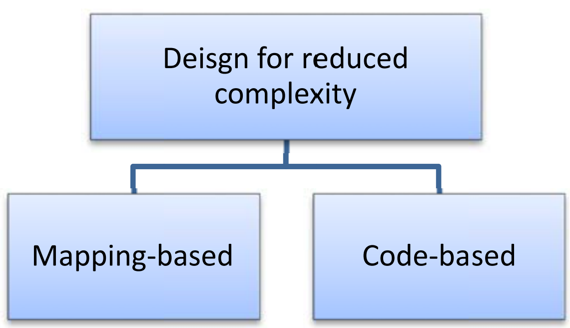



Figure 6. 1 Two methods of design for reduced complexity

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APPENDICES

# APPENDIX A

## HANDLING AND INSERTION ATTRIBUTES FOR SELECTED PRODUCTS

Appendix (A) presents the handling and insertion complexity attributes of individual parts of selected products: three-pin electric power plug (#2, #3, #4), car fan motor, and domestic appliance drive. Tables (A.1 – A.6) show the manual handling and insertion attributes for the three-pin electric power plugs.

Table A. 1 Parts handling complexity attributes matrix for electric power plug #2

| Part name | Handling complexity factor, $C_{h,f}$ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number | Symmetry | Size | Thickness | Weight | Grasping / manipulation | Assistance | Nesting / tangling | Optical magnification | J | SUM | $C_h$ | SUM* $C_h$ |
| **Base sub.** | 1 | 0.7 | 0.74 | 0.27 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 4.84 | 0.61 | 2.93 |
| **Fuse sub.** | 1 | 1 | 1 | 0.5 | 0.5 | 1 | 1 | 0.58 | 0.8 | 8 | 6.38 | 0.80 | 5.09 |
| **Pin 1** | 1 | 1 | 0.81 | 0.5 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 5.44 | 0.68 | 3.70 |
| **Fuse** | 1 | 0.7 | 1 | 1 | 0.5 | 1 | 1 | 0.58 | 0.8 | 8 | 6.58 | 0.82 | 5.41 |
| **Pin 2** | 1 | 1 | 0.81 | 0.5 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 5.44 | 0.68 | 3.70 |
| **Pin 3** | 1 | 1 | 0.81 | 0.5 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 5.44 | 0.68 | 3.70 |
| **Cover** | 1 | 0.7 | 0.74 | 0.27 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 4.84 | 0.61 | 2.93 |

Table A. 2Parts insertion complexity attributes matrix for electric power plug #2

| Part name | Insertion complexity factor, $C_{i,f}$ | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number | Holding down | Alignment | Insertion resistance | Accessibility | Fastening process | Non-mechanical | Non-fastening process | K | SUM | $C_i$ | SUM * $C_i$ |
| **Base sub.** | 1 | 0.54 | 0.86 | 0.87 | 0.57 | - | - | - | 4 | 2.84 | 0.71 | 2.02 |
| **Fuse sub.** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Pin 1** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Fuse** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Pin 2** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Pin 3** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Cover** | 1 | 0.54 | 1 | 0.87 | 0.57 | 0.42 | - | - | 5 | 3.4 | 0.68 | 2.31 |

Table A. 3 Parts handling complexity attributes matrix for electric power plug #3

| Part name | Number | Symmetry | Size | Thickness | Weight | Grasping / manipulation | Assistance | Nesting / tangling | Optical magnification | J | SUM | $C_h$ | SUM* $C_h$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Handling complexity factor, $C_{h,f}$ | | | | | | | | | | | | |
| **Base sub.** | 1 | 1 | 0.74 | 0.27 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 5.14 | 0.64 | 3.30 |
| **Fuse sub.** | 1 | 1 | 1 | 0.5 | 0.5 | 1 | 1 | 0.58 | 0.8 | 8 | 6.38 | 0.80 | 5.09 |
| **Pin 1** | 1 | 1 | 0.81 | 0.5 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 5.44 | 0.68 | 3.70 |
| **Fuse** | 1 | 0.7 | 1 | 1 | 0.5 | 1 | 1 | 0.58 | 0.8 | 8 | 6.58 | 0.82 | 5.41 |
| **Pin 2** | 1 | 1 | 0.81 | 0.5 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 5.44 | 0.68 | 3.70 |
| **Pin 3** | 1 | 1 | 0.81 | 0.5 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 5.44 | 0.68 | 3.70 |
| **Cover** | 1 | 1 | 0.74 | 0.27 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 5.14 | 0.64 | 3.30 |

Table A. 4 Parts insertion complexity attributes matrix for electric power plug #3

| Part name | Number | Holding down | Alignment | Insertion resistance | Accessibility | Fastening process | Non-mechanical | Non-fastening process | K | SUM | $C_i$ | SUM * $C_i$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Insertion complexity factor, $C_{i,f}$ | | | | | | | | | | | |
| **Base sub.** | 1 | 0.54 | 0.86 | 0.87 | 0.57 | - | - | - | 4 | 2.84 | 0.71 | 2.02 |
| **Fuse sub.** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Pin 1** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Fuse** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Pin 2** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Pin 3** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Cover** | 1 | 0.54 | 1 | 0.87 | 0.57 | 0.34 | - | - | 5 | 3.32 | 0.66 | 2.20 |

Table A. 5 Parts handling complexity attributes matrix for electric power plug #4

| Part name | Number | Symmetry | Size | Thickness | Weight | Grasping / manipulation | Assistance | Nesting / tangling | Optical magnification | J | SUM | $C_h$ | SUM* $C_h$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Handling complexity factor, $C_{h,f}$ | | | | | | | | | | | | |
| **Base sub.** | 1 | 0.7 | 0.74 | 0.27 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 4.84 | 0.61 | 2.93 |
| **Fuse sub.** | 1 | 1 | 1 | 0.5 | 0.5 | 1 | 1 | 0.58 | 0.8 | 8 | 6.38 | 0.80 | 5.09 |
| **Pin 1** | 1 | 1 | 0.81 | 0.5 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 5.44 | 0.68 | 3.70 |
| **Fuse** | 1 | 0.7 | 1 | 1 | 0.5 | 1 | 1 | 0.58 | 0.8 | 8 | 6.58 | 0.82 | 5.41 |
| **Pin 2** | 1 | 1 | 0.81 | 0.5 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 5.44 | 0.68 | 3.70 |
| **Pin 3** | 1 | 1 | 0.81 | 0.5 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 5.44 | 0.68 | 3.70 |
| **Cover** | 1 | 0.7 | 0.74 | 0.27 | 0.5 | 0.91 | 0.34 | 0.58 | 0.8 | 8 | 4.84 | 0.61 | 2.93 |

Table A. 6 Parts insertion complexity attributes matrix for electric power plug #4

| Part name | Insertion complexity factor, $C_{i,f}$ | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number | Holding down | Alignment | Insertion resistance | Accessibility | Fastening process | Non-mechanical | Non-fastening process | K | SUM | $C_i$ | SUM * $C_i$ |
| **Base sub.** | 1 | 0.54 | 0.86 | 0.87 | 0.57 | - | - | - | 4 | 2.84 | 0.71 | 2.02 |
| **Fuse sub.** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Pin 1** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Fuse** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Pin 2** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Pin 3** | 1 | 0.54 | 1 | 0.87 | 0.57 | - | - | - | 4 | 2.98 | 0.75 | 2.22 |
| **Cover** | 1 | 0.54 | 1 | 0.87 | 0.57 | 0.34 | - | - | 5 | 3.32 | 0.66 | 2.20 |

Tables (A.7 – A.8) present the automatic handling and insertion complexity attributes of individual parts of the car fan motor.

