Complexity Analysis of Assembly Systems

SADAF AFREEN

NUST201362443MCEME35113F

Supervisor

DR. SAJID ULLAH BUTT

DEPARTMENT OF MECHANICAL ENGINEERING

COLLEGE OF ELECTRICAL & MECHANICAL ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY

ISLAMABAD

SEPT,2017

Complexity Analysis of Assembly Systems

SADAF AFREEN

NUST201362443MCEME35113F

A thesis submitted in partial fulfilment of the requirements for the degree of

MS Mechanical Engineering

Thesis Supervisor:

DR. SAJID ULLAH BUTT

Thesis Supervisor's Signature:____

DEPARTMENT OF MECHANICAL ENGINEERING

COLLEGE OF ELECTRICAL & MECHANICAL ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY,

ISLAMABAD

SEPT, 2017

Declaration

I certify that this research work titled "*Complexity analysis of assembly systems*" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

Signature of Student

SADAF AFREEN

NUST201362443MCEME35113F

Language Correctness Certificate

This thesis has been read by an English expert and is free of typing, syntax, semantic, grammatical and spelling mistakes. Thesis is also according to the format given by the university.

Signature of Student

SADAF AFREEN

NUST201362443MCEME35113F

Signature of Supervisor

Copyright Statement

Acknowledgements

I would like to express my gratitude to ALLAH SWT for all the benevolence and blessings throughout this work at every step that helped me complete my work with integrity. Indeed I could have done nothing without HIS priceless help and guidance. I would also like to thank all those people who helped and guided me throughout my thesis and made is possible.

I would also like to express special thanks to my supervisor, Assistant Professor Dr. Sajid Ullah Butt for his help throughout my thesis, He has been always available to supervise, help and guide me. In short, without his help and support I would not have completed my work.

I would also like to pay special thanks to Assistant Professor Dr. Aamer Ahmed Baqai for being an external member of my Guidance and Evaluation Committee (GEC) and for taking out time from his busy schedule. Hi guidance and cooperation made this thesis a successful work.

I would also like to express my special thanks to Assistant Professor Dr. Hasan Aftab Saeed for an inter member of my Guidance and Evaluation Committee (GEC) and for his time and availability in all the important meetings.

I would also like to thank entire honorable faculty and staff of Mechanical Department of College of E & ME for all the help, support and guidance they have given me for my work.

Finally, I would like to thank my beloved parents who raised me and supported me in every pursuit of my life. I want to thank them for their love and encouragement. I would also like to thank my fiancé for motivating me throughout my thesis.

Dedicated to my beloved parents, family, teachers and fiancé...

Abstract

In today's market there is a lot of competition. Companies have to respond to the quick market changes in order to keep going with the flow. There is rapid change in the market demand so, in order to cope up with this change the manufacturing and assembly systems of the companies should be so as to respond to these changes. In order to meet the changes manufacturers are making systems that are becoming more and more complex. Complexity is increased due to the addition of parts, replacing the parts or modules with better parts, adding more machines in the operation sequence and more operations, all these things add to the complexity of a system. Complexity leads to more cost, time and it decreases profitability and competitiveness. The objective of this thesis is to analyse the complexity of automatic welding assembly system by adding new information to machine classification codes and, using machine availability as an information content because, machine availability greatly affects the assembly process i.e. whether the machine is available for less period of time or more period of time affects the whole manufacturing and assembly system so graphs are used to analyse the effect of machine availability on machine complexity.

Keywords: *Complexity Analysis, Assembly Systems, Structural Complexity, Availability Complexity, Welding Assembly*

Contents

LIST OF SYMBOLS

a_M	Shaded area in the radar plot using normalized values of machine structural codes
A_M	Complete area of a radar plot for a machine
a_{MHS}	Shaded area in the radar plot using normalized values of material handling equipment structural codes
A_{MHS}	Complete area of a radar plot for a machine
a_B	Shaded area in the radar plot using normalized values of buffer structural codes
A_B	Complete area of a radar plot for a buffer
I_M	Complexity index of machines
I_{MHS}	Complexity index for material handling equipment
I_B	Complexity index of Buffers
n_{MHS}	Unique number of machines
n_M	Unique number of material handling equipment
n_B	Unique number of buffers
N_M	Total number of machines
N_{MHS}	Total number of material handling equipment
N_B	Total number of buffers
$\bar{I}_M$	Average complexity index of machines
$\bar{I}_{MHS}$	Average complexity index of material handling equipment

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

Introduction

Chapter 1

Introduction

For the existing and the upcoming manufacturing systems, complexity is a big challenge. Complexity cannot just be simplified and it cannot be fully eliminated in near future. For the top executives and managers managing complexity should be a core ability. Defining complexity meaning itself is hard. Many researchers have tried defining complexity in a universal way. But, such definition still does not exist. Complexity definition is related to its target. Cost of assembly manufacturing complexity and the quality of finished part has a big contribution in determining the design of a product in which design of assembly and most feasible manufacturing process are considered [2].

Studies have proved that in manufacturing setups there is a firm relation between the complexity that is measured and the loss in productivity. Study is made to quantify and measure complexity with the help of either heuristics methods or entropy/information content method. The main idea behind the definition of entropy/information method is when a model or framework has more information it is more complex. The information entropy/ method has a benefit which is, it creates single value showing the complexity quantity. Which is helpful in selection of a system among different based on single digit complexity value. But, to estimate probabilities, it's hard to achieve data needed in this methodology. This methodology has one more disadvantage which is there is no dependence between variables, and in actual systems that is not possible and its applicability is restricted due to this point [2].

To attain the best functional needs, complexity was expressed as a degree of uncertainty by the axiomatic design methodology. Sometimes in order to achieve the range of a system it is not easy to use the axiomatic methodology, because in decoupled designs it is done using many parameters of design. The methodology created by individual knowledge and experience is practiced by Heuristic methods. It is not hard to implement on actual systems, ease in collecting data, translate and finally make systems better. These methodologies are critiqued frequently because these are subjective, so the complexity of a system might not really be imitated by these methodologies. We can classify complexity into two types i.e. structural and functional complexity, structural is due to the information of the system and functional is due to the variety [2].

We can also define complexity of the manufacturing systems in an analytical way as a degree of how much a process could be complicated by product variety. Product variety has a very big and bad effect on worker's cost, productivity, assembly line idle time, repair and maintenance, and the levels of inventory. Complexity is presented using three different levels of the variety i.e. system process and product. Also, there are two different types of variety i.e. Dependent variety and independent variety. Variety in individual levels is an independent variety and dependent variety is the variety that comes up due to the variety added to other levels. Among these three dissimilar levels a mapping was presented in matrix form of these two different variety types in the levels of systems, processes and products [2].

1.1. Complexity in Assembly Systems

In production assembly is very vital part and it includes assemblies, Sub-assemblies and adding oils and other important things to the part. By calculating complexity of an assembly system, a system designer can design an assembly line with low complexity and in that way a better production line that has less interruptions and maintenance. It helps designers to choose between different processes, sequences, equipment and system layouts. Also by choosing a less complex system it becomes more economic because it is cost effective. It can be done by managing complexity and finding out where it is coming from [2].

Many researchers tried to analyse the assembly complexity. Design for Assembly (DFA) methodology was presented in [16] which relies on individual experiences and observations. This approach relies on random estimation and not on actual systems. The complexity of an assembly was measured in [17] with the help of estimating the time of an assembly task needs in order to complete it. A time complexity measure was presented by them as an information content linear function in order to measure the overall time of assembly. Complexity in terms of DFA methodology was also measured by Rodriguez-Toro et al. 2004, at two different levels i.e. complexity of an assembly and complexity of a component. Complexity of a Component focuses on complexity related to an individual component. We can then be divided it into complexity of manufacturing (geometric shape) and process complexity (handling and insertion). Assembly complexity is a major part of product complexity. We can also divide it into complexity of an assembly sequence and structural complexity (elements of configuration) and. For the product and assembly structure we must consider a complexity measure [2].

1.1. Types of Assembly Systems

In great nations where industry has a huge importance in their annual income assembly is very important. Because, assembly more specifically in heavy machinery is present in a lot of companies also in a lot of other companies where metal work is done assembly is a part of their production process. 50% of overall production time is covered by assembly tasks also 20% total cost is used in a part production (Figure 1.1). Generally, a big portion of workers are a part of the assembly operations which is about one-third. In the automobile industry, 50% cost of worker is covered by assembly; it shows a possible money that can be saved using better assembly technology and systems [4]. There are three types of assembly systems shown in Fig 1.2.

I. Manual Assembly
II. Automatic Assembly
III. Hybrid Assembly

1.1.1. Manual Assembly

Manual assembly process is used where the products are complex and have large number of parts i.e. electrical engineering and fine mechanics. Workers sit at a centralized location and perform their tasks with the help of different tools and their skills.

1.1.2. Automatic Assembly

For mass production, normally automated assembly systems are preferred. In an area of indexing tool machines, the difference is created among indexing rotary turn tables also straight-lined transferring machine tools. Main distinction among the main types of different workstations is the spacial organisation. Rotary indexing turn tables comes under the category of small distances for transport. The drawback of this type is limited amount of assembly setups due to inadequate space. A lot of assembly setups can be kept by rectilinear type transferring machines. Though, the attainable time of cycle depreciates as the distances amongst the distinct assembly setups increase. We can categorize indexing machines using firm line of assembly setups. How much a product to be attached is complex, determines the design of its construction. Electrical motor is used as a drive using an improved ratchet mechanism or lever gears and cam or could be executed by pneumatic or hydraulic power. Also, auxiliary movements are achieved using mechanical, electro-mechanic, or pneumatic power [4].

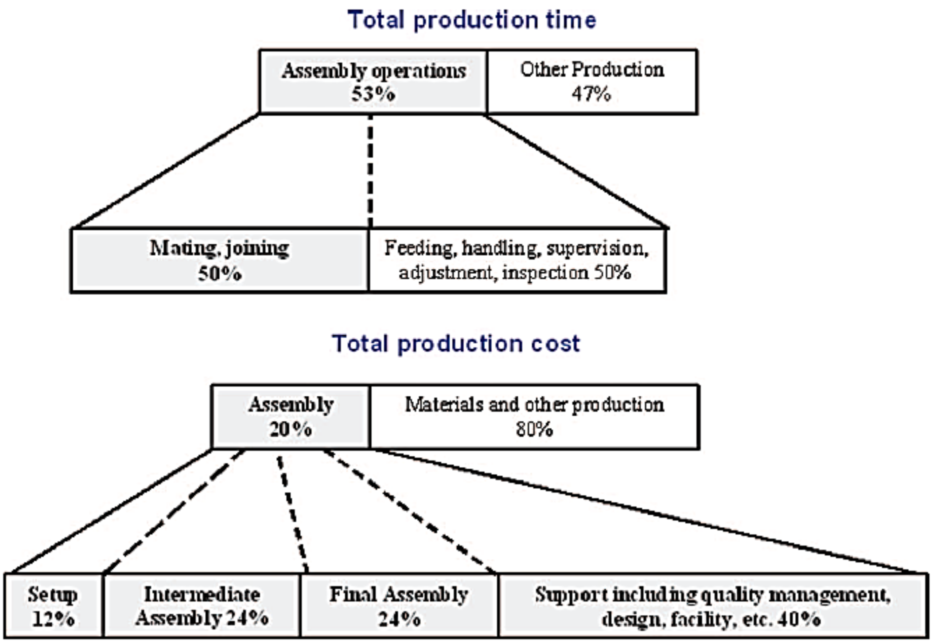

Figure: 1-1 Assembly according to the types of assemblers [4]

1.1.3. Hybrid Assembly

Hybrid assembly systems means automated and manual workstations combined. The cooperation among human workers and assembly equipment in these systems is encouraged using flexibility and changeability of the assembly procedures. Safety of the cooperation between human and machine should be managed. The efficiency of hybrid assembly systems is improved by serving workpieces to the supportive workplace [4].

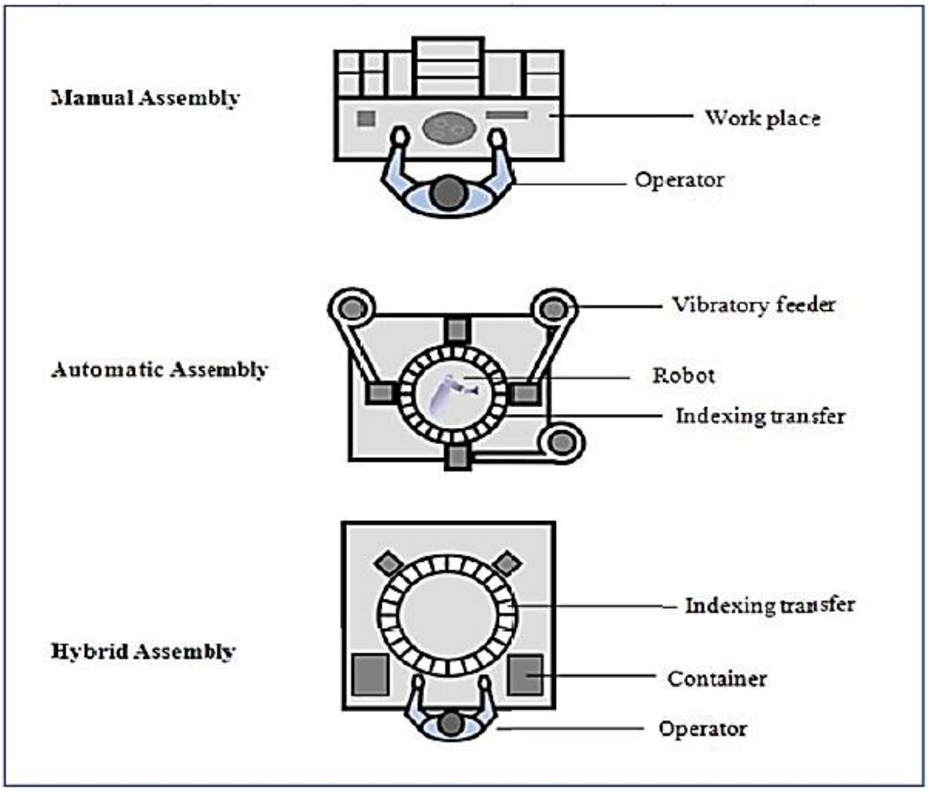

Figure: 1-2 Assembly time and cost contribution in production [4]

1.2. Methodology

In this thesis, a modified mathematical model for calculating complexity of an automatic welding system is presented by incorporating machine, material handling equipment and buffer availability into the existing model. Availability of machines greatly affects their complexity because how much the machine is available for assembly will affect the overall assembly process and time, it means the more machine is available lesser its complexity will be.

The existing model for complexity is designed for the temporary of removable assembly of products but it is not applicable to the other types of assembly processes such as welding, so this thesis focuses on making welding assembly complexity model by changing the machine SCC table by adding welding related parameters such as heat required, type of welding, pressure required etc. Some other generic parameters are also added to SCC tables which were not present before and which affect assembly complexity. After modifying the SCC tables for machine, MHS and buffers complexities of welding assembly plant have been calculated.

The next step is to modify the existing complexity model presented in [6] and to add availability based complexity model [5] in it to make hybrid model for measuring complexity and see the effect of availability on complexity. Using the hybrid model of complexity, complexity of a welding assembly plant has been calculated and results of both complexities are compared and clearly availability based complexity model shows more complexity because less machine availability leads to more complexity. This model can be used to compare the complexities of different assembly setups to see which one is compatible for the company.

1.3. Thesis Outline

This Thesis comprises of five chapters. Chapter two covers the details of types of complexity analysis in assembly systems and chapter three explains the methodology used to calculate the complexity of a welding assembly plant using hybrid complexity model. Chapter four covers the case study done to check the results of proposed methodology using an example welding assembly model, finally chapter 5 explains all the results, conclusions and future work of the presented work.

Chapter 2

Literature Review

Chapter 2

Literature Review

As explained in the previous chapter complexity is the core problems of manufacturing and assembly systems. And it needs to be taken care of for the assembly processes to go smoothly. For that purpose, different researchers have presented their own methodologies to measure and manage complexity to increase productivity and reduce assembly time. In this chapter, some of the complexity measures are discussed that help managing complexity of the assembly systems.

2.1. Complexity Measure

There is no complexity between completely ordered system as there are limited and simple relationships between parts, on the other hand completely disordered system also does not have any complexity because there is no relationship between parts. So, complexity lies in between an ordered and disordered system. Design structures of different manufacturing systems can be compared by measuring their complexity. Dividing the complexity into two types can make its measure easier. One can be used to calculate system configuration and another for calculating the uncertainty of a system. Complexity was measured structural as a systems structure and dynamic as uncertainties of machine breakdowns [18]. According to [19] "the complexity of a system should be proportional to the amount of information required to describe the system." And he measured complexity as the total information in the system and the variety in that information. Variety was presented in [19] as the uniqueness or distinction between the equipment parameters which were "Similar". As similarity becomes high, variety is reduced, so complexity also reduces. The two measures of complexity presented in [1] are:

2.1.1. Product Structure Complexity Measure

There are four different types of elements of the structure of a product that causes complexity. These elements are, the amount of commonality of a part, the amount of levels in the structure of a product, the number of manufactured products in the finished products' BOM (bill of materials) and the amount of end items [1].

2.1.2. Routing Complexity Measure

This measure consists of distinct parts. That are, the amount of routing steps, the number of manufactured products in the finished products' BOM (bill of materials), and the number of finished products.

This measure can be extended by calculating routing commonality. Furthermore, other elements of structure of a system, for example its layout, contributes to the complexity due to structure. This measure can be improved by adding effective computable measures related to commonality and multiplicity [1].

2.2. Complexity and Product Variety

The change in the market demand leads to the various changes in the product and system structure that must be made to cope up with those changes so manufacturing systems are changing day by day to respond to these changes. These changes adds to the variety in system and product structure. By increasing variety manufacturing systems can meet the demands of the customer, but it can also be a big cause in increasing complexity of assembly.

Manufacturing systems face challenges due to complexity and it is believed as a big cause of problems such as expensive and long processes of design, very high cost of life cycles also presence of a lot of modes of failure. It is very expensive to run, maintain, execute and control the Complex systems of assembly. Less complex assembly systems can be implemented by designers by assessing complexity at first place. Also, decreasing complexity of assembly aids in decreasing time and cost of assembly, and increases profitability, quality of product, productivity and competitiveness.

In order to assess and manage the complexity, products and their respective systems of assembly should be considered together. The in-built static complexity of usual equipment of assembly is considered. So, the resultant complexity of assembly systems uses the information content, diversity and the number and in individual types of equipment for the system of assembly [15].

The total complexity is the summation of nine variety-based complexities given by eq. 2.1

$$C_{total} = \sum_{i=1}^{M}\sum_{j=1}^{N} C_{Product} + \sum_{i=1}^{K}\sum_{j=1}^{L} C_{Process} + \sum_{i=1}^{U}\sum_{j=1}^{V} C_{System} \tag{2.1}$$

		Dependent Variety											
		Product				Process				System			
Independent Variety		V_1	V_2	V_3	V_M	V_1	V_2	V_3	V_K	V_1	V_2	V_3	V_U
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: 2-1 Matrix representation of dependent and independent varieties and their relationships at various levels [15]

2.3. Types of complexity

Information Content is utilized by the Axiomatic Design approach as a complexity measure that is expressed as the degree of uncertainty in attaining the desired practical needs. An approach was presented in [18] in which complexity is measured with the help of entropy in the operational and structural fields of manufacturing systems.

Complexity has two major types' i.e. static complexity and dynamic complexity. The static complexity does not depend on time and it is present in a system or product due to its configuration or structure. And dynamic complexity depends on time or it changes with time and arises due to sequence of operations or machine breakdowns of the manufacturing system.

We can decrease static complexity by simplifying the structure of a product or processes being carried out as presented in [18] also the complexity of a design process due to its structure and function [17]. With the help of calculating design size and design effort an idea of operand and operators was presented to define the structural complexity and the design. In order to calculate the complexity on the functional levels the information content method was used.

The distinct quantity of the operands and operators were used in [17] to calculate the size of design and the also calculated diversity of information and size that uses work of design in order to measure mental work for reducing issues related to effort and design, and has inverse relation with information content. The two types of complexity are:

2.3.1. Static complexity

The static complexity is linked with the system structure and relationships among the elements of the structure and the variety of components and strength of their relations.

2.3.2. Dynamic complexity

This type of complexity normally is linked to the operational behaviour and system's unpredictable behaviour in a certain period of the time.

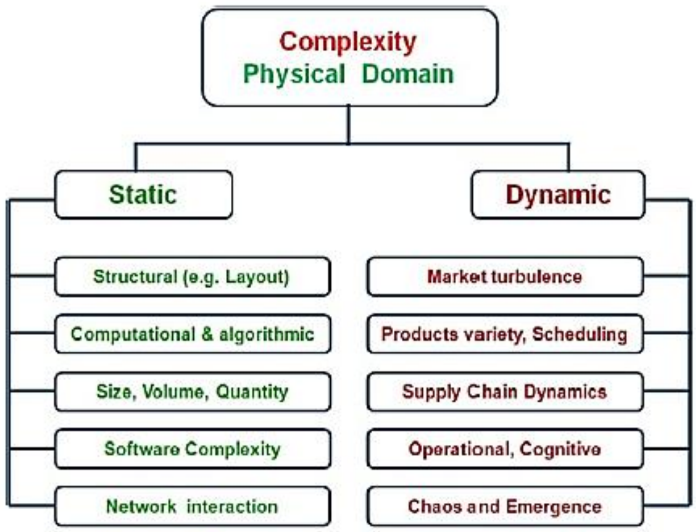

Figure: 2-2 Difference between static and dynamic complexity [4]

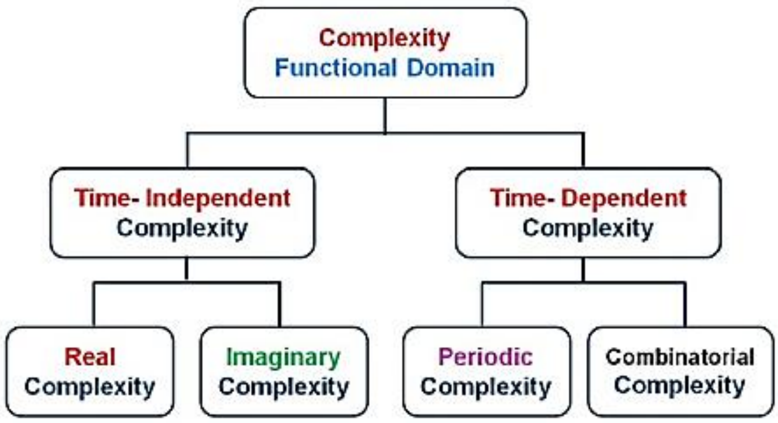

Figure: 2-3 Different types of complexity in the functional domain [4]

2.4. Information theory/uncertainty/entropy

Different methods are there that are used to find the measures of complexity and complexity of the system. The Shannon Information Theory presents one of the method. In which the information is utilized as a degree of uncertainty. The axiom 2 of the Axiomatic Design Theory defines the Information Content as a complexity measure and it is utilized by the other method. Complexity due to Uncertainty increases due to the upcoming procedures and it could just be calculated using probabilities. It is usually calculated with the help of probability theory and Shannon's entropy formalizes it. As an event x occurs having a less probability P(x) ($0 \leq P(x) \leq 1$), It will have more impact than the other events which have large probability [4].

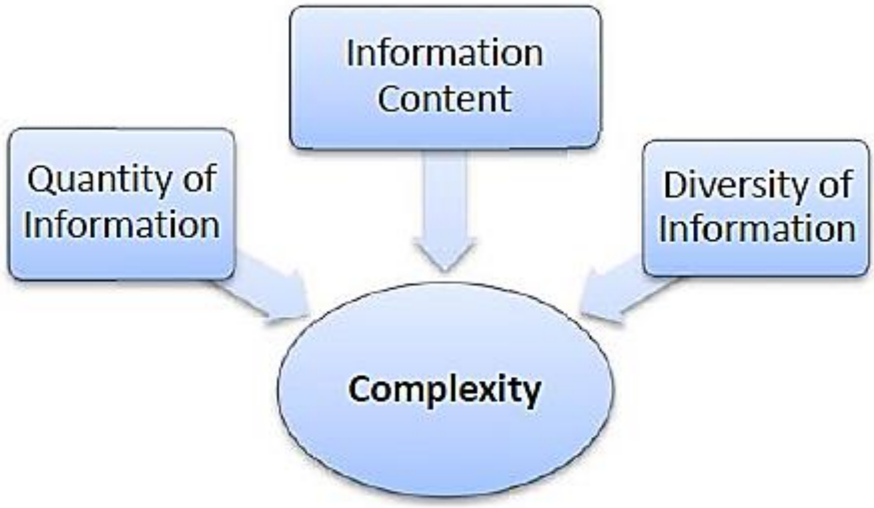

Figure: 2-4 Basic components of complexity [4]

2.5. A MANUFACTURING SYSTEMS COMPLEXITY CODE

A new coding system is made to measure and categorize the complexity that does not depend on time that is related to the main parts for the manufacturing setups. This can help in the comparison of the early design substitutes of the systems, alternatives for re-designing or suggestions for volume functionality variations and situations of reconfiguration. The type of configurations which fulfil the needed abilities are presented by system designers are the variable assets (people) and the fixed assets (equipment types, programs, control schemes and capabilities), also the amount of these assets that fulfil rate and scope of production. Their design is highlighted in the system also the relationship among them.

With changing values of complexity and costs related to them several substitutes are there. So, the expected complexity measure of the system could be used for making decisions and drawing comparisons. The following main components are a part of manufacturing system i.e. Machines that perform different manufacturing processes, Buffers used as decouplers, to make sure that there is enough supply of parts for smooth production, Material handling equipment for shifting parts among machines and the operators to accompany operations of system and machine also supervisory work.

The type of system parts and quantity of can have a great variation that is needed to attain certain objectives with the help of these resources. The part of complexity code used for manufacturing systems is presented that shows the information needed to explain the different equipment types. In order to signify the numbers in an individual class are used these are 1) Type and general structure configuration, 2) Controls of the equipment, 3) Programming type, and 4) Operation type. The overall quantity of information is increased by the amount and distinction of these parameters. [5]

For design of monitoring forms and storage of material and recovery, “coding and classification were initially used. Though, by the growth of group technology and figures of work, this practice of classification and coding has spread into the control, production planning and the parts choice for machining in groups. Similarly, due to the development in the application area of the computers, the usage of classification and coding exclusively for the retrieval of information and information storage is extended.

Classification and Coding is an approach of establishing knowledge with the help of analysing and categorizing the needed information and making the groups of same elements, facts and features. Coding means to assign an entity using a symbol. These symbols alphabetic, numeric or could be made combining both. These symbols show those attributes of the parts that we can use later to make the families of parts or similarity analysis or for improving CNC programmes and process plans. The coding process is preceded by classifying all the important attributes. Which the help of these classifications the part can be categorized in part families. These coding and classification systems were created for the parts that were manufactured.

Before the development of the SCC system by H. ElMaraghy, identical there were no coding and classification systems present for manufacturing systems. All digits in the created SCC code that is a chain type poly-code have distinct meaning. Every class and category comprises of a digit string which shows the degree of complexity which is related to all those entities such as controls structure etc. We can also compare this digit string with the DNA biological code. All these values of string digits show the amount or degree of complexity and the amount of variety present in the control, programs, structure and operations. Complexity of the feature increases by increasing its value. All these digit values that are used to represent the complexity of a feature totally depend on the individual’s personal experiences and knowledge of the machine and related systems. By using these codes many manufacturing systems can be compared to choose which one suits the company’s needs better [6].