Table A. 7 Parts handling complexity attributes matrix for car fan motor

| Part name | Handling complexity factor, $C_{h,f}$ | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number | Symmetry | Size | Flexibility | Delicateness | Stickiness | Nesting / tangling | J | SUM | $C_h$ | SUM* $C_h$ |
| **Bearing plates** | 2 | 1 | 0.81 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.88 | 0.81 | 3.97 |
| **Cup bearings** | 2 | 0.45 | 1 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.52 | 0.75 | 3.41 |
| **Retaining plates** | 2 | 0.45 | 1 | 0.67 | 0.8 | 0.8 | 1 | 6 | 4.72 | 0.79 | 3.71 |
| **Magnets** | 2 | 0.66 | 0.74 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.47 | 0.75 | 3.33 |
| **Brushes** | 2 | 1 | 0.81 | 0.67 | 1 | 0.8 | 1 | 6 | 5.28 | 0.88 | 4.67 |
| **Retaining springs** | 1 | 1 | 0.81 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.88 | 0.81 | 3.97 |
| **Housing** | 1 | 0.66 | 0.74 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.47 | 0.75 | 3.33 |
| **Armature** | 1 | 0.66 | 0.74 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.47 | 0.75 | 3.33 |
| **Thrust washers** | 2 | 0.45 | 1 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.52 | 0.75 | 3.41 |

Table A. 8 Parts insertion complexity attributes matrix for car fan motor

| Part name | Insertion complexity factor, $C_{i,f}$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Number | Secure assembly | Insertion resistance | Alignment | Joining | Insertion direction | K | SUM | $C_i$ | SUM * $C_i$ |
| **Bearing plates** | 2 | 0.75 | 0.67 | 1 | 0.56 | 0.5 | 5 | 3.48 | 0.70 | 2.72 |
| **Cup bearings** | 2 | 1 | 0.67 | 1 | 0 | 0.5 | 4 | 3.17 | 0.79 | 2.51 |
| **Retaining plates** | 2 | 1 | 0.67 | 1 | 0 | 0.5 | 4 | 3.17 | 0.79 | 2.51 |
| **Magnets** | 2 | 1 | 0.67 | 1 | 0 | 0.5 | 4 | 3.17 | 0.79 | 2.51 |
| **Brushes** | 2 | 1 | 0.67 | 1 | 0 | 0.5 | 4 | 3.17 | 0.79 | 2.51 |
| **Retaining springs** | 1 | 0.75 | 0.67 | 1 | 0 | 0.5 | 4 | 2.92 | 0.73 | 2.13 |
| **Housing** | 1 | 1 | 0.67 | 1 | 0 | 0.5 | 4 | 3.17 | 0.79 | 2.51 |
| **Armature** | 1 | 1 | 0.67 | 1 | 0 | 0.5 | 4 | 3.17 | 0.79 | 2.51 |
| **Thrust washers** | 2 | 1 | 0.67 | 1 | 0 | 0.5 | 4 | 3.17 | 0.79 | 2.51 |

Tables (A.9 – A.10) present the automatic handling and insertion complexity attributes of individual parts of the domestic appliance drive.

Table A. 9 Parts handling complexity attributes matrix for domestic appliance drive

| Part name | Handling complexity factor, $C_{h,f}$ | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number | Symmetry | Size | Flexibility | Delicateness | Stickiness | Nesting / tangling | J | SUM | $C_h$ | SUM* $C_h$ |
| **Gear wheels** | 3 | 0.45 | 0.81 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.33 | 0.72 | 3.13 |
| **Cylindrical pins** | 3 | 0.45 | 1 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.52 | 0.75 | 3.41 |
| **Spring nut** | 1 | 0.66 | 1 | 0.67 | 0.8 | 0.8 | 1 | 6 | 4.93 | 0.82 | 4.10 |
| **Drive shaft** | 1 | 0.66 | 0.74 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.47 | 0.75 | 3.33 |
| **Drive** | 1 | 0.66 | 0.74 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.47 | 0.75 | 3.33 |
| **Stepped shaft** | 1 | 0.66 | 0.74 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.47 | 0.75 | 3.33 |
| **Fan wheel** | 1 | 0.66 | 0.74 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.47 | 0.75 | 3.33 |
| **Bearing** | 1 | 0.45 | 0.81 | 0.67 | 0.8 | 0.8 | 0.8 | 6 | 4.33 | 0.72 | 3.13 |
| **Trust washer** | 1 | 0.45 | 1 | 0.67 | 0.8 | 0.8 | 1 | 6 | 4.72 | 0.79 | 3.71 |

Table A. 10 Parts insertion complexity attributes matrix for domestic appliance drive

| **Part name** | **Insertion complexity factor, $C_{i,f}$** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Number** | **Secure assembly** | **Insertion resistance** | **Alignment** | **Joining** | **Insertion direction** | **K** | **SUM** | $C_i$ | **SUM** * $C_i$ |
| **Gear wheels** | 3 | 1 | 0.6 | 1 | 0 | 0.5 | 4 | 3.17 | 0.79 | 2.51 |
| **Cylindrical pins** | 3 | 0.75 | 1 | 1 | 0 | 0.5 | 4 | 3.25 | 0.81 | 2.64 |
| **Spring nut** | 1 | 0.75 | 0.67 | 1 | 0.5 | 0.5 | 5 | 3.42 | 0.68 | 2.34 |
| **Drive shaft** | 1 | 1 | 0.67 | 1 | 0 | 0.5 | 4 | 3.17 | 0.79 | 2.51 |
| **Drive** | 1 | 1 | 0.67 | 1 | 0 | 0.5 | 4 | 3.17 | 0.79 | 2.51 |
| **Stepped shaft** | 1 | 1 | 0.67 | 1 | 0 | 0.5 | 4 | 3.17 | 0.79 | 2.51 |
| **Fan wheel** | 1 | 1 | 0.67 | 1 | 0.5 | 0.5 | 5 | 3.67 | 0.73 | 2.69 |
| **Bearing** | 1 | 1 | 1 | 1 | 0 | 0.5 | 4 | 3.5 | 0.88 | 3.10 |
| **Trust washer** | 1 | 1 | 0.67 | 1 | 0 | 0.5 | 4 | 3.17 | 0.79 | 2.51 |

APPENDIX B

EQUIPMENT STRUCTURAL CLASSIFICATION CODE ANALYSIS FOR SELECTED ASSEMBLY SYSTEMS

Appendix (B) presents the structural classification code analysis of the selected assembly system: three-pin electric power plug and automobile engine piston. Tables (B.1 – B.9) show the main characteristics, normalized digit value, and complexity index of individual equipment of the three-pin electric power plug assembly system.