2.6. Structural classification code for assembly systems

To add the structural features related to assembly of usual equipment which is used in the assembly of the products, the existing SCC of the equipment is modified. The digits present in the existing code are modified and re grouped together. But, the layout classification scheme stays unaltered. The modified SCC classification code comprises of different digits for describing different equipment for example seven-digit number for the types of machine and MHS and for buffers four digits are used. And for the rest of the equipment i.e. operation, programming and control nine digits are used additionally. So, 16 is the maximum number of the digits that are being used here [6]. The various digits are described in Table 2.1, 2.2 and 2.3

Table 2-1 Machine Classification code [6]

No.	Machine CC	Description	Value	Max. 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
No.	Controls CC	Description	Value	Max. 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
No.	Programming CC	Description	Value	Max. 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
No.	Operation CC	Description	Value	Max. 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 2-2 Handling equipment classification code [6]

No.	MHS CC	Description	Value	Max. Value	Normalized Value
1	Type	Conveyer	1	7	1/7
		Monorail	2		2/7
		Fork lift truck	3		3/7
		AGV	4		4/7
		Cranes and gantries	5		5/7
		Robots	6		6/7
		Feeders	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	Part Holder	None	1	4	1/4
		Pallet	2		2/4
		Fixture	3		3/4
		Gripper	4		4/4
6	Part Types	Single	1	2	1/2
		Multiple	2		2/2
7	Part Orientation	Passive	1	2	1/2
		Active	2		2/2
No.	Controls CC	Description	Value	Max. 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
No.	Programming CC	Description	Value	Max. 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
No.	Operation CC	Description	Value	Max. 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 2-3 Buffer classification code [6]

No.	Buffer CC	Description	Value	Max. 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 Type	Single	1	2	1/2
		Multiple	2		2/2
3	Access	FIFO	1	3	1/3
		LIFO	2		2/3
		Random	3		3/3
4	Location	With Machine	1	3	1/3
		Separate	2		2/3
		central	3		3/3
No.	Controls CC	Description	Value	Max. 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
No.	Programming CC	Description	Value	Max. Value	Normalized Value
9	Mode	Manual	1	2	1/2
		Programmable	2		2/2
10	Difficulty	Low	1	3	1/3
		Medium	2		2/3
		High	3		3/3
No.	Operation CC	Description	Value	Max. 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

2.7. Assembly system components complexity index

From the digit codes that are calculated before by assigning different values to different attributes of an equipment a complexity index is calculated. Complexity index is calculated by first of all finding the value of a_M which is the area plotted on a radar plot and it shows the total complexity a system has the complexity index in calculated by putting all the digit values in the equations of a_M and then dividing this by total area A_M. The equations for machines and material handling equations are similar because the total number of codes is same i.e. 16 and the buffer one's is different because its complexity codes are different in number than the others. Fig 2.5 shows the example radar plot which is plotted using the values of complexity of an equipment in excel. The area a_M being the combination of small triangles that join together to represent the whole are which is the complexity of a system given by eqs. 2.2, 2.3 and 2.4 [6].

$$a_M = \frac{1}{2}\left[\sum_{i=1}^{i=15}(Ci \times Ci + 1) + (C_1 \times C_{16})\right]Sin(\frac{360}{16}) \quad (2.2)$$

$$a_{MHS} = \frac{1}{2}\left[\sum_{i=1}^{i=15}(Ci \times Ci + 1) + (C_1 \times C_{16})\right]Sin(\frac{360}{16}) \quad (2.3)$$

$$a_B = \frac{1}{2}\left[\sum_{i=1}^{i=12}(Ci \times Ci+1) + (C_1 \times C_{13})\right]Sin\left(\frac{360}{13}\right) \quad (2.4)$$

a_M, a_{MHS} and a_B represent the shaded are in the radar plot for machines, material handling and buffer equipment and C_i shows the normalized values of the complexity code of an equipment. The total areas of the radar plot for machines, material handling and buffer equipment are given by eqs. 2.5, 2.6 and 2.7.

$$A_M = \left(\frac{16}{2}\right)Sin\left(\frac{360}{16}\right) \quad (2.5)$$

$$A_{MHS} = \left(\frac{16}{2}\right)Sin\left(\frac{360}{16}\right) \quad (2.6)$$

$$A_B = \left(\frac{13}{2}\right)Sin\left(\frac{360}{13}\right) \quad (2.7)$$

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

Complexity index of all the equipment is then calculated by dividing the small area with the overall area of the radar plot given by eqs. 2.8, 2.9 and 2.10.

$$I_M = \frac{a_M}{A_M} \quad (2.8)$$

$$I_{MHS} = \frac{a_{MHS}}{A_{MHS}} \quad (2.9)$$

$$I_B = \frac{a_B}{A_B} \quad (2.10)$$

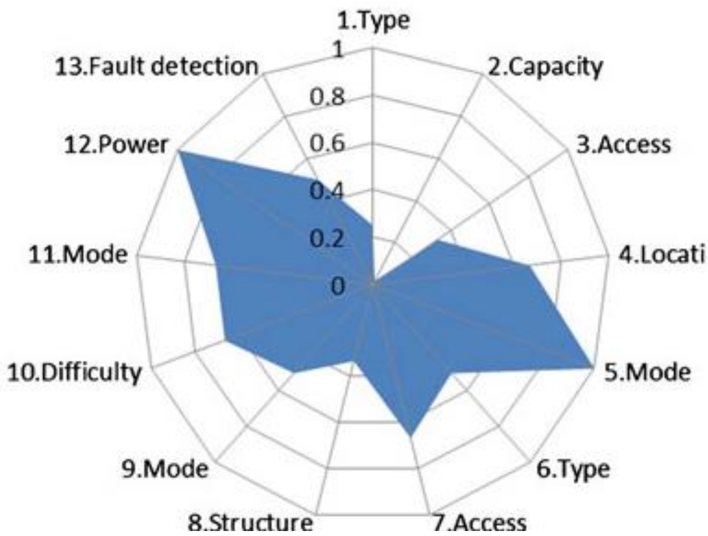

Figure: 2-5 Radar Plot for buffer equipment [6]

2.8. Equipment complexity

The information content is defined previously and in addition to three indices of complexity that are calculated previously the diversity ratio n/N and the quantity of an information of the equipment $\log_2(N_i + 1)$ is added to the equation and the complexity of that equipment is calculated using the equations 2.11, 2.12 and 2.13.

$$C_M = \left[\frac{n_M}{N_M} + \bar{I}_M\right][log_2(N_M + 1)] \quad (2.11)$$

$$C_{MHS} = \left[\frac{n_{MHS}}{N_{MHS}} + \bar{I}_{MHS}\right][log_2(N_{MHS} + 1)] \quad (2.12)$$

$$C_B = \left[\frac{n_B}{N_B} + \bar{I}_B\right][log_2(N_B + 1)] \quad (2.13)$$

In the equations above the n represents the unique number of equipment and N represents the total number of equipment where I_m I_{MHS} and I_B are the complexity index for machines material handling equipment and buffer equipment also (n_M/N_M), (n_{MHS}/N_{MHS}) and (n_B/N_B) show the uniqueness in information for machines, material handling equipment and buffer equipment, respectively. The terms $\log_2(N_M+1)$, $\log_2(N_{MHS}+1)$ and $\log_2(N_B+1)$ show the total quantity of information the machines, MHS and the buffers have [6].

2.9. System complexity model

The overall system's complexity is calculated by adding all the complexities of the equipment and giving them some weighted factors according to their importance. The total system's complexity is given by eq. 2.14.

$$C_{SYS} = w_1 C_M + w_2 C_{MHS} + w_3 C_B \quad (2.14)$$

C_{system} is the complexity of an assembly system and C_M, C_{MHS}, C_B are the complexities of machine, material handling and buffer equipment. Also, w_1, w_2, w_3 represent the weights or the importance of each equipment one can give more importance to specific equipment depending upon their requirements but for simplification all of these are assumed to be 1 here [6].

2.10. Complexity based on availability

The demand of market is changing day by day and it's getting hard for the companies to quickly respond to those abrupt changes. The designers of the manufacturing systems these days are trying to design such systems which can quickly respond to the market changes. But, in order to respond to those changes the machine should be readily available for production all the time so that the production goes in a smooth way but sometimes this is not the case.

Routine maintenance and sometimes breakdowns and failures in the machines cause huge disturbance in the production process and the production delay cost the company a lot of money because company will not be able to respond or fulfil the demands of the market if the machines are not working properly. This leads to complexity in manufacturing so in order to manage this complexity a company should make sure that the machines are available all the time during the production process. So, more availability of the machine leads to lower complexity as production process runs smoothly.

There are several modules in the manufacturing and assembly process, these modules can be available for sometimes out of total hours weeks or days. These modules will have a probability which will be presented by p= n/m. Also, the information content is given by, $\log_2$ (l/p) = - $\log_2$ (p). The availability of these modules is assumed to be fixed for simplification at the start of this analysis.

The analysis is applied on machines, MHS and buffers with the help of an equation 2.15.

$$I = log_2 \frac{1}{P} \qquad (2.15)$$

P= Availability

Table 2-4 Machine availability based on number of distinct parts [5]

Machines	Number of Distinct Components	Availability
M1	10	0.349
M2	21	0.109
M3	12	0.282
M4	26	0.065
M5	11	0.569

The table 2.4 shows that by increasing the number of unique parts the availability of an equipment increases. The cylinder block is used as a study by considering three different scenarios to make it that is CNC machine, broach and dedicated machine. All the machines are given the value of availability as 0.9 the total complexity of a system is calculated by adding all the complexities of equipment.
According to the results it's been shown that the CNC machine has the lowest value of complexity because its configuration is parallel and the dedicated machine has the highest value of complexity because its configuration is serial but the complexity of MHS in CNC is higher compared to others as it has more MHS and they are distinct. The results are shown in the Fig 2.5.

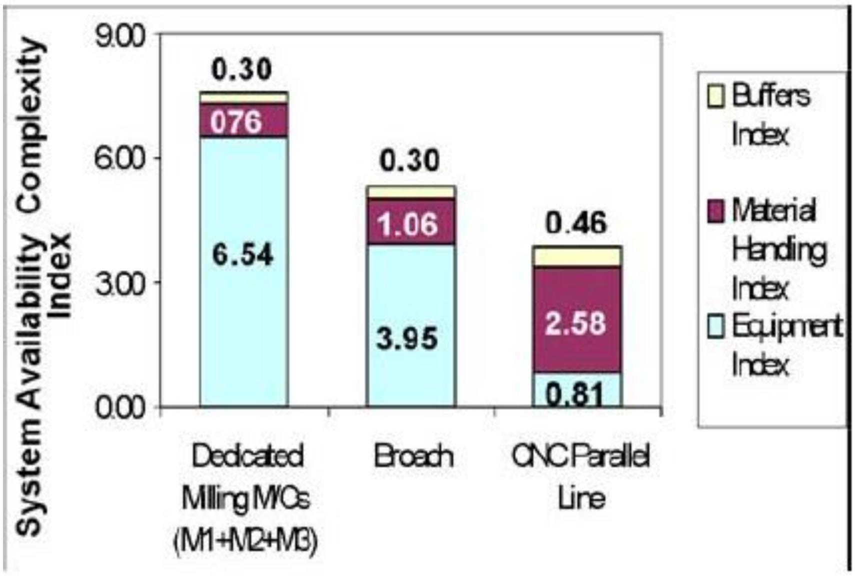

Figure: 2-6 Availability complexity index for different setups [5]

2.11. Complexity of the assembled products

By calculating the complexity of a product assembly, one can choose between different equipment and product designs which are suitable and leads to lower complexity. Samy and ElMaraghy [6] used physical attributes of product assembly i.e. handling and insertion attributes to define complexity of a product. These attributes help in understanding the complexity of a manual product assembly. The methodology used to assess this complexity is DFA in which the assembly time is checked i.e. different attributes such as handling and insertion leads to different times for assembly. The more time a part takes to assemble the more complex it is. The overall complexity of a part is calculated with the help of adding these attributes in an equation which gives the final value of complexity.

Fig 2.6. Shows the model of complexity using these attributes and these attributes provide information and the diversity in information of the individual parts of a product. In the manual assembly process of the product complexity is considered using different types of information such as holding inserting and orienting part for assembly. But in an automatic assembly complexity means the quantity or the type of equipment required to assemble a product and the diversity in that equipment. These results have shown that in case of manual assembly complexity leads to greater assembly time and in case of automatic assembly complexity leads to greater equipment cost [4].

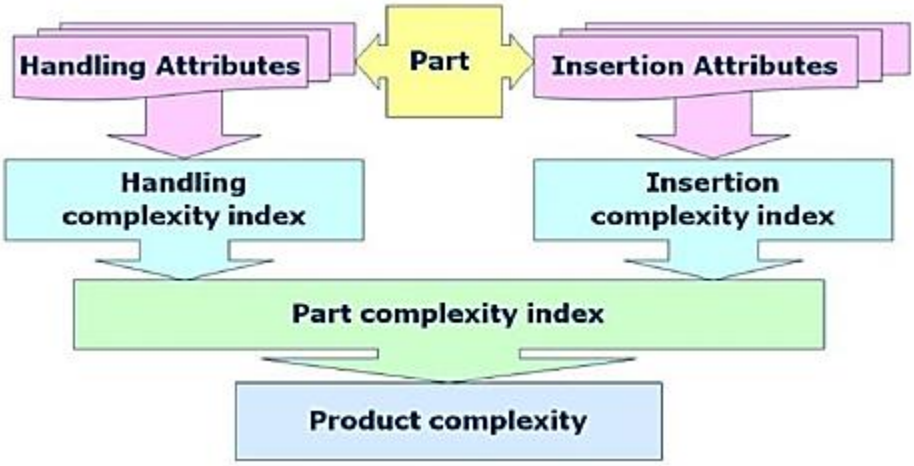

Figure: 2-7 Product assembly complexity [4]

2.12. Types of assembly processes

There are mainly two types of assembly processes

1. Permanent Assembly (welding, riveting)
2. Temporary Assembly (Temporary fasteners threads etc.)

2.12.1. Temporary Assembly

In temporary assembly, the parts are assembled together to make a product with the help of fasteners these fasteners are normally mechanical type fasteners and these can be disassembled when required. Mechanical type assembly or fastening has a wide application in different fields such as automobile industry metal working industries and jet industries that make parts of jet engine or others there are plenty of other types of industries that uses Mechanical fastening [11]. Fig 2.7 shows the dis assembled piston which is the example of temporary assembly.

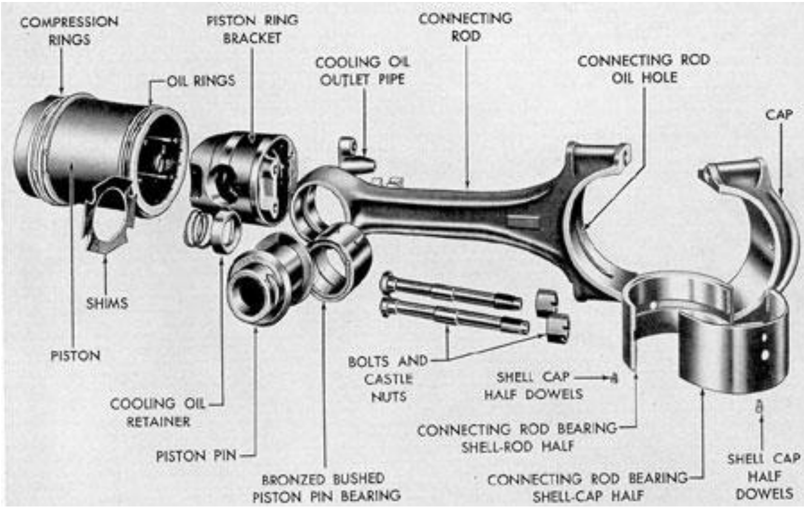

Figure: 2-8 Temporary assembly of an engine's piston [20]

2.12.2. Permanent assembly

There are different types of permanent assembly processes i.e. riveting and welding. Riveting comes under the category of mechanical assembly process while welding comes under joining processes (welding, brazing, soldering and adhesive bonding). Fig 2.9 shows the rivets which is the example of permanent mechanical assembly.

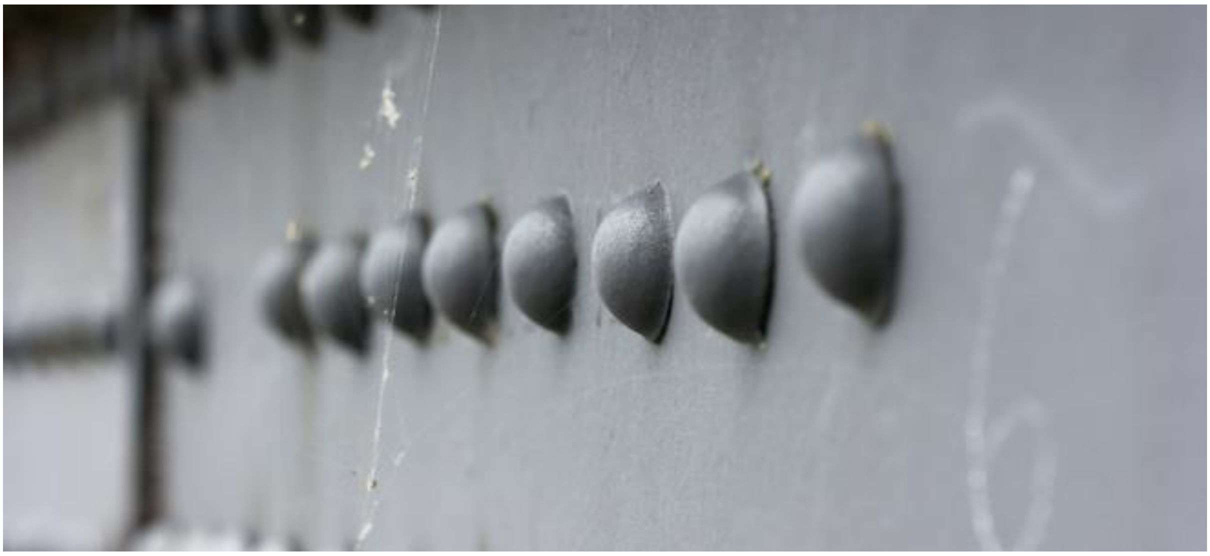

Figure: 2-9 Rivets (permanent assembly) [21]

Figure 2.10 shows different types of assembly processes done on an automobile. And shows the importance of different types of joining and assembly processes.

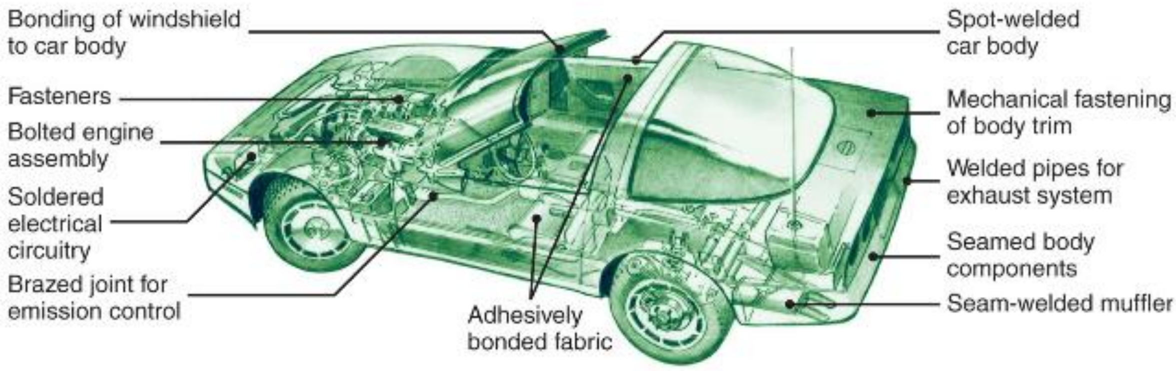

Figure: 2-10 Different types of assembly and joining processes in an automobile [22]

2.13. Types of welding processes

The two main types of welding processes or categories are:

1. Solid state welding
2. Fusion welding

2.13.1. Solid state welding

Solid state welding is a welding process that uses high pressure and electric current to weld two parts together. Unlike fusion welding process it does not uses any fillers materials also the welding parts do not melt during the welding process the examples of this type of welding process are forge welding, friction welding, diffusion welding explosion welding etc.

2.13.2. Fusion welding

In this type of welding process, the welding parts are joined together with the help of filler material and they melt during the welding process**.** Parts are welding together because of very high temperature produced by welding energy sources [13]. There are different types of fusion welding processes given below:

- **(AW) Arc welding**– Metals are melted together using electric arc that comes from the welding machine
- **(RW) Resistance welding** -Metals are joined together with the help of resistance caused by electrical current and pressure is used to weld metals together
- **(OFW) Oxyfuel gas welding**– Metals are melted and joined together using oxy-acetylene gas

2.14. Automatic welding machines

Welding environments are extremely tough to work in because of the high temperatures and safety issues workers spend hours to perform the welding process in these harsh environments and in order to perfect the quality of weld workers need more experience also manual welding process is slow to out of 8 hours workers are able to produce for not more than three hours a day So, In order to cope with this problem the automatic welding machines or robots are made which can mass produce the welding products with no safety issues for workers and with less or no labour costs. But, sometimes it is difficult of even the robots to make different types of joints because market demands keep on changing to deal with this problem a feedback or adaptive systems are made which effectively work according to the product and can produce different types of joints and welds. Also, it doesn't require any supervision by the welder or the manual adjustment of part. This is the great economic advantage of an adaptive system.

2.15. Summary

After research and study, it has been concluded that, the complexity analysis of assembly systems is present and done by different researchers. But, the complexity analysis of a permanent assembly process such as welding is not available or done yet. So, the purpose of this thesis is to analyse the complexity of a welding assembly plant using existing models but, modifying it by heuristic approach. Also, equipment availability will be used to incorporate in the existing model to see its effects on complexity.

CHAPTER 3

Proposed Methodology

CHAPTER 3

Proposed Methodology

A modified model of finding complexity of assembly system is made using automatic welding assembly plant's design and new parameters have been added related o welding also some generic one's, in addition to that complexity model has been modified considering machine availability as an information content i.e. complexity depends on machine availability if the machine is available for a greater period then the complexity of the machine decreases and vice versa. A modified model focuses solely on the machine availability rest of the parameter details are taken from existing case study. Availability of the machines depends upon number of distinct components, as these components increase availability decreases and so the complexity increases. The flow chart of proposed methodology is given below:

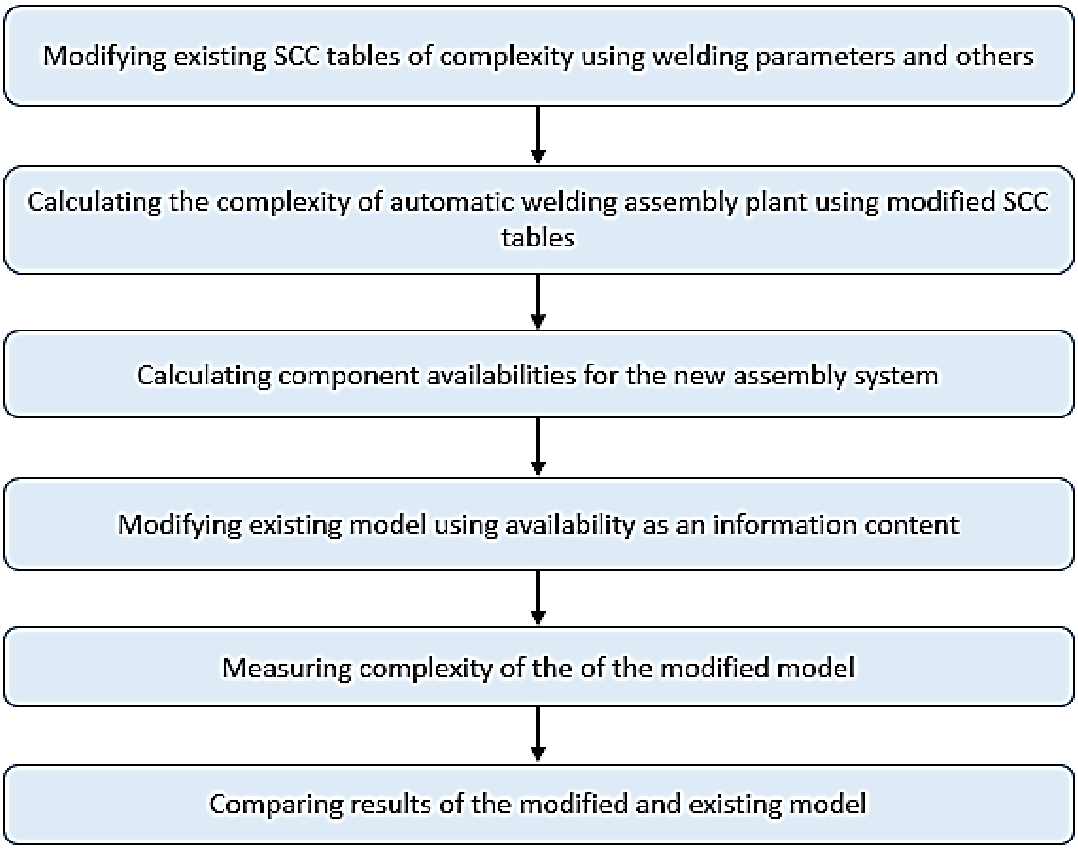

Figure: 3-1 Proposed Methodology for measuring welding assembly plant complexity

3.1. Availability based Hybrid Complexity Model

Complexity model of the assembly systems is presented in [6] which is based on structural codes, total and unique number of parts and this information is incorporated in an equation in the form of diversity ratio, information content and quantity of information. The modification done in this work is the addition of new parameters most of them are welding specific also addition to information content based on machine availability and the idea is taken from [5] where complexity is calculated based on availability. Different values of availability are considered for analysis to get better understanding of the modification different parameters that are used in an analysis.

3.2. Modification of SCC tables using welding assembly system structure classification code

To add the structural features related to assembly of usual equipment which is used in the assembly of the products, the existing SCC of the equipment is modified. The digits present in the existing code are modified and re grouped together. But, the layout classification scheme stays unaltered. The modified SCC classification code comprises of different digits for describing different equipment for example twelve-digit number for the types of machine nine for MHS and for buffers five digits are used. And for the rest of the equipment i.e. operation, programming and control nine digits are used additionally. So, 21 is the maximum number of the digits that are being used here. Various digits are described in Table 3.1, 3.2 and 3.3.

Newly added parameters

Table 3-1 Structural codes for welding machine of welding assembly system

#	Machine CC	Description	Value	Max value	Normalized value
1	Structure	Fixed Reconfigurable Flexible	1 2 3	1	1/3 2/3 3/3
2	N of Work heads	N	1	2	½ 2/2
3	Pin Fixtures	Fixed Moving	1 2	2	½ 2/2
4	Type of welding	Spot welding Gas welding Arc welding	1 2 3	3	1/3 2/3 3/3
5	Required heat	High Very High	1 2	2	1/2 2/2
6	Pressure required	None Medium High	1 2 3	3	1/3 2/3 3/3
7	Source of energy	Chemical Electrical	1 2	2	1/2 2/2
8	Type of electrode	No electrode Consumable Non-consumable	1 2 3	3	1/3 2/3 3/3
9	Shielding	None Flux Gas	1 2 3	3	1/3 2/3 3/3

10	Torch	No torch Single torch Double torch	1 2 3	3	1/3 2/3 3/3
11	Maintenance	Low Medium High	1 2 3	3	1/3 2/3 3/3
12	Axes	N	N	6	N/6
Controls CC					
14	Structure	Fixed Modular	1 2	2	½ 2/2
15	Type	Adaptive Non-adaptive	1 2	2	½ 2/2
16	Access	Open Limited Closed	1 2 3	3	1/3 2/3 3/3
17	Mode	Manual Programmable	1 2	2	½ 2/2
Programming CC					
18	Mode	Manual Programmable	1 2	2	½ 2/2
19	Difficulty	Low Medium High	1 2 3	3	1/3 2/3 3/3
Operations CC					
20	Mode	Manual Semi-automated Fully automated	1 2 3	3	1/3 2/3 3/3
21	Power	Un-powered Powered	1 2	2	½ 2/2
22	Fault detection	Manual Automated	1 2	2	½ 2/2

Table 3-2 Handling equipment classification codes for welding assembly system

No.	MHS CC	Description	Value	Max. Value	Normalized Value
1	Type	Conveyer	1	7	1/7
		Monorail	2		2/7
		Fork lift truck	3		3/7
		AGV	4		4/7
		Cranes and gantries	5		5/7
		Robots	6		6/7
		Feeders	7		7/7
2	Structure	Fixed	1	3	1/3
		Reconfigurable	2		2/3
		Flexible	3		3/3
3	Motion	Uni-directional, synchronized	1	6	1/6
		Uni-directional, asynchronized	2		2/6
		Bi-directional, synchronized	3		3/6
		Bi-directional, asynchronized	4		4/6
		Multi-directional synchronized	5		5/6
		Multi-directional asynchronized	6		6/6
4	Axes	N	N	6	N/6
5	Path	Fixed	1	2	1/2
		Variable	2		2/2
6	Part Holder	None	1	4	1/4
		Pallet	2		2/4
		Fixture	3		3/4
		Gripper	4		4/4
7	Part Types	Single	1	2	1/2
		Multiple	2		2/2
8	Part Orientation	Passive	1	2	1/2
		Active	2		2/2
9	Maintenance	low	1	3	1/3
		Medium	2		2/3