Table B. 1 SCARA robot, three-pin electric power plug assembly system

| # | Machine CC | Description | Digit value | Max. value | Normalized value | $I_M$ |
|---|---|---|---|---|---|---|
| 1 | Structure | Fixed | 1 | 3 | 0.333 | **0.460** |
| 2 | N Axes of motion | N | 4 | 6 | 0.667 | |
| 3 | N Work heads | N | 1 | 2 | 0.500 | |
| 4 | N spindles | N | 1 | 2 | 0.500 | |
| 5 | Tools | Changeable | 2 | 2 | 1.000 | |
| 6 | Tool magazine | None | 1 | 3 | 0.333 | |
| 7 | Pin fixtures | Fixed | 1 | 2 | 0.500 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Limited | 2 | 3 | 0.667 | |
| 11 | Structure | Fixed | 1 | 3 | 0.333 | |
| 12 | Mode | Programmable | 2 | 2 | 1.000 | |
| 13 | Difficulty | Medium | 2 | 3 | 0.667 | |
| 14 | Mode | Fully-automated | 3 | 3 | 1.000 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Auto | 2 | 2 | 1.000 | |

Table B. 2 Bowl feeder, three-pin electric power plug assembly system

| # | MHS CC | Description | Digit | Max. value | Normalized value | $I_{MHS}$ |
|---|---|---|---|---|---|---|
| 1 | Type | Feeder | 7 | 7 | 1 | **0.318** |
| 2 | Structure | Fixed | 1 | 2 | 0.5 | |
| 3 | Motion | Uni-dir, synch. | 1 | 4 | 0.25 | |
| 4 | Path | Fixed | 1 | 2 | 0.5 | |
| 5 | Parts holder | None | 1 | 4 | 0.25 | |
| 6 | Part types | Single | 1 | 2 | 0.5 | |
| 7 | Parts orientation | Passive | 1 | 2 | 0.5 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Open | 1 | 3 | 0.333 | |
| 11 | Structure | Fixed | 1 | 3 | 0.333 | |
| 12 | Mode | Programmable | 2 | 2 | 1.000 | |
| 13 | Difficulty | Low | 1 | 3 | 0.333 | |
| 14 | Mode | Semi- | 2 | 2 | 0.667 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Manual | 1 | 2 | 0.500 | |

Table B. 3 Stacked Bowl feeder, three-pin electric power plug assembly system

| # | MHS CC | Description | Digit | Max. value | Normalized value | $I_{MHS}$ |
|---|---|---|---|---|---|---|
| 1 | Type | Feeder | 7 | 7 | 1 | **0.438** |
| 2 | Structure | Fixed | 1 | 2 | 0.5 | |
| 3 | Motion | Uni-dir, synch. | 1 | 4 | 0.25 | |
| 4 | Path | Fixed | 1 | 2 | 0.5 | |
| 5 | Parts holder | None | 1 | 4 | 0.25 | |
| 6 | Part types | Multiple | 2 | 2 | 1 | |
| 7 | Parts orientation | Active | 2 | 2 | 1 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Open | 1 | 3 | 0.333 | |
| 11 | Structure | Fixed | 1 | 3 | 0.333 | |
| 12 | Mode | Programmable | 2 | 2 | 1.000 | |
| 13 | Difficulty | Medium | 2 | 3 | 0.667 | |
| 14 | Mode | Semi-automated | 2 | 2 | 0.667 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Automatic | 2 | 2 | 1.000 | |

Table B. 4 Vibratory bowl feeder with screw driver, three-pin electric power plug assembly system

| # | MHS CC | Description | Digit | Max. value | Normalized value | $I_{MHS}$ |
|---|---|---|---|---|---|---|
| 1 | Type | Feeder | 7 | 7 | 1 | **0.408** |
| 2 | Structure | Fixed | 1 | 2 | 0.5 | |
| 3 | Motion | Uni-dir, synch. | 1 | 4 | 0.25 | |
| 4 | Path | Fixed | 1 | 2 | 0.5 | |
| 5 | Parts holder | None | 1 | 4 | 0.25 | |
| 6 | Part types | Single | 1 | 2 | 0.5 | |
| 7 | Parts orientation | Passive | 1 | 2 | 0.500 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Limited | 1 | 3 | 0.333 | |
| 11 | Structure | Modular | 2 | 3 | 0.667 | |
| 12 | Mode | Programmable | 2 | 2 | 1.000 | |
| 13 | Difficulty | Low | 1 | 3 | 0.333 | |
| 14 | Mode | Semi- | 2 | 2 | 0.667 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Automatic | 2 | 2 | 1.000 | |

Table B. 5 Linear vib. feeder, three-pin electric power plug assembly system

| # | MHS CC | Description | Digit | Max. value | Normalized value | $I_{MHS}$ |
|---|---|---|---|---|---|---|
| 1 | Type | Feeder | 7 | 7 | 1 | **0.318** |
| 2 | Structure | Reconfigurable | 2 | 2 | 1 | |
| 3 | Motion | Uni-dir, synch. | 1 | 4 | 0.25 | |
| 4 | Path | Fixed | 1 | 2 | 0.5 | |
| 5 | Parts holder | None | 1 | 4 | 0.25 | |
| 6 | Part types | Single | 1 | 2 | 0.5 | |
| 7 | Parts orientation | Passive | 1 | 2 | 0.5 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Limited | 1 | 3 | 0.333 | |
| 11 | Structure | Fixed | 1 | 3 | 0.333 | |
| 12 | Mode | Programmable | 2 | 2 | 1.000 | |
| 13 | Difficulty | Low | 1 | 3 | 0.333 | |
| 14 | Mode | Semi-automated | 2 | 2 | 0.667 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Manual | 1 | 2 | 0.500 | |

Table B. 6 Index transfer, three-pin electric power plug assembly system

| # | Buffer CC | Description | Digit value | Max. value | Normalized value | $I_B$ |
|---|---|---|---|---|---|---|
| 1 | Type | Indexing tables | 2 | 4 | 0.500 | **0.421** |
| 2 | Part types | Single | 1 | 2 | 0.500 | |
| 3 | Access | FIFO | 1 | 3 | 0.333 | |
| 4 | Location | Separate | 2 | 3 | 0.667 | |
| 5 | Mode | Programmable | 2 | 2 | 1.000 | |
| 6 | Type | Non-adaptive | 1 | 2 | 0.500 | |
| 7 | Access | Limited | 2 | 3 | 0.667 | |
| 8 | Structure | Fixed | 1 | 3 | 0.333 | |
| 9 | Mode | Manual | 1 | 2 | 0.500 | |
| 10 | Difficulty | Medium | 2 | 3 | 0.667 | |
| 11 | Mode | Semi-automated | 2 | 3 | 0.667 | |
| 12 | Power | Powered | 2 | 2 | 1.000 | |
| 13 | Fault detection | Automatic | 2 | 2 | 1.000 | |