		High	3		3/3
No.	Controls CC	Description	Value	Max. Value	Normalized Value
10	Mode	Manual	1	2	1/2
		Programmable	2		2/2
11	Type	Non-adaptive	1	2	1/2
		Adaptive	2		2/2
12	Access	Open	1	3	1/3
		Limited	2		2/3
		Closed	3		3/3
13	Structure	Fixed	1	3	1/3
		Modular	2		2/3
		Reconfigurable	3		3/3
No.	Programming CC	Description	Value	Max. Value	Normalized Value
14	Mode	Manual	1	2	1/2
		Programmable	2		2/2
15	Difficulty	Low	1	3	1/3
		Medium	2		2/3
		High	3		3/3
No.	Operation CC	Description	Value	Max. Value	Normalized Value
16	Mode	Manual	1	3	1/3
		Semi-Automated	2		2/3
		Fully Automated	3		3/3
17	Power	Un-powered	1	2	1/2
		Powered	2		2/2
18	Fault Detection	Manual	1	2	1/2
		Automated	2		2/2

Table 3-3 Buffer classification code for welding assembly system

No.	Buffer CC	Description	Value	Max. 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 Type	Single	1	2	1/2
		Multiple	2		2/2

3	Access	FIFO	1	3	1/3
		LIFO	2		2/3
		Random	3		3/3
4	Location	With Machine	1	3	1/3
		Separate	2		2/3
		central	3		3/3
5	Maintenance	Low	1	3	1/3
		Medium	2		2/3
		High	3		3/3
No.	**Controls CC**	**Description**	**Value**	**Max. Value**	**Normalized Value**
6	Mode	Manual	1	2	1/2
		Programmable	2		2/2
7	Type	Non-adaptive	1	2	1/2
		Adaptive	2		2/2
8	Access	Open	1	3	1/3
		Limited	2		2/3
		Closed	3		3/3
9	Structure	Fixed	1	3	1/3
		Modular	2		2/3
		Reconfigurable	3		3/3
No.	**Programming CC**	**Description**	**Value**	**Max. Value**	**Normalized Value**
10	Mode	Manual	1	2	1/2
		Programmable	2		2/2
11	Difficulty	Low	1	3	1/3
		Medium	2		2/3
		High	3		3/3
No.	**Operation CC**	**Description**	**Value**	**Max. Value**	**Normalized Value**
12	Mode	Manual	1	3	1/3
		Semi-Automated	2		2/3
		Fully Automated	3		3/3
13	Power	Un-powered	1	2	1/2
		Powered	2		2/2
14	Fault Detection	Manual	1	2	1/2
		Automated	2		2/2

3.3. Welding assembly system components complexity index

From the digit codes that are calculated before by assigning different values to different attributes of an equipment a complexity index is calculated. Complexity index is calculated by first finding the value of a_M which is the area plotted on a radar plot and it shows the total complexity a system has the complexity index in calculated by putting all the digit values in the equations of a_M and then dividing this by total area A_M. The equations for machines and material handling equations are similar because the total number of codes is same i.e. 21 and the buffer one's is different because its complexity codes are different in number than the others. Fig 3.2 shows the example radar plot which is plotted using the values of complexity of an equipment in excel. The area a_M being the combination of small triangles that are joined together to represent the whole are which is the complexity of a system the equations are given below [6]. Eq. 3.1, 3.2 and 3.3 are the modified equations for area shown on a radar plot based on automatic welding assembly system.

$$a_M = \frac{1}{2}[\sum_{i=1}^{i=20}(Ci \times Ci + 1) + (C_1 \times C_{21})]Sin(\frac{360}{21}) \quad (3.1)$$

$$a_{MHS} = \frac{1}{2}[\sum_{i=1}^{i=17}(Ci \times Ci + 1) + (C_1 \times C_{18})]Sin(\frac{360}{18}) \quad (3.2)$$

$$a_B = \frac{1}{2}[\sum_{i=1}^{i=13}(Ci \times Ci + 1) + (C_1 \times C_{14})]Sin(\frac{360}{14}) \quad (3.3)$$

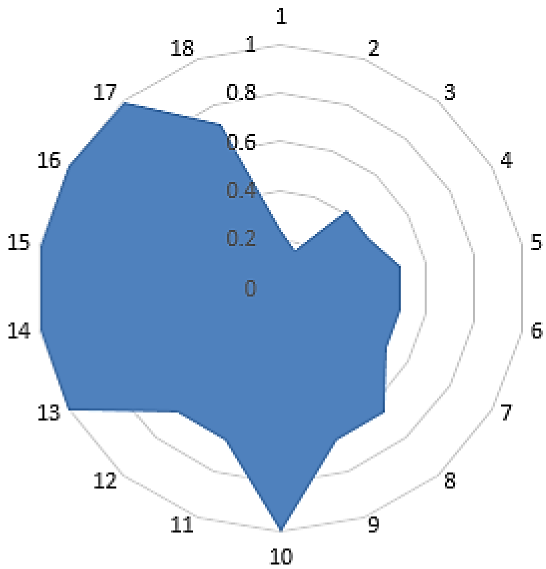

Figure: 3-2 Radar Plot for material handling crane of welding assembly plant

a_M, a_{MHS} and a_B represent the shaded are in the radar plot for machines, material handling and buffer equipment and C_i shows the normalized values of the complexity code of an equipment the total areas of the radar plot for machines, material handling and buffer equipment are given below:

Maximum Radar chart area is given by:

$$A_M = \left(\frac{21}{2}\right) Sin(\frac{360}{21}) \quad \text{(i)}$$

$$A_{MHS} = \left(\frac{18}{2}\right) Sin(\frac{360}{18}) \quad \text{(ii)}$$

$$A_B = \left(\frac{14}{2}\right) Sin(\frac{360}{14}) \quad \text{(iii)}$$

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

Complexity index of all the equipment is then calculated by dividing the small area with the overall area of the radar plot i.e.

The eq. 2.8, 2.9 and 2.10 represents the complexity index of machine, MHS and buffers.

3.4. Complexity of each equipment

The information content is defined previously and in addition to three indices of complexity that are calculated previously the diversity ratio n/N and the quantity of an information of the equipment $\log_2(N_i + 1)$ is added to the equation and the complexity of that equipment is calculated using the equations 2.11, 2.12 and 2.13.

In the equations above the n represents the unique number of equipment and N represents the total number of equipment where I_m I_{MHS} and I_B are the complexity index for machines material handling equipment and buffer equipment also (n_M/N_M), (n_{MHS}/N_{MHS}) and (n_B/N_B) show the uniqueness in information for machines, material handling equipment and buffer equipment, respectively. The terms $\log_2(N_M + 1)$, $\log_2(N_{MHS} + 1)$ and $\log_2(N_B + 1)$ show the total quantity of information the machines, MHS and the buffers have [6].

3.5. System complexity model

The overall system's complexity is calculated by adding all the complexities of the equipment and giving them some weighted factors according to their importance. The total system's complexity is given by eq. 2.14.

C_{SYS} is the complexity of an assembly system and C_M, C_{MHS}, C_B are the complexities of machine, material handling and buffer equipment. Also, w_1, w_2, w_3 represent the weights or the importance of each equipment one can give more importance to specific equipment depending upon their requirements but for simplification these are assumed to be 1 here [6]. The complexity is calculated using the steps given below:

1. Divide the equipment of the system in three categories i.e. machines, handling equipment and buffer equipment.
2. Lay down the physical characteristics of the individual equipment in individual classes in Tables 3.1, 3.2 and 3.3.
3. The next step is to generate the string of structural classification code for individual equipment.
4. Then calculate the complexity index for individual equipment given by Eqs. (i), (ii) and (iii), i.e. I_M, I_{MHS}, I_B.
5. Next step is to calculate the normalized complexity index of the three classes of equipment, i.e. $\bar{I}_M$, $\bar{I}_{MHS}$ and $\bar{I}_B$ using Eqs. 3.4, 3.5 and 3.6.
6. The next step is to count the total equipment number in each category of equipment, i.e. N_M, N_{MHS}, N_B.
7. Count the number of unique equipment within each class, i.e. n_M, n_{MHS}, n_B.
8. Calculate the complexity of each class of equipment as defined by Eqs. 3.7, 3.8 and 3.9, 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 overall assembly system complexity as defined by Eq. 3.10.

3.6. Availability Based Complexity Model

There are several modules in the manufacturing and assembly process, these modules can be available for sometimes out of total hours weeks or days. These modules will have a probability which will be presented by p= n/m. Also, the information content is given by, $\log_2$ (l/p) = - $\log_2$ (p). The availability of these modules is assumed to be fixed for simplification at the start of this analysis.

The analysis is applied on machines, MHS and buffers with the help of an equation 3.11.

$$I_i = log_2(\frac{1}{P_i}) \quad (3.11)$$

P= Availability

P= Availability and i= type of assembly component

$$P_i = [A]^n \quad (3.12)$$

Where in eq. 3.12, A is the availability of the module and n is the distinct number of modules/components of assembly system.

3.7. Modified Model of complexity based on availability

Availability is used as an information content and is added to the existing complexity model to calculate the complexity of modified model using different values of availability. Availability of different components of assembly systems is given by eq. 3.13.

$$I_{PM} = log_2(\frac{1}{P_M}) \quad (3.13)$$

I_{PM} shows availability complexity index of machine present in an assembly system, where $\bar{I}_{PM}$ shows normalized availability complexity of machine and n is total number of availabilities considered for analysis now for material handling equipment complexity is given by eqs. 3.14 and 3.15.

$$I_{PMHS} = log_2(\frac{1}{P_{MHS}}) \quad (3.14)$$

I_{PMHS} shows availability complexity index of material handling equipment present in an assembly system, where $\bar{I}_{PMHS}$ shows availability complexity of material handling equipment

Similarly, for buffer equipment

$$I_{PB} = log_2(\frac{1}{P_{PB}}) \quad (3.15)$$

I_{PB} shows availability complexity index of Buffer present in an assembly system, and $\bar{I}_{PB}$ shows normalized availability complexity of buffer equipment

$$C_{M\_P} = \left[\frac{n_M}{N_M} + (w_M \bar{I}_M + w_{PM} \bar{I}_{PM})\right] [log_2(N_M + 1)] \quad (3.16)$$

The equation 3.16 is the modified version of existing equation used by S. N. Samy & H. ElMaraghy [6]. Where $\bar{I}_M$ is the average complexity index of machine based on its structural codes and $\bar{I}_{PM}$ is the normalized complexity index based on availability of that machine. Also, w_M and w_{PM} are the weights given to the complexity indices of machines due to codes and availability and are given to these indices according to their importance. By inducing availability based complexity into the existing model we can better calculate the value of complexity. Complexity will be decreased by increasing availability of the machine and vice versa.

$$C_{MHS\_P} = \left[\frac{n_{MHS}}{N_{MHS}} + (w_{MHS} \bar{I}_{MHS} + w_{PMHS} \bar{I}_{PMHS})\right] [log_2(N_{MHS} + 1)] \quad (3.17)$$

Similarly, the equation 3.17 shows the complexity of material handling equipment where $\bar{I}_{MHS}$ shows the average complexity of the material handling equipment which is calculated using structural codes and $\bar{I}_{PMHS}$ is the normalized complexity index of material handling equipment based on availability of that equipment. Also, w_{MHS} and w_{PMHS} are the weights given to the complexity indices of material handling equipment due to codes and availability and are given to these indices according to their importance.

$$C_{B\_P} = \left[\frac{n_B}{N_B} + w_B\bar{I}_B + w_{PB}\bar{I}_{PB}\right][log_2(N_B + 1)] \qquad (3.18)$$

Similarly, the equation 3.18 shows the complexity of buffer equipment and $\bar{I}_{PB}$ is the average complexity index of Buffer equipment based on availability of that equipment. Also, w_B and w_{PB} are the weights given to the complexity indices of buffers due to codes and availability and are given to these indices according to their importance. And $\bar{I}_{PB}$ shows the normalized complexity index of buffer equipment.
Now the total system complexity is given by eq. 3.19

$$C_{SYS} = w_1 C_{M\_P} + w_2 C_{MHS\_P} + w_3 C_{B\_P} \qquad (3.19)$$

3.8. Steps for calculating availability based assembly system complexity

Steps for calculating availability based complexity are same as described in section 3.6. Except for the few steps given below:

1. Assume the value of A (availability of the module from 0.1-1.
2. Find the number of unique components.
3. Calculate P_M, P_{MHS} and P_B using eq. 3.12.
4. Calculate I_{PM}, I_{PMHS} and I_{PB} using eqs. 3.13, 3.14 and 3.15.
5. Calculate $\bar{I}_{PM}$, $\bar{I}_{PMHS}$ and $\bar{I}_{PB}$ by normalizing all the values of I_{PM}, I_{PMHS} and I_{PB} by the maximum value of complexity index.
6. Assign weights w_M and w_{PM} to machines complexity indices, w_{MHS} and w_{PMHS} to MHS complexity indices, and w_B and w_{PB} to buffers complexity indices.
7. Calculate C_{M_P}, C_{MHS_P} and C_{B_P} using eqs. 3.16, 3.17 and 3.18.
8. Define the relative importance of each class, i.e. w_1, w_2, w_3.
9. Now calculate total system complexity by adding all the complexities using eq. 3.19.

3.9. Comparison of the two complexities

After the two complexities are calculated they are compared according to their results. The hybrid complexity model will lead to more complexity because availability complexity is added to it and more availability of machine leads to lower complexity value.

3.10. Summary

The hybrid complexity model is presented in this chapter which uses availability as an information content in the existing model of complexity [6]. First of all the SCC tables are modified using welding specific parameters and then the existing equations of the complexity are modified using those modified SCC tables. The SCC table of welding machine is welding specific only and it is not applicable to all types of assembly systems.

Chapter 4
Case Study

Chapter 4
Case Study

In this chapter, a sample welding assembly system is used for the analysis. This assembly system is designed using the idea from [10]. The modified SCC tables of complexity will be used to calculate the complexity indices using the existing equations. Then the availability complexity of the welding assembly plant will be calculated. After that the hybrid model will be used to calculate the complexity of the system. In the end, the two complexities will be compared to see the effect of adding availability complexity in the existing system.

4.1. Analysis of complexity of automatic welding assembly

Complexity of modified model of the welding assembly system (Fig 4.1) is calculated and results are explained using tables and graphs. An assembly system is taken from [10] which is welding robot assembly system of a beam and plate. It consists of two welding robots which can move on the rail, one material handling robot which is used to hold the plate on the beam it can also move on the beam, crane for loading and unloading beam, a rotating fixture for holding the beam and rotating it at the desired angle and a chute magazine which is a buffer equipment and it carry plates that a MHS robot then picks up for joining. And its complexity is calculated here and this work uses availability as an additional variable to modify existing model and analyze the complexity of welding assembly plant.

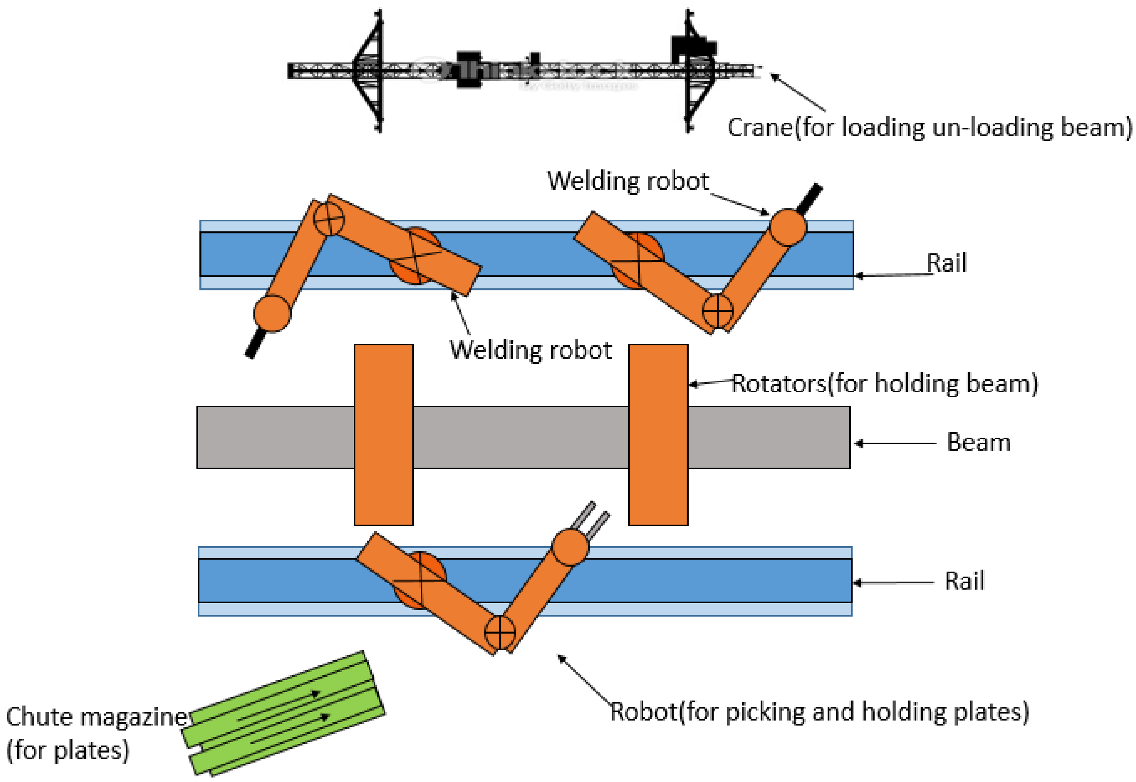

Figure: 4-1 Beam and plate welding assembly plant (Idea adopted from Voortman automatic welding assembly plant)

4.2. SCC Welding Machine (Welding Robot)

The next step is to modify existing tables of assembly systems by adding new welding specific parameters. The highlighted parameters are the ones added to these tables and their details are given in appendix A. Another step is to assign complexity values of the components of an assembly system i.e. machines, MHS and buffers. Table 4.2, 4.3 and 4.4 show the SCC tables of the welding machines, MHS and buffers. Figure 4.3-4.6 show the radar plots of all the components of welding assembly plant using normalized values. Shaded area shows the amount of complexity.

Table 4-1 MHS robots Classification code

#	Machine CC	Description	Digit Value	Max value	Normalized value
1	Structure	Fixed	**1**	3	0.3333
2	N of Work heads	N	**1**	2	0.5
3	Pin Fixtures	Moving	**2**	2	1
4	Type of welding	Arc welding	**3**	3	1
5	Required heat	Very High	**2**	2	1
6	Pressure required	None	**1**	2	0.5
7	Source of energy	Electricity	**2**	2	1
8	Type of electrode	Non - Consumable	**3**	3	1
9	Shielding	Gas	**3**	3	1
10	Torch	Single torch	**2**	3	0.666667
11	Maintenance	High	**3**	3	1
12	Axes	N	**5**	6	0.833333
Controls CC					
13	Structure	Modular	**2**	2	1
14	Type	Adaptive	**2**	2	1
15	Access	Limited	**2**	3	0.666667
16	Mode	Programmable	**2**	2	1
Programming CC					
17	Mode	Programmable	**2**	2	1
18	Difficulty	High	**3**	3	1
Operations CC					
19	Mode	Fully automated	**3**	3	1
20	Power	Powered	**2**	2	1
21	Fault detection	Automated	**2**	2	1
I_M =0.775					

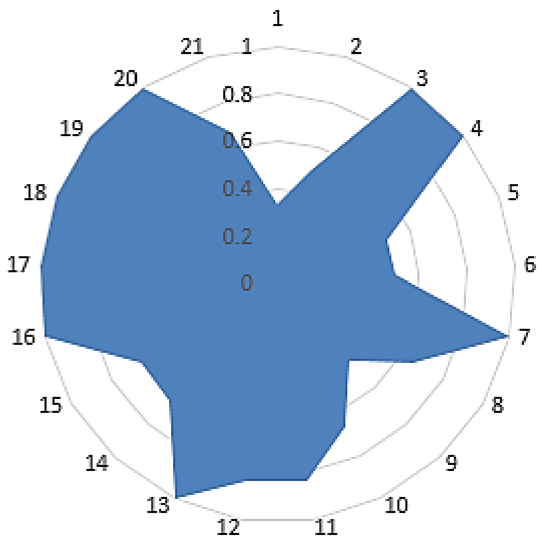

Figure: 4-2 Welding robot of automated welding assembly system

Table 4-2 MHS robots Classification code

#	MHS CC	Description	Digit value	Maximum value	Normalized
1	Type	Robot	**6**	7	0.857143
2	Structure	Fixed	**1**	3	0.5
3	Axes*	N	**4**	6	0.666667
4	Motion	Multi-directional synchronized	**5**	6	0.833333
5	Path	Fixed	**1**	2	0.5
6	Part holder	gripper	**4**	4	1
7	Part type	Single	**1**	2	0.5
8	Part orientation	Active	**2**	2	1
9	Maintenance	Medium	**2**	3	0.666667
#	Controls CC	Description	Digit value	Maximum value	Normalized
10	Mode	Programmable	**2**	2	1
11	Type	Adaptive	**2**	2	1
12	Access	Limited	**2**	2	1
13	Structure	Reconfigurable	**3**	3	1
#	Programming CC	Description	Digit value	Maximum value	Normalized
14	Mode	Programmable	**2**	2	1
15	Difficulty	High	**3**	3	1
#	Operations CC	Description	Digit value	Maximum value	Normalized

16	Mode	Fully-automated	**3**	3	1
17	Power	Powered	**2**	2	1
18	Fault detection	Auto	**2**	2	1
I_{MHS} = 0.745					

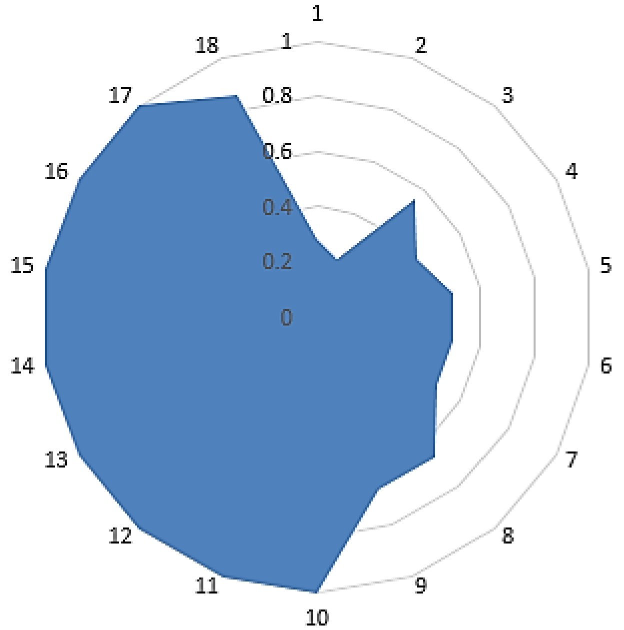

Figure: 4-3 Material-handling Robot of automated welding assembly system

Table 4-3 Crane classification code (for loading and unloading beam)

#	MHS CC	Description	Digit value	Maximum value	Normalized
1	Type	Crane	**5**	7	0.714286
2	Structure	Fixed	**1**	3	0.5
3	Axes	N	**3**	6	0.5
4	Motion	Multi-directional synchronized	**5**	6	0.833333
5	Path	Fixed	**1**	2	0.5
6	Part holder	gripper	**4**	4	1
7	Part type	Single	**1**	2	0.5
8	Part orientation	Active	**2**	2	1
9	Maintenance	Medium	**2**	3	0.666667
#	Controls CC	Description	Digit value	Maximum value	Normalized
10	Mode	Programmable	**2**	2	1
11	Type	Adaptive	**2**	2	1
12	Access	Limited	**2**	3	0.666667

13	Structure	Reconfigurable	**3**	3	1
#	Programming CC	Description	Digit value	Maximum value	Normalized
14	Mode	Programmable	**2**	2	1
15	Difficulty	High	**3**	3	1
#	Operations CC	Description	Digit value	Maximum value	Normalized
16	Mode	Fully-automated	**3**	3	1
17	Power	Powered	**2**	2	1
18	Fault detection	Auto	**2**	2	1
I_{MHS} =0.684					

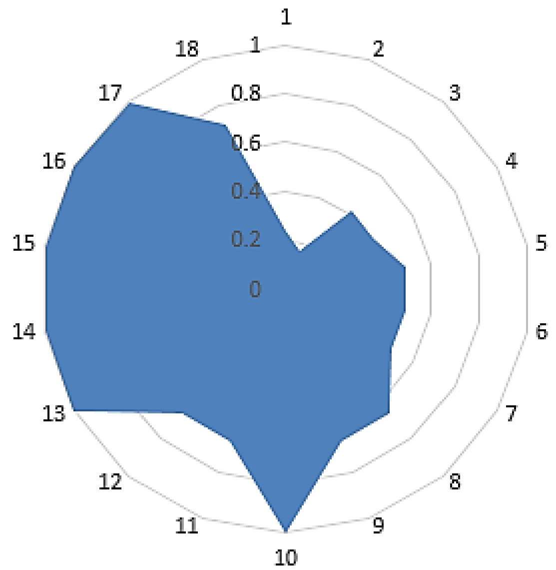

Figure: 4-4 Crane of automated welding assembly system

Table 4-4 Chute magazine (for plates)

#	Buffer CC	Description	Digit Value	Maximum value	Normalized value
1	Type	Magazine	**1**	4	0.25
2	Part Type	Single	**1**	2	0.5
3	Access	FIFO	**1**	3	0.333333
4	Location	Separate	**1**	3	0.333333
5	Maintenance	Medium	**2**	3	0.666667
6	Type	Adaptive	**2**	2	1
#	Controls CC	Description	Digit Value	Maximum value	Normalized value
7	Mode	Programmable	**2**	2	1

8	Access	Open	**1**	3	0.333333
9	Structure	Reconfigurable	**3**	3	1
#	Programming CC	Description	Digit Value	Maximum value	Normalized value
10	Mode	Programmable	**2**	2	1
11	Difficulty	High	**3**	3	1
#	Operations CC	Description	Digit Value	Maximum value	Normalized value
12	Mode	Fully-automated	**3**	3	1
13	Power	Powered	**2**	2	1
14	Fault detection	Auto	**2**	2	1
I_B = 0.578					

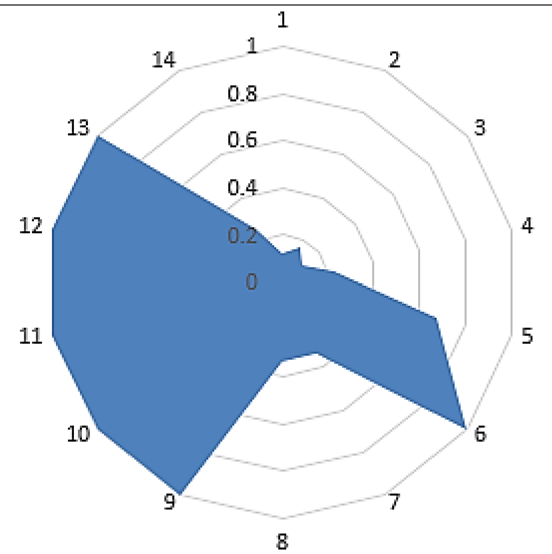

Figure: 4-5 Chute magazine of automated welding assembly system (Buffer)

4.3. Calculating complexity of welding plant

The next step is to calculate the complexity of the welding system. For that purpose, the individual complexities of all the equipment are calculated first then the complexities are added according to their importance, weighted factors are assigned to each class of equipment. Here, equal importance is given to each class of equipment. Now calculating complexity indices for all machines. In addition, for calculating the complexities of equipment we have.

For Welding Machine robot, values of complexity index and complexity are calculated using eqs. 2.8 and 2.11:

I_M =0.775

C_M =2.0196

Similarly, for MHS, values of complexity index and complexity are calculated using eqs. 2.9 and 2.12:

$I_{MHS} = 0.745811$

Similarly, for MHS Crane

$I_{MHS} = 0.6845$

$C_{MHS} = 2.695$

Similarly, for buffers, values of complexity index and complexity are calculated using eqs. 2.10 and 2.13:

$I_B = 0.586$

$C_B = 1.586$

For total system complexity is calculated by using eq. 2.14:

$C_{SYS} = w_1 C_M + w_2 C_{MHS} + w_3 C_B$

$C_{SYS} = 6.295$

Where, w_1, w_2 and w_3 are assumed to be 1, and equal importance is given to all the equipment.

The table 4.5 shows the overall system complexity of the welding system. In addition, all the other values of parameters that are used to calculate the complexity. This table is an easy way to understand all the parameters in one place.

Table 4-5 Complexity analysis of a welding assembly plant

Class	Equipment	I	$\bar{I}$	n	N	C
Machine	Welding Robot1 Welding Robot2	0.777 0.777	0.777	1	2	2.019
MHS	Robot(MHS) Crane	0.731 0.673	0.701	2	2	2.695
Buffer	Chute magazine	0.578	0.578	1	1	1.578
System Complexity	$w_1C_M+w_2C_{MHS}+w_3C_B$					6.295

4.5. Availability based complexity for Machines, MHS and buffer

The next step is to calculate the availability based complexity of the welding plant. First of all, the availability of the assembly components i.e. machines, MHS and buffers is assumed to be between 10-100%, then the probability of these components is calculated using eq. 3.12. and after that complexity is calculated using eq. 3.13, 3.14, 3.15.