Table B. 7 Magazine, three-pin electric power plug assembly system

| # | Buffer CC | Description | Digit value | Max. value | Normalized value | $I_B$ |
|---|---|---|---|---|---|---|
| 1 | Type | Magazine | 1 | 4 | 0.250 | **0.182** |
| 2 | Part types | Single | 1 | 2 | 0.500 | |
| 3 | Access | FIFO | 1 | 3 | 0.333 | |
| 4 | Location | Separate | 2 | 3 | 0.667 | |
| 5 | Mode | Manual | 1 | 2 | 0.500 | |
| 6 | Type | Non-adaptive | 1 | 2 | 0.500 | |
| 7 | Access | Open | 1 | 3 | 0.333 | |
| 8 | Structure | Fixed | 1 | 3 | 0.333 | |
| 9 | Mode | Manual | 1 | 2 | 0.500 | |
| 10 | Difficulty | Low | 1 | 3 | 0.333 | |
| 11 | Mode | Manual | 1 | 3 | 0.333 | |
| 12 | Power | Un-Powered | 1 | 2 | 0.500 | |
| 13 | Fault detection | Manual | 1 | 2 | 0.500 | |

Table B. 8 Stacked Magazine, three-pin electric power plug assembly system

| # | Buffer CC | Description | Digit value | Max. value | Normalized value | $I_B$ |
|---|---|---|---|---|---|---|
| 1 | Type | Magazine | 1 | 4 | 0.250 | **0.247** |
| 2 | Part types | Multiple | 2 | 2 | 1.000 | |
| 3 | Access | LIFO | 2 | 3 | 0.667 | |
| 4 | Location | Separate | 2 | 3 | 0.667 | |
| 5 | Mode | Manual | 1 | 2 | 0.500 | |
| 6 | Type | Non-adaptive | 1 | 2 | 0.500 | |
| 7 | Access | Open | 1 | 3 | 0.333 | |
| 8 | Structure | Fixed | 1 | 3 | 0.333 | |
| 9 | Mode | Manual | 1 | 2 | 0.500 | |
| 10 | Difficulty | Low | 1 | 3 | 0.333 | |
| 11 | Mode | Manual | 1 | 3 | 0.333 | |
| 12 | Power | Un-Powered | 1 | 2 | 0.500 | |
| 13 | Fault detection | Manual | 1 | 2 | 0.500 | |

Table B. 9 Power-and-free conveyor, three-pin electric power plug assembly system

| # | MHS CC | Description | Digit value | Max. value | Normalized value | $I_{MHS}$ |
|---|---|---|---|---|---|---|
| 1 | Type | Conveyor | 1 | 7 | 0.143 | **0.403** |
| 2 | Structure | Fixed | 1 | 2 | 0.500 | |
| 3 | Motion | Uni-dir, asynch. | 2 | 4 | 0.500 | |
| 4 | Path | Variable | 2 | 2 | 1.000 | |
| 5 | Parts holder | Pallet | 2 | 4 | 0.500 | |
| 6 | Part types | Single | 1 | 2 | 0.500 | |
| 7 | Parts orientation | Passive | 1 | 2 | 0.500 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Limited | 2 | 3 | 0.667 | |
| 11 | Structure | Modular | 2 | 3 | 0.667 | |
| 12 | Mode | Programmable | 2 | 2 | 1.000 | |
| 13 | Difficulty | Medium | 2 | 3 | 0.667 | |
| 14 | Mode | Automated | 2 | 2 | 0.833 | |
| 15 | Power | Powered | 2 | 2 | 0.667 | |
| 16 | Fault detection | Manual | 1 | 2 | 0.500 | |

Tables (B.10 – B.21) show the main characteristics, normalized digit value, and complexity index of individual equipment of the engine piston assembly system.

Table B. 10 Press, automobile engine piston assembly system

| # | Machine CC | Description | Digit value | Max. value | Normalized value | $I_M$ |
|---|---|---|---|---|---|---|
| 1 | Structure | Fixed | 1 | 3 | 0.333 | 0.262 |
| 2 | N Axes of motion | N | 4 | 6 | 0.167 | |
| 3 | N Work heads | N | 1 | 2 | 0.500 | |
| 4 | N spindles | N | 1 | 2 | 0.500 | |
| 5 | Tools | Fixed | 1 | 2 | 0.500 | |
| 6 | Tool magazine | Fixed | 1 | 3 | 0.333 | |
| 7 | Pin fixtures | Fixed | 1 | 2 | 0.500 | |
| 8 | Mode | Programmable | 2 | 2 | 0.500 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Closed | 3 | 3 | 1.000 | |
| 11 | Structure | Fixed | 1 | 3 | 0.333 | |
| 12 | Mode | Manual | 1 | 2 | 0.500 | |
| 13 | Difficulty | Low | 1 | 3 | 0.333 | |
| 14 | Mode | Semi- | 2 | 3 | 0.667 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Manual | 1 | 2 | 0.500 | |

Table B. 11 Vibratory feede, automobile engine piston assembly system

| # | MHS CC | Description | Digit value | Max. value | Normalized value | $I_{MHS}$ |
|---|---|---|---|---|---|---|
| 1 | Type | Feeder | 7 | 7 | 1.000 | 0.547 |
| 2 | Structure | Fixed | 1 | 2 | 0.500 | |
| 3 | Motion | Uni-dir, asynch. | 2 | 4 | 0.500 | |
| 4 | Path | Fixed | 1 | 2 | 0.500 | |
| 5 | Parts holder | None | 1 | 4 | 0.250 | |
| 6 | Part types | Single | 1 | 2 | 0.500 | |
| 7 | Parts orientation | Active | 2 | 2 | 1.000 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Open | 3 | 3 | 1.000 | |
| 11 | Structure | Fixed | 1 | 3 | 0.333 | |
| 12 | Mode | Programmable | 2 | 2 | 1.000 | |
| 13 | Difficulty | Medium | 2 | 3 | 0.667 | |
| 14 | Mode | Automated | 2 | 2 | 1.000 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Automatic | 2 | 2 | 1.000 | |

Table B. 12 Conveyor belt, automobile engine piston assembly system

| # | MHS CC | Description | Digit value | Max. value | Normalized value | $I_{MHS}$ |
|---|---|---|---|---|---|---|
| 1 | Type | Conveyor | 1 | 7 | 0.143 | **0.396** |
| 2 | Structure | Fixed | 1 | 2 | 0.500 | |
| 3 | Motion | Uni-dir, asynch. | 1 | 4 | 0.250 | |
| 4 | Path | Fixed | 1 | 2 | 0.500 | |
| 5 | Parts holder | Pallet | 2 | 4 | 0.500 | |
| 6 | Part types | Multiple | 2 | 2 | 1.000 | |
| 7 | Parts orientation | Passive | 1 | 2 | 1.000 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Limited | 1 | 3 | 0.333 | |
| 11 | Structure | Fixed | 1 | 3 | 0.333 | |
| 12 | Mode | Programmable | 2 | 2 | 1.000 | |
| 13 | Difficulty | Medium | 2 | 3 | 0.667 | |
| 14 | Mode | Fully automated | 3 | 3 | 1.000 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Manual | 1 | 2 | 0.500 | |