The table 4.6 shows the machine availability A_M values ranging between 0.1-1 and the corresponding values of machine availability P_M and availability complexity I_{PM}. And, the fig 4.7 shows the relation between machine availability and machine complexity index. Where, $\bar{I}_{PM}$ shows the normalized values of machine complexity index I_{PM}. And it is achieved by dividing machine complexity indices I_{PB} by the maximum value of complexity index.

Table 4-6 Availability and availability complexity of welding robots

A_M	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
P_M	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
I_{PM}	3.321	2.321	1.736	1.321	1	0.736	0.514	0.321	0.152	0
$\bar{I}_{PM}$	0.332	0.232	0.173	0.132	0.1	0.073	0.051	0.032	0.015	0

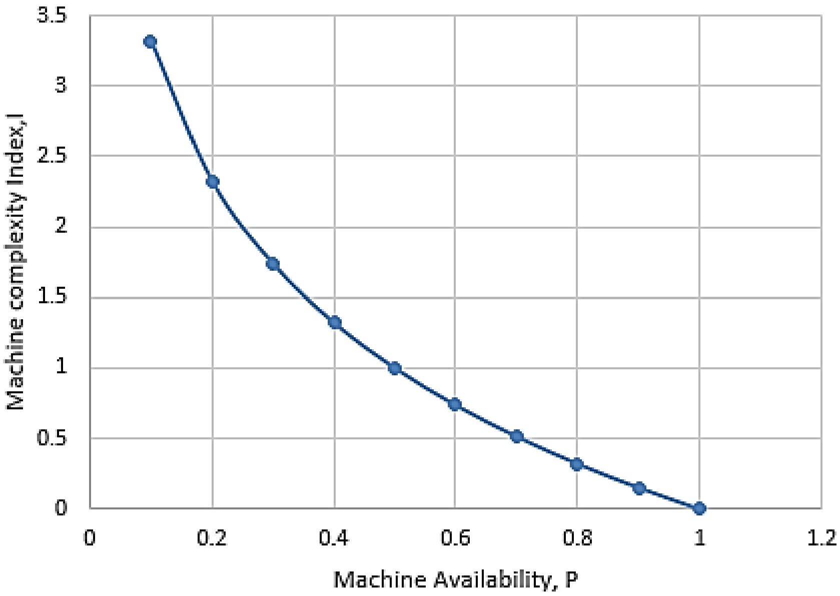

Figure: 4-6 Relation between welding robot availability and availability complexity Index

The table 4.7 shows the Material handling availability A_{MHS} values ranging between 0.1-1 and the corresponding values of machine availability P_{MHS} and availability complexity I_{PMHS}. And, the fig 4.8 shows the relation between machine availability and machine complexity index. Where, $\bar{I}_{PMHS}$ shows the normalized values of material handling complexity index I_{PMHS}. And it is achieved by dividing MHS complexity indices I_{PMHS} by the maximum value of complexity index.

Table 4-7 MHS availabilities and complexities for n=2

A_{MHS}	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
P_{MHS}	0.01	0.04	0.09	0.16	0.25	0.36	0.49	0.64	0.81	1
I_{PMHS}	6.644	4.644	3.474	2.644	2.000	1.474	1.029	0.644	0.304	0
$\bar{I}_{PMHS}$	0.664	0.464	0.347	0.264	0.200	0.147	0.103	0.064	0.030	0.664

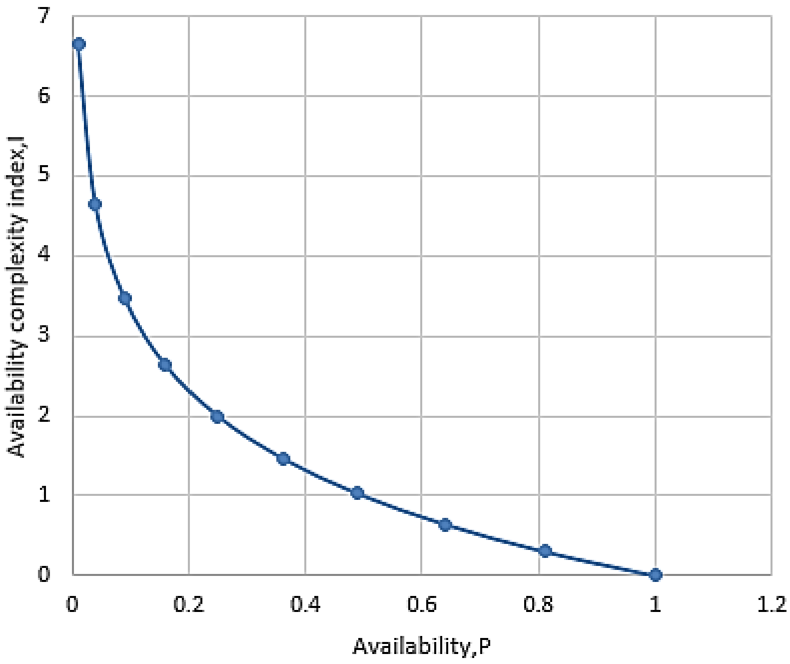

Figure: 4-7 Relation between MHS availability and complexity index

Similarly, for buffers n=1 and the table 4.8 shows the buffer availability A_B values ranging between 0.1-1 and the corresponding values of machine availability P_B and availability complexity I_{PB}. And, the fig 4.9 shows the relation between buffer availability and buffer complexity index. Where, $\bar{I}_{PB}$ shows the normalized values of buffer complexity index I_{PB}. And it is achieved by dividing buffer complexity indices I_{PB} by the maximum value of complexity index.

Table 4-8 Buffer availabilities and complexities

A_B	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
P_B	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
I_{PB}	3.322	2.322	1.737	1.322	1.000	0.737	0.515	0.322	0.152	0
$\bar{I}_{PB}$	0.332	0.232	0.174	0.132	0.100	0.074	0.051	0.032	0.015	0

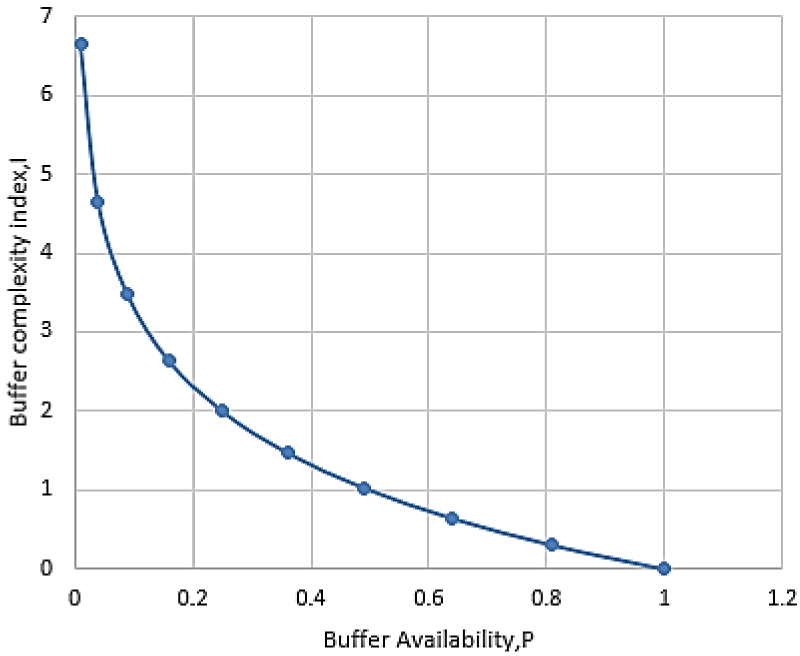

Figure: 4-8 Relation between buffer availability and complexity index

4.6. Hybrid Complexity a welding assembly plant

The next step is to modify the existing model of complexity shown by eqs. 4.2, 4.5 and 4.7 and modify it in the form of eqs. 3.16, 3.17 and 3.18 by incorporating availability complexity index which is calculated in the section 4.4. Now for finding the complexity of the welding assembly system, when the availability is 0.9 for all the equipment we have:

C_{M_P} =2.073

Similarly, for MHS we have

C_{MHS_P} =2.767

Similarly, for buffers

C_{B_P} = 1.608

Total system complexity will be the sum all the values of equipment complexities above given by equation 3.19 as:

$$C_{SYS} = w_1 C_{M\_P} + w_2 C_{MHS\_P} + w_3 C_{B\_P}$$

$$C_{SYS} = 6.440$$

Where, w_1, w_2 and w_3 are assumed to one equal importance is given to all the equipment.

The availability complexity of the machines (welding robots), MHS (robot and crane) and buffer (chute magazine) is given by tables 4.9, 4.10 and 4.11. And fig 4.10, 4.11 and 4.12 show the relationship between machines, MHS and buffer availabilities (A_M, A_{MHS} and A_B) and machine, MHS and buffer complexities C_{M_P} , C_{MHS_P} and C_{B_P} . The machine availability is assumed in between 0.1-1 for all the equipment.

Table 4-9 Machine availabilities and hybrid complexities

A_M	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
P_M	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
I_{PM}	3.321	2.321	1.736	1.321	1	0.736	0.514	0.321	0.152	0
I_{PM}	0.500	0.350	0.261	0.199	0.151	0.111	0.077	0.048	0.023	0
C_{M_P}	7.285	5.700	4.773	4.116	3.605	3.188	2.836	2.531	2.261	2.020

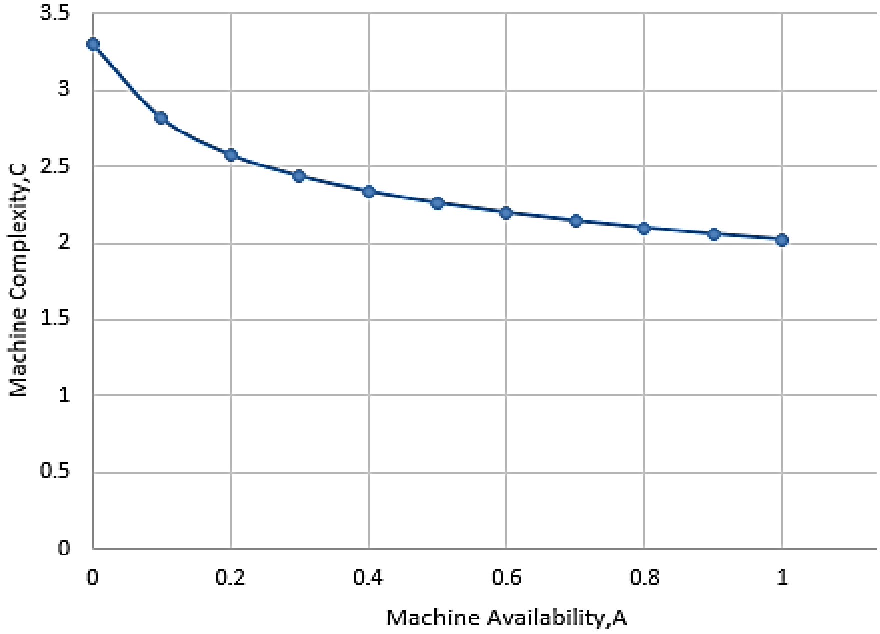

Figure: 4-9 Relation between machine availabilities and hybrid complexities

Table 4-10 MHS availabilities and hybrid complexities

A_{MHS}	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
P_{MHS}	0.01	0.04	0.9	0.16	0.25	0.36	0.49	0.64	0.81	1
I_{PMHS}	6.644	4.644	3.474	2.644	2.000	1.474	1.029	0.644	0.304	0
I_{PMHS}	1.000	0.699	0.523	0.398	0.301	0.222	0.155	0.097	0.046	0
C_{MHS_P}	4.302	3.825	3.545	3.347	3.194	3.068	2.962	2.870	2.789	2.717

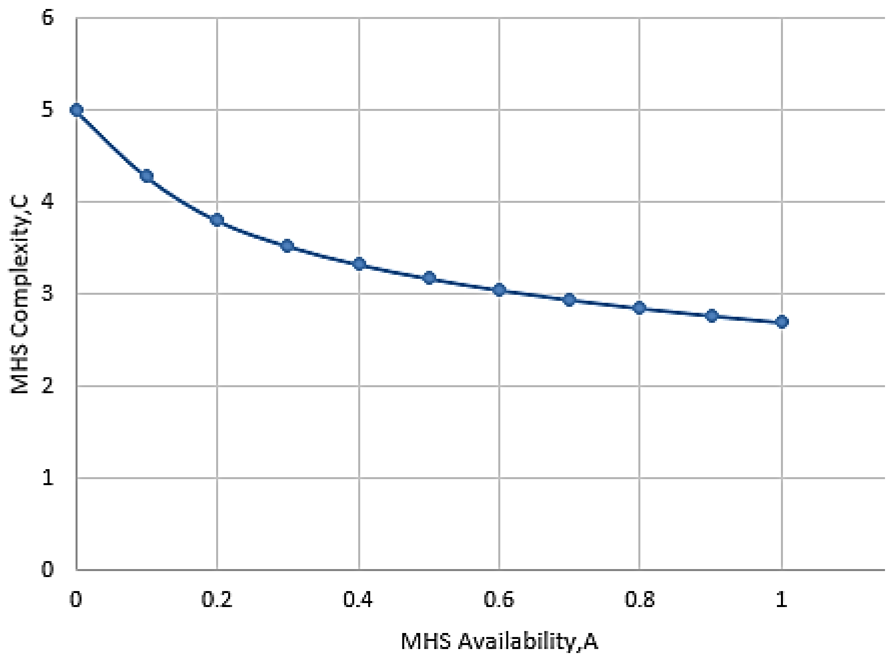

Figure: 4-10 Relation between MHS availability and hybrid complexities

Table 4-11 Buffer availabilities and hybrid complexities

A_B	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
P_B	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
I_{PB}	3.322	2.322	1.737	1.322	1.000	0.737	0.515	0.322	0.152	0
I_{PB}	0.500	0.350	0.261	0.199	0.151	0.111	0.077	0.048	0.023	0
C_{B_P}	2.086	1.936	1.847	1.785	1.737	1.697	1.663	1.634	1.609	1.586