Table B. 13 Magazine, automobile engine piston assembly system

| # | Buffer CC | Description | Digit value | Max. value | Normalized value | $I_B$ |
|---|---|---|---|---|---|---|
| 1 | Type | Magazine | 1 | 4 | 0.250 | **0.182** |
| 2 | Part types | Single | 1 | 2 | 0.500 | |
| 3 | Access | FIFO | 1 | 3 | 0.333 | |
| 4 | Location | With machine | 1 | 3 | 0.333 | |
| 5 | Mode | Manual | 1 | 2 | 0.500 | |
| 6 | Type | Non-adaptive | 1 | 2 | 0.500 | |
| 7 | Access | Open | 1 | 3 | 0.333 | |
| 8 | Structure | Fixed | 1 | 3 | 0.333 | |
| 9 | Mode | Manual | 1 | 2 | 0.500 | |
| 10 | Difficulty | Low | 1 | 3 | 0.333 | |
| 11 | Mode | Semi-automated | 2 | 3 | 0.667 | |
| 12 | Power | Un-Powered | 1 | 2 | 0.500 | |
| 13 | Fault detection | Manual | 1 | 2 | 0.500 | |

Table B. 14 Main indexing table, automobile engine piston assembly system

| # | Buffer CC | Description | Digit value | Max. value | Normalized value | $I_B$ |
|---|---|---|---|---|---|---|
| 1 | Type | Indexing | 2 | 4 | 0.500 | **0.530** |
| 2 | Part types | Single | 1 | 2 | 1.000 | |
| 3 | Access | FIFO | 1 | 3 | 0.333 | |
| 4 | Location | With machine | 1 | 3 | 1.000 | |
| 5 | Mode | Manual | 1 | 2 | 1.000 | |
| 6 | Type | Non-adaptive | 1 | 2 | 0.500 | |
| 7 | Access | Limited | 2 | 3 | 0.667 | |
| 8 | Structure | Fixed | 1 | 3 | 0.333 | |
| 9 | Mode | Manual | 1 | 2 | 0.500 | |
| 10 | Difficulty | Medium | 2 | 3 | 0.667 | |
| 11 | Mode | Fully auto. | 3 | 3 | 1.000 | |
| 12 | Power | Powered | 2 | 2 | 1.000 | |
| 13 | Fault detection | Automatic | 2 | 2 | 1.000 | |

Table B. 15 Small indexing table, automobile engine piston assembly system

| # | Buffer CC | Description | Digit value | Max. value | Normalized value | $I_B$ |
|---|---|---|---|---|---|---|
| 1 | Type | Indexing | 2 | 4 | 0.500 | **0.404** |
| 2 | Part types | Single | 1 | 2 | 0.500 | |
| 3 | Access | FIFO | 1 | 3 | 0.333 | |
| 4 | Location | Separate | 2 | 3 | 0.667 | |
| 5 | Mode | Programmable | 2 | 2 | 1.000 | |
| 6 | Type | Non-adaptive | 1 | 2 | 0.500 | |
| 7 | Access | Open | 1 | 3 | 0.333 | |
| 8 | Structure | Fixed | 1 | 3 | 0.333 | |
| 9 | Mode | Manual | 1 | 2 | 0.500 | |
| 10 | Difficulty | Low | 1 | 3 | 0.333 | |
| 11 | Mode | Fully-auto. | 3 | 3 | 1.000 | |
| 12 | Power | Powered | 2 | 2 | 1.000 | |
| 13 | Fault detection | Automatic | 2 | 2 | 1.000 | |

Table B. 16 Wave motion conveyor, automobile engine piston assembly system

| # | MHS CC | Description | Digit value | Max. value | Normalized value | $I_{MHS}$ |
|---|---|---|---|---|---|---|
| 1 | Type | Conveyor | 1 | 7 | 0.143 | **0.440** |
| 2 | Structure | Fixed | 1 | 2 | 0.500 | |
| 3 | Motion | Uni-dir, synch. | 1 | 4 | 0.250 | |
| 4 | Path | Fixed | 1 | 2 | 0.500 | |
| 5 | Parts holder | Fixture | 3 | 4 | 0.75 | |
| 6 | Part types | Multiple | 2 | 2 | 1.000 | |
| 7 | Parts orientation | Passive | 1 | 2 | 0.500 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Limited | 1 | 3 | 0.333 | |
| 11 | Structure | Fixed | 1 | 3 | 0.333 | |
| 12 | Mode | Programmable | 2 | 2 | 1.000 | |
| 13 | Difficulty | Medium | 2 | 3 | 0.667 | |
| 14 | Mode | Fully automated | 2 | 2 | 1.000 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Automatic | 2 | 2 | 1.000 | |

Table B. 17 Gantry robot with suction heads, automobile engine piston assembly system

| # | MHS CC | Description | Digit value | Max. value | Normalized value | $I_{MHS}$ |
|---|---|---|---|---|---|---|
| 1 | Type | Robot | 5 | 7 | 0.714 | **0.518** |
| 2 | Structure | Fixed | 1 | 2 | 0.500 | |
| 3 | Motion | Bi-dir, synch. | 3 | 4 | 0.750 | |
| 4 | Path | Fixed | 1 | 2 | 0.500 | |
| 5 | Parts holder | Gripper | 4 | 4 | 1.000 | |
| 6 | Part types | Single | 1 | 2 | 0.500 | |
| 7 | Parts orientation | Passive | 1 | 2 | 0.500 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Limited | 2 | 3 | 0.667 | |
| 11 | Structure | Fixed | 1 | 3 | 0.333 | |
| 12 | Mode | Programmable | 2 | 2 | 1.000 | |
| 13 | Difficulty | Medium | 2 | 3 | 0.667 | |
| 14 | Mode | Fully automated | 2 | 2 | 1.000 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Automatic | 2 | 2 | 1.000 | |

Table B. 18 Overhead asynchronized conveyor, automobile engine piston assembly system

| # | MHS CC | Description | Digit value | Max. value | Normalized value | $I_{MHS}$ |
|---|---|---|---|---|---|---|
| 1 | Type | Conveyor | 1 | 7 | 0.143 | **0.420** |
| 2 | Structure | Fixed | 1 | 2 | 0.500 | |
| 3 | Motion | Bi-dir, asynch. | 4 | 4 | 0.500 | |
| 4 | Path | Variable | 2 | 2 | 0.500 | |
| 5 | Parts holder | Fixture | 3 | 4 | 0.750 | |
| 6 | Part types | Multiple | 2 | 2 | 1.000 | |
| 7 | Parts orientation | Passive | 1 | 2 | 0.500 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Limited | 2 | 3 | 0.333 | |
| 11 | Structure | Fixed | 1 | 3 | 0.333 | |
| 12 | Mode | Programmable | 2 | 2 | 1.000 | |
| 13 | Difficulty | Medium | 2 | 3 | 0.667 | |
| 14 | Mode | Fully automated | 2 | 2 | 1.000 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Automatic | 2 | 2 | 0.500 | |

Table B. 19 Nut runner, automobile engine piston assembly system

| # | Machine CC | Description | Digit value | Max. value | Normalized value | $I_M$ |
|---|---|---|---|---|---|---|
| 1 | Structure | Fixed | 1 | 3 | 0.333 | **0.271** |
| 2 | N Axes of motion | N | 2 | 6 | 0.333 | |
| 3 | N Work heads | N | 1 | 2 | 0.500 | |
| 4 | N spindles | N | 1 | 2 | 0.500 | |
| 5 | Tools | Fixed | 1 | 2 | 0.500 | |
| 6 | Tool magazine | Fixed | 1 | 3 | 0.333 | |
| 7 | Pin fixtures | Fixed | 1 | 2 | 0.500 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Closed | 3 | 3 | 1.000 | |
| 11 | Structure | Fixed | 1 | 3 | 0.333 | |
| 12 | Mode | Manual | 1 | 2 | 0.500 | |
| 13 | Difficulty | Low | 1 | 3 | 0.333 | |
| 14 | Mode | Semi-automated | 2 | 3 | 0.667 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Manual | 1 | 2 | 0.500 | |

Table B. 20 Pick and place, automobile engine piston assembly system

| # | MHS CC | Description | Digit value | Max. value | Normalized value | $I_{MHS}$ |
|---|---|---|---|---|---|---|
| 1 | Type | Robot | 6 | 7 | 0.857 | **0.491** |
| 2 | Structure | Fixed | 1 | 2 | 0.500 | |
| 3 | Motion | Bi-dir, synch. | 3 | 4 | 0.750 | |
| 4 | Path | Fixed | 1 | 2 | 0.500 | |
| 5 | Parts holder | Gripper | 4 | 4 | 1.000 | |
| 6 | Part types | Multiple | 2 | 2 | 0.500 | |
| 7 | Parts orientation | Passive | 1 | 2 | 0.500 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Limited | 2 | 3 | 0.333 | |
| 11 | Structure | Fixed | 1 | 3 | 0.667 | |
| 12 | Mode | Programmable | 2 | 2 | 1.000 | |
| 13 | Difficulty | Medium | 2 | 3 | 0.667 | |
| 14 | Mode | Fully automated | 2 | 3 | 0.667 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Manual | 1 | 2 | 0.500 | |

Table B. 21 Handling robot, automobile engine piston assembly system

| # | MHS CC | Description | Digit value | Max. value | Normalized value | $I_{MHS}$ |
|---|---|---|---|---|---|---|
| 1 | Type | Robot | 6 | 7 | 0.857 | **0.657** |
| 2 | Structure | Fixed | 1 | 2 | 0.500 | |
| 3 | Motion | Bi-dir, asynch. | 4 | 4 | 1.000 | |
| 4 | Path | Variable | 2 | 2 | 1.000 | |
| 5 | Parts holder | Gripper | 4 | 4 | 1.000 | |
| 6 | Part types | Multiple | 2 | 2 | 1.000 | |
| 7 | Parts orientation | Passive | 1 | 2 | 0.500 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Adaptive | 2 | 2 | 1.000 | |
| 10 | Access | Limited | 2 | 3 | 0.667 | |
| 11 | Structure | Fixed | 1 | 3 | 0.333 | |
| 12 | Mode | Programmable | 2 | 2 | 1.000 | |
| 13 | Difficulty | Medium | 2 | 3 | 0.667 | |
| 14 | Mode | Fully automated | 3 | 3 | 1.000 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Automatic | 2 | 2 | 1.000 | |

Tables (B.22 – B.27) show the main characteristics, normalized digit value, and complexity index of individual equipment of the car fan motor assembly system.

Table B. 22 Peening unit, car fan motor assembly system

| # | Machine CC | Description | Digit value | Max. value | Normalized value | $I_M$ |
|---|---|---|---|---|---|---|
| 1 | Structure | Fixed | 1 | 3 | 0.667 | **0.481** |
| 2 | N Axes of motion | N | 2 | 6 | 0.333 | |
| 3 | N Work heads | N | 1 | 2 | 0.500 | |
| 4 | N spindles | N | 1 | 2 | 0.500 | |
| 5 | Tools | Fixed | 1 | 2 | 1.000 | |
| 6 | Tool magazine | Fixed | 2 | 3 | 0.667 | |
| 7 | Pin fixtures | Moving | 2 | 2 | 1.000 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Closed | 3 | 3 | 1.000 | |
| 11 | Structure | Fixed | 1 | 3 | 0.333 | |
| 12 | Mode | Manual | 1 | 2 | 0.500 | |
| 13 | Difficulty | Low | 1 | 3 | 0.333 | |
| 14 | Mode | Semi-automated | 2 | 3 | 0.667 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Manual | 1 | 2 | 1.000 | |

Table B. 23 Pneumatic press, car fan motor assembly system

| # | Machine CC | Description | Digit value | Max. value | Normalized value | $I_M$ |
|---|---|---|---|---|---|---|
| 1 | Structure | Modular | 2 | 3 | 0.667 | **0.417** |
| 2 | N Axes of motion | N | 1 | 6 | 0.167 | |
| 3 | N Work heads | N | 1 | 2 | 0.500 | |
| 4 | N spindles | N | 1 | 2 | 0.500 | |
| 5 | Tools | Fixed | 1 | 2 | 1.000 | |
| 6 | Tool magazine | Fixed | 2 | 3 | 0.667 | |
| 7 | Pin fixtures | Moving | 1 | 2 | 0.500 | |
| 8 | Mode | Programmable | 2 | 2 | 0.500 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Closed | 3 | 3 | 1.000 | |
| 11 | Structure | Fixed | 1 | 3 | 0.667 | |
| 12 | Mode | Manual | 1 | 2 | 0.500 | |
| 13 | Difficulty | Low | 1 | 3 | 0.333 | |
| 14 | Mode | Semi-automated | 2 | 3 | 0.667 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Manual | 1 | 2 | 1.000 | |

Table B. 24 Vibratory feeder, car fan motor assembly system

| # | MHS CC | Description | Digit value | Max. value | Normalized value | $I_{MHS}$ |
|---|---|---|---|---|---|---|
| 1 | Type | Feeder | 7 | 7 | 1.000 | **0.589** |
| 2 | Structure | Fixed | 1 | 2 | 0.500 | |
| 3 | Motion | Uni-dir, asynch. | 2 | 4 | 0.500 | |
| 4 | Path | Fixed | 1 | 2 | 0.500 | |
| 5 | Parts holder | None | 1 | 4 | 0.250 | |
| 6 | Part types | Single | 1 | 2 | 0.500 | |
| 7 | Parts orientation | Active | 2 | 2 | 1.000 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Open | 3 | 3 | 1.000 | |
| 11 | Structure | Modular | 2 | 3 | 0.667 | |
| 12 | Mode | Programmable | 2 | 2 | 1.000 | |
| 13 | Difficulty | Medium | 2 | 3 | 0.667 | |
| 14 | Mode | Automated | 2 | 2 | 1.000 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Automatic | 2 | 2 | 1.000 | |

Table B. 25 Pick and place, car fan motor assembly system

| # | MHS CC | Description | Digit value | Max. value | Normalized value | $I_{MHS}$ |
|---|---|---|---|---|---|---|
| 1 | Type | Feeder | 7 | 7 | 0.857 | 0.596 |
| 2 | Structure | Fixed | 1 | 2 | 0.500 | |
| 3 | Motion | Bi-dir, asynch. | 3 | 4 | 0.750 | |
| 4 | Path | Fixed | 1 | 2 | 0.500 | |
| 5 | Parts holder | None | 1 | 4 | 1.000 | |
| 6 | Part types | Single | 1 | 2 | 0.500 | |
| 7 | Parts orientation | Active | 2 | 2 | 1.000 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 1.000 | |
| 10 | Access | Open | 3 | 3 | 0.333 | |
| 11 | Structure | Modular | 2 | 3 | 0.667 | |
| 12 | Mode | Programmable | 2 | 2 | 1.000 | |
| 13 | Difficulty | Medium | 2 | 3 | 0.667 | |
| 14 | Mode | Automated | 2 | 3 | 0.667 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Automatic | 2 | 2 | 1.000 | |