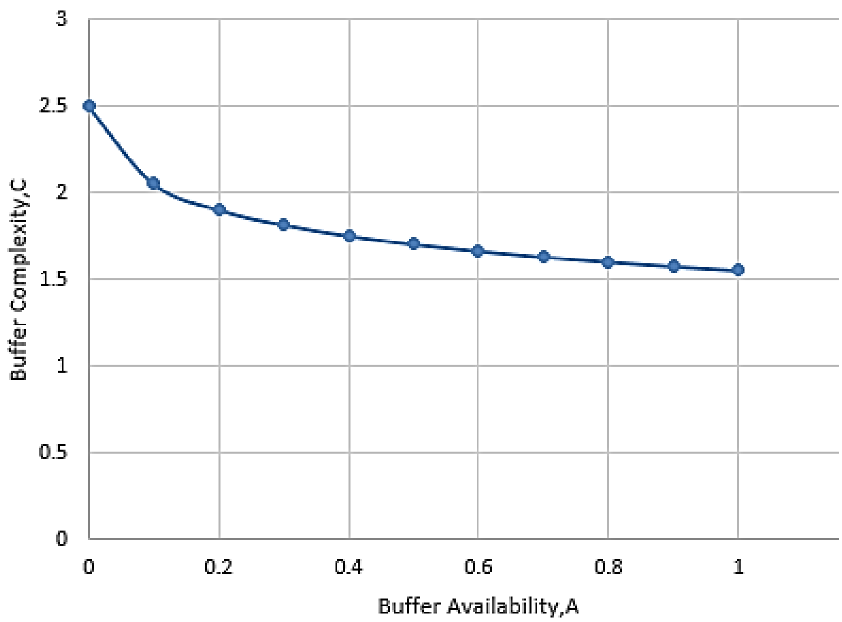

Figure: 4-11 Relation between buffer availability and complexity

Table 4.12 shows both types of complexities i.e. complexity due to structural codes C and complexity due to availability C_{P_i} and their comparison. All other related parameters are also added in the table to show their values and the effect of their values on complexities

Table 4-12 Availability complexity when machines are available 90% of the time

Class	Equipment	I	$\bar{I}$	$\bar{I}_{Pi}$	n	N	C	C_{P_i}
Machine	Welding Robot Welding robot	0.775 0.775	0.775	0.022	1	2	2.022	2.073
MHS	Robot(MHS) Crane	0.731 0.673	0.702	0.045	2	2	2.695	2.767
Buffer	Chute magazine	0.578	0.578	0.022	1	1	1.578	1.60
System Complexity1	$w_1C_{M\_P}+w_2C_{MHS\_P}+w_3C_{B\_P}$						6.295	6.440

Where, w_1, w_2 and w_3 are assumed to one equal importance is given to all the equipment.

4.7. Effect of availability on complexity

By changing the availability of an equipment, the complexity of the system changes i.e. when the availability is decreased complexity increases and vice versa as shown in Fig 4.13 (a) Similarly Fig 4.13(b) shows the percentage increase in complexity due to decrease in availability of an equipment

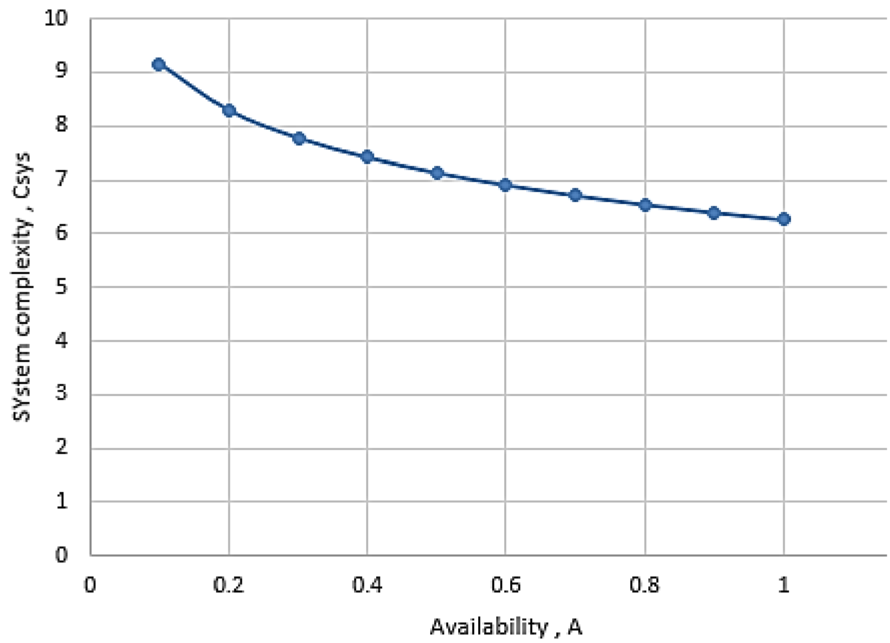

Figure: 4-12(a) Relation between availability and system complexity

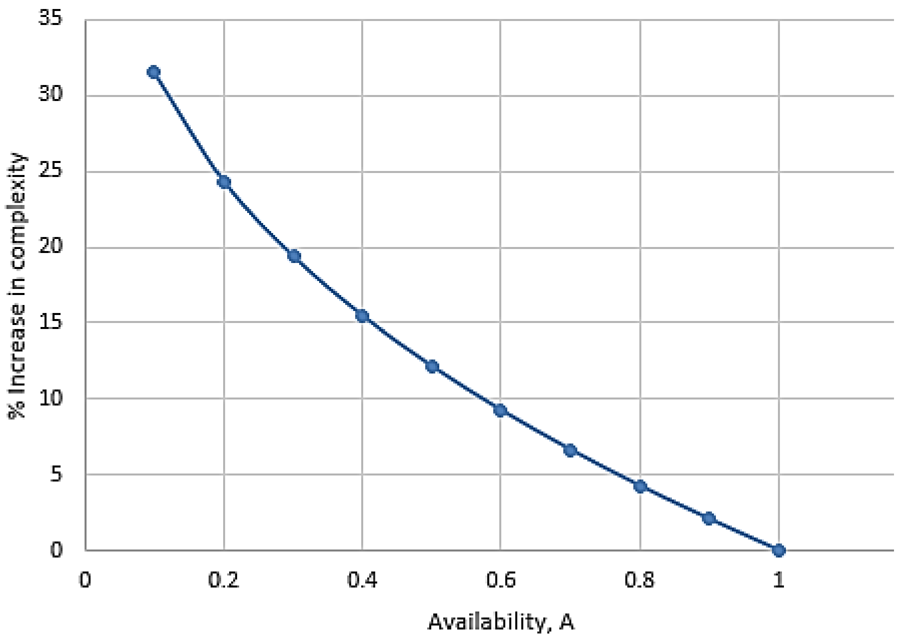

Figure: 4-12 (b) Relation between availability and percentage increase in system complexity

4.8. Summary

In this chapter, the complexity of a welding assembly plant is calculated. First of all, the new parameters in the SCC tables are added. Then the structural classification codes to all the assembly components are assigned, after that the complexity is calculated according to the model presented in [6] and complexity is also calculated using the modified model presented in this chapter. In the end, the comparison is made to see the effect of availability on complexity of welding assembly plant. And it has been deduced that the complexity increases with the decrease in machine availability. Results are shown with the help of graphs and tables.

Chapter 5
Conclusion and future work

CHAPTER 5

Conclusion and future work

5.1. Conclusions

The first objective of this thesis was to analyse the complexity of welding assembly system by introducing welding specific parameters in addition to others defined in literature. As, no work was done for the complexity of welding assembly also complexity greatly affects the assembly process by increasing production time and process cost. By managing complexity, the productivity can very much be increased and assembly cost and time be reduced. For that purpose, a case study is made on a welding assembly system, and idea is taken from Voortman machinery [10]. The current work is the extension of the model presented in [6], In that model mechanical type assembly systems were used for analysis.

The type of welding process considered, in this work, was TIG (tungsten inert gas). The welding system considered is completely automated and adaptive and so the total complexity of the system is quite high because of these features. However, by changing the systems configuration and features according to the requirement complexity of the system can be reduced. For example, one can choose between the controls such as mode (programmable, non-programmable) that gives same output but still be less complex. In addition, to this adaptive control and fully automatic system leads to more complexity. Although, it eliminates the entire manual work done by workers but adds complexity to the system. Because, more flexible systems are usually more complex. Therefore, by changing those parameters that doesn't affect the overall quality of weld/product and process, we can go for less complex options. Also, less variety or number of distinct parts in an individual class of equipment can be used which in turn reduces complexity. In that way, we can reduce the complexity of the existing systems that will eventually reduce the overall cost of the system.

The second part of this thesis was to introduce availability based complexity index as an information content [5] to the existing model of assembly system complexity [6]. The hybrid model is proposed and is applied to the automated welding assembly system. The results of the analysis show that the complexity of an assembly system increases by incorporating equipment availabilities into the system. More availability leads to lower overall complexity and vice versa. And, it was concluded that when the availability of an equipment is 100%, the availability complexity index has no effect on the overall system's complexity. By reducing the availability, the complexity of the system increases. And complexity will be maximum if availability of an equipment approaches to zero. Availability of an equipment also depends on variety of equipment in that class so less variety leads to more availability. By choosing greater availability in each class of assembly equipment (Machines, MHS and buffers) complexity of the system can be reduced which in turn reduces assembly cost and time.

5.2. Future Work

This work is extended to the permanent joining process i.e. welding and, the welding considered in this work was TIG (Tungsten inert gas) welding, which comes under the category of fusion welding. This work can be extended to the assembly processes given below:

- The other types of welding process i.e. solid-state welding can be used for analysis because; it will need additional parameters for analysis. And will help managers choose between different options.
- Riveting is another field which can be explored. Riveting is a permanent mechanical type assembly process and no work is done in this field.
- The other types of assembly processes such as printed circuit boards can also be used for analysis. Which will help in choosing between different assembly systems and equipment.

REFERENCES

1. Lawrence D. Fredendall “Manufacturing Complexity: A Quantitative Measure, POMS Conference, April 4 – April 7”, 2003, Savannah, GA
2. S. N. Samy & H. ElMaraghy “A model for measuring products assembly complexity, International Journal of Computer Integrated Manufacturing” (2010) 23:11, 1015-1027
3. Badrous, Sameh Nozhy Samy, "Complexity of products and their assembly systems" (2011). *Electronic Theses and Dissertations.* Paper 5560.
4. Waguih ElMaraghy, Hoda ElMaraghy, Tetsuo Tomiyama, Laszlo Monostori Complexity in engineering design and manufacturing, CIRP Annals - Manufacturing Technology 61 (2012) 793–814
5. H. A. EIMaraghy(l), 0. Kuzgunkaya, R. J. Urbanic, “Manufacturing Systems Configuration Complexity” 2005
6. S. N. Samy & H. ElMaraghy “A model for measuring complexity of automated and hybrid assembly systems”,2012,
7. Y. Koren, General RMS Characteristics. Comparison with Dedicated and Flexible Systems
8. Rampersad HK, “Integrated and simultaneous design for robotic assembly”. A Wiley Series in Product Development: Planning, Designing, Engineering, (1994) Chichester, UK
9. Lotter B, Manufacturing assembly handbook, (1989) Butterworths, London
10. Voortman machinery. (2014, October 18) “Voortman - The Fabricator | Fully automatic assembling and welding”, https://www.youtube.com/watch?v=D_LvKtmNlPI
11. John Wiley & Sons, Inc. M. P. Groover (2002), “Fundamentals of Modern Manufacturing2/e″, http://www.me.nchu.edu.tw/lab/CIM/www/courses/Manufacturing%20Processes/Ch33-MechanicalAssembly-Tseng.pdf
12. Cheng li (2017, August 4), http://www.engr.mun.ca/~adfisher/3941/Ch30_Fusion-Welding.pdf
13. *Schey, John A. (2000) [1977],* Introduction to Manufacturing Processes*,* McGraw-Hill series in mechanical engineering and materials science (3rd ed.)*,* McGraw-Hill Higher Education*,* ISBN 978-0-07-031136-7, retrieved May 15, 2010*,*
14. George E. cook, “Robotic arc welding: research in sensory feedback”, IEEE transactions on industrial electronics, Volume IE-30, No. 3, August 1983
15. S.N. Samy, H. A. el Maraghy, “Complexity of products and their assembly systems.” PhD Thesis University of Windsor, 2012.
16. Boothroyd, G., Dewhurst, P., and Knight, W.A., “Product design for manufacture and assembly” 2002 New York: Marcel Dekker.
17. Braha, D. and Maimon, O. (1998) “The measurement of a design structural and functional complexity” IEEE Transactions on Systems, Man & Cybernetics, Part A (Systems & Humans), 28 (4), 527–535.

18. Frizelle, G. (1996). "Getting the measure of complexity." Manufacturing Engineer 75(6):268-270.
19. Klir, G. (1985). "Complexity: Some General Observations." Systems Research 2: 131-140.
20. Temporary assembly of an engine’s piston, San Francisco maritime national park association, (2009, Feb 10), https://maritime.org/doc/fleetsub/diesel/img/fig3-47.jpg
21. Rivets (permanent assembly), Do it yourself (2017, August 05), http://www.doityourself.com/stry/the-best-way-to-install-a-solid-rivet
22. Different types of assembly and joining process done on an automobile, Newfoundland and Labrador University (2017, August 05), http://www.engr.mun.ca/~adfisher/3941/Ch30_Fusion-Welding.pdf

APPENDIX A

Welding machine type CC annotations

Digit Number	Description	Explanation
6	high heat Very High heat	Some welding processes require comparatively low heat i.e. gas welding while others require high i.e. electric arc welding
7	No Pressure High pressure	Some welding operation require no pressure i.e. fusion welding Welding processes like friction welding require comparatively high pressure
8	Chemical Electrical	Welding process such as gas welding uses gas as a welding source which is chemical Welding process such as arc welding uses electric current as a welding source
9	Consumable Non-consumable	Electrode is consumed during welding process for example SMAW(shielded metal arc welding) Electrode is not consumed during welding process for example TIG (Tungsten inert gas) welding
10	Flux shielding Gas shielding	Electrodes are either flux coated or flux cored it helps the weld from outer conditions A separate cylinder is needed to use this gas for shielding during welding process
11	Single Torch Double Torch	Welding robot is equipped with one torch Welding robot is equipped with two torches
12	Maintenance	Machine require maintenance on daily or weekly monthly or yearly basis which includes cleaning, repairing and refilling etc.

Material handling CC annotations

Digit number	Description	Explanation
1	Axes	The number of axes involved in material handling equipment i.e. robots have several axes of motion
2	Multi-directional motion	Some material handling equipment can move in more than two directions such as a robot so its motion will be considered as multi directional motion