Table B. 26 Conveyor belt, car fan motor assembly system

| # | MHS CC | Description | Digit value | Max. value | Normalized value | $I_{MHS}$ |
|---|---|---|---|---|---|---|
| 1 | Type | Feeder | 7 | 7 | 0.333 | 0.483 |
| 2 | Structure | Fixed | 1 | 2 | 0.500 | |
| 3 | Motion | Bi-dir, asynch. | 3 | 4 | 0.750 | |
| 4 | Path | Fixed | 1 | 2 | 0.500 | |
| 5 | Parts holder | Pallet | 2 | 4 | 0.500 | |
| 6 | Part types | Multiple | 2 | 2 | 1.000 | |
| 7 | Parts orientation | Passive | 1 | 2 | 0.500 | |
| 8 | Mode | Programmable | 2 | 2 | 1.000 | |
| 9 | Type | Non-Adaptive | 1 | 2 | 0.500 | |
| 10 | Access | Limited | 2 | 3 | 0.667 | |
| 11 | Structure | Fixed | 1 | 3 | 0.333 | |
| 12 | Mode | Programmable | 2 | 2 | 1.000 | |
| 13 | Difficulty | Medium | 2 | 3 | 0.667 | |
| 14 | Mode | Automated | 2 | 2 | 1.000 | |
| 15 | Power | Powered | 2 | 2 | 1.000 | |
| 16 | Fault detection | Automatic | 2 | 2 | 1.000 | |

Table B. 27 Magazine, car fan motor assembly system

| # | Buffer CC | Description | Digit value | Max. value | Normalized value | $I_B$ |
|---|---|---|---|---|---|---|
| 1 | Type | Magazine | 1 | 4 | 0.250 | 0.311 |
| 2 | Part types | Multiple | 2 | 2 | 1.000 | |
| 3 | Access | Random | 3 | 3 | 1.000 | |
| 4 | Location | Local machine | 2 | 3 | 0.667 | |
| 5 | Mode | Manual | 1 | 2 | 0.500 | |
| 6 | Type | Non-adaptive | 1 | 2 | 0.500 | |
| 7 | Access | Limited | 2 | 3 | 0.333 | |
| 8 | Structure | Fixed | 1 | 3 | 0.333 | |
| 9 | Mode | Manual | 1 | 2 | 0.500 | |
| 10 | Difficulty | Low | 1 | 3 | 0.333 | |
| 11 | Mode | Semi - auto. | 2 | 3 | 0.667 | |
| 12 | Power | Powered | 2 | 2 | 0.500 | |
| 13 | Fault detection | Automatic | 2 | 2 | 0.500 | |

# APPENDIX C

# HANDLING DESIGN FOR ASSEMBLY ANALYIS FOR THE THREE-PIN ELECTRIC POWER PLUG

Appendix (C) presents the manual DFA analysis of the three-pin electric power plug manual assembly as shown in Tables (C.1 – C.4).

Table C. 1 Manual DFA analysis of plug#1

| Part name | Handling code | Handling time | Insertion code | Insertion time | Total assembly time |
|---|---|---|---|---|---|
| **Base sub.** | 30 | 1.95 | 0.0 | 1.5 | 3.45 |
| **Fuse clip sub.** | 35 | 2.73 | 0.0 | 1.5 | 4.23 |
| **Pin 1** | 20 | 1.8 | 0.0 | 1.5 | 3.3 |
| **Fuse** | 0.0 | 1.13 | 31 | 5 | 6.13 |
| **Pin 2** | 20 | 1.8 | 0.0 | 1.5 | 3.3 |
| **Pin 3** | 20 | 1.8 | 0.0 | 1.5 | 3.3 |
| **Cover** | 30 | 1.95 | 0.6 | 5.5 | 7.45 |
| **Cover screw** | 10 | 1.5 | 38 | 6 | 7.5 |
| | | | | **Sum =** | **38.66** |

Table C. 2 Manual DFA analysis of plug#2

| Part name | Handling code | Handling time | Insertion code | Insertion time | Total assembly time |
|---|---|---|---|---|---|
| **Base sub.** | 10 | 1.13 | 0.0 | 1.5 | 2.63 |
| **Fuse clip sub.** | 35 | 2.73 | 0.0 | 1.5 | 4.23 |
| **Pin 1** | 20 | 1.8 | 0.0 | 1.5 | 3.3 |
| **Fuse** | 0.0 | 1.13 | 31 | 5 | 6.13 |
| **Pin 2** | 20 | 1.8 | 0.0 | 1.5 | 3.3 |
| **Pin 3** | 20 | 1.8 | 0.0 | 1.5 | 3.3 |
| **Cover** | 10 | 1.13 | 0.6 | 5.5 | 6.63 |
| **Cover screw** | 10 | 1.5 | 38 | 6 | 7.5 |
| | | | | **Sum =** | **37.02** |

Table C. 3 Manual DFA analysis of plug#3

| Part name | Handling code | Handling time | Insertion code | Insertion time | Total assembly time |
|---|---|---|---|---|---|
| **Base sub.** | 30 | 1.95 | 0.0 | 1.5 | 3.45 |
| **Fuse clip sub.** | 35 | 2.73 | 0.0 | 1.5 | 4.23 |
| **Pin 1** | 20 | 1.8 | 0.0 | 1.5 | 3.3 |
| **Fuse** | 0.0 | 1.13 | 31 | 5 | 6.13 |
| **Pin 2** | 20 | 1.8 | 0.0 | 1.5 | 3.3 |
| **Pin 3** | 20 | 1.8 | 0.0 | 1.5 | 3.3 |
| **Cover** | 30 | 1.95 | 0.6 | 5.5 | 7.45 |
| | | | | **Sum =** | **31.16** |

Table C. 4 Manual DFA analysis of plug#4

| Part name | Handling code | Handling time | Insertion code | Insertion time | Total assembly time |
|---|---|---|---|---|---|
| **Base sub.** | 10 | 1.13 | 0.0 | 1.5 | 2.63 |
| **Fuse clip sub.** | 35 | 2.73 | 0.0 | 1.5 | 4.23 |
| **Pin 1** | 20 | 1.8 | 0.0 | 1.5 | 3.3 |
| **Fuse** | 0.0 | 1.13 | 31 | 5 | 6.13 |
| **Pin 2** | 20 | 1.8 | 0.0 | 1.5 | 3.3 |
| **Pin 3** | 20 | 1.8 | 0.0 | 1.5 | 3.3 |
| **Cover** | 10 | 1.13 | 0.6 | 5.5 | 6.63 |
| | | | | **Sum =** | **29.52** |

APPENDIX D

STRUCTURAL CLASSIFICATION CODE (SCC) ANNOTATIONS

Appendix (D) presents the annotations of the various digits of the Structural Classification Code (SCC) as shown in Tables (D.1 – D.6).

Table D. 1 Machine Type CC Annotations

| Digit number | Description | Explanation |
|---|---|---|
| **1** | Fixed structure | Machine components cannot be changed or replaced |
| | Modular structure | Structure modular design allows the possibility of replacing some modules of the machine. |
| | Changeable structure | Both hard (add or remove some components of the machine structure) and soft (operation and control software) are changeable. |
| **2** | N Axes of motion | Axes of motion are all axes which are controlled and moved during the assembly process.<br>N is the total number of axes of motion - it ranges from 1 to 6. |
| **3** | N Work heads | A workhead performs the actual attachment of the component. Typical workheads include automatic screwdrivers, staking or riveting machines, welding heads, and other joining devices.<br>N is the total number of workheads. A robot has one workhead, other assembly machines could have more than one workhead. |
| **4** | N Spindles | Spindles are very specific to some machines; it rotates about a rotary axis and is independent from it in direction of the rotary axis (translation).<br>N is the total number of spindles. A robot is considered to have one spindle, other machines could have more than one spindle. |
| **5** | Fixed tools | Tools cannot be adjusted, changed or removed. |
| | Changeable tools | Tools can be modified, changed or adjusted. |
| **6** | No Tool magazine | Tool magazine is an arrangement of multiple tools that allows a machine to rapidly change from one operation to the next.<br>Some machines have no tool magazine. |
| | Fixed tool magazine | The magazine cannot be replaced or removed. |
| | Replaceable tool magazine | The magazine cannot be replaced or removed. |
| **7** | Fixed pin fixtures | A fixture that securely holds a part for a certain operation. The fixed fixture is part specific and cannot be changed or expanded. |
| | Moving pin fixtures | Moving fixtures is the opposite of fixed fixtures. |

Table D. 2 Handling Equipment CC Annotations

| Digit number | Description | Explanation |
|---|---|---|
| **1** | Conveyor | A conveyor is a horizontal, inclined, or vertical device for moving or transporting bulk material, packages, or objects in a path pre-determined by the design of the device, and having points of loading and unloading.<br>Many kinds of conveyors are available such as conveyor belts, chain conveyor, and roller conveyor. |
| | Monorail | A monorail is a single run of overhead track on which carriers (trolleys) travel |
| | Forklift trucks | A forklift truck is a material handling vehicle designed to move loads by means of steel fingers or forks inserted under a load. Also known as a lift truck. |
| | AGV | An automatic guided vehicle system (AGV) consists of one or more computer controlled, wheel-based load carriers that run on the plant floor without the need for a driver. AGVs have defined paths or areas within which they can navigate. |
| | Cranes and gantries | A crane is handling equipment used for lifting and lowering a load, and moving it horizontally.<br>A gantry crane is similar to an overhead crane except that the bridge for carrying the trolley is floor supported rather than overhead supported (wall-mounted). |
| | Robot | An industrial robot is used in positioning to provide variable programmed motions of loads. Industrial robots also used for parts fabrication, inspection and assembly tasks.<br>An industrial robot consists of a chain of several rigid links connected in series by revolute or prismatic joints with one end of the chain attached to a supporting base and the other end free and equipped with an end effector. The robot's end effector can be equipped with mechanical grippers, vacuum grippers, welding heads, paint spray heads or any other tooling. |
| | Feeder | A common feeder is the vibratory feeder. It is a device that uses vibration to feed small parts to a machine. Vibratory feeders use both vibration and gravity to move material. Gravity is used to determine the direction, either down, or down and to a side, and then vibration is used to move the parts.<br>A common vibratory feeder is bowl shaped. |
| **2** | Fixed structure | The structure the MHS equipment cannot be changed. |
| | Reconfigurable structure | The structure can be expanded (shortened) by adding (removing) components. |
| **3** | Uni-directional motion | Operating or moving or allowing movement in one direction only |
| | Bi- directional motion | Operating or moving or allowing movement in two usually opposite directions |
| | Synchronized motion | Make motion exactly simultaneous with the action. |
| | Asynchronized motion | Is the opposite of synchronized motion |

Table D.2 Handling Equipment CC Annotations (cont.)

| | | |
|---|---|---|
| **4** | Fixed path | Some equipment has defined paths which they can navigate. Fixed path guidance refers to a physical guide path (e.g., wire, tape, paint, rail) on the floor that is used for guidance. |
| | Variable path | Variable or Free-ranging guidance has no physical guide path (e.g., Optical-guided Laser-guided) |
| **5** | Parts holders | A device used to hold and secure parts. It could be a pallet, a fixture, or a gripper. |
| **6** | Part types | A single or multiple types of parts can be handled by the equipment. |
| **7** | Parts orientation | Passive orientation, e.g. gravity feeders, and active orientation feeders such as bowel feeders with specific orientation devices |

Table D. 3 Buffers Equipment CC Annotations

| Digit number | Description | Explanation |
|---|---|---|
| **1** | Indexing tables | Mechanical device by which the assembly part is transferred from work point to work point in the sequence of assembly operations. |
| | Magazine | With this type of equipment, parts are stacked into a container that constraints the parts in the desired orientation. Magazines can be subdivided into flat and chute magazines. |
| | Carousel | Equipment used to store items for eventual picking or retrieval. There are two types of carousels horizontal and vertical carousel. |
| | ASRS | Automatic storage & retrieval system (AS/RS) refers to a variety of means under computer control for automatically depositing and retrieving loads from defined storage locations. |
| **2** | Part Types | A single or multiple types of parts can be stored or retrieved. |
| **3** | FIFO Access | The way of organizing and manipulation of parts is First in, First out. |
| | LIFO Access | The way of organizing and manipulation of parts is First out, First in. |
| | Random Access | No specific order of organizing and manipulation of parts. |
| **4** | Location | A buffer could be integrated with machine, or next to machine, or could be a central buffer that serves more than one machine. |

Table D. 4 Controls CC Annotations

| Digit number | Description | Explanation |
|---|---|---|
| **1** | Mode | Assembly equipment can be controlled manually or automatically. |
| **2** | None-adaptive control | Also known as open loop control. It does not use feedback to determine if its output has achieved the desired goal of the input. |
| | Adaptive control | Also known as closed loop control. It feeds the output of the system back to the inputs of the controller |
| **3** | Access | The way that user interacts with controller. Three types exist: open, limited, closed access. |
| **4** | Fixed structure | No change is allowed in the control software |
| | Modular structure | Limited hooks are provided for replacing some modules of the controller. |
| | Reconfigurable structure | Total plug and play type of control system that allows adding or removing some components of the controller. |

Table D. 5 Programming CC Annotations

| Digit number | Description | Explanation |
|---|---|---|
| **1** | Mode | An assembly equipment can be manual or programmable. |
| **2** | Difficulty | The effort and time of programming by user. It ranges from low to high difficulty. |

Table D. 6 Operation CC Annotations

| Digit number | Description | Explanation |
|---|---|---|
| **1** | Mode | Is the level of automation of the operation. It can be manual, semi-automated, or fully automated operations. |
| **2** | Power | Some equipment require power to operate, some are operated manually. |
| **3** | Fault detection | Faults and errors can be detected manually by operator, or automatically by sensors. |

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