A Model for Assessment and Integration of Product's Manufacturing and Assembly Complexity

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ISLAMABAD
AUGUST 2022

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

MS Mechanical Engineering

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Declaration

I certify that this research work titled "*A Model for Assessment and Integration of Product's Manufacturing and Assembly Complexity"* 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.

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Copyright Statement

Acknowledgements

I would like to thank Almighty Allah; whose guidance led this work to be completed in time and whose blessings and benevolent help kept me sheltered all the time.

I would like to thank my advisor Dr. Sajid Ullah Butt, and GEC members Dr. Aamer Ahmed Baqai & Dr. Uzair Khaleeq uz Zaman for their many contributions to both my work as well as my personal and professional development throughout my time at the NUST College of E&ME.

I would like to thank my beloved parents and family, who always guided me in the right way and whose endless effort and support made it possible for me, to be, what I am today.

In the end I would like to thank the entire honorable faculty of Mechanical Department of the college, whose professional approach and vision groomed me.

Dedicated to my beautiful parents and beloved siblings, whose unwavering support and cooperation enabled me to achieve this fantastic goal

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Nomenclature

A_{ijk}	Sum of sequences of operations rejected (due to constraints)
C_P	Product Complexity
$C_{h,f}$	Relative handling complexity factor
C_h	Average handling complexity factor
C_F	Feature based complexity coefficient.
C_{FC}	Complexity coefficient of curved features for part k.
C_{FI}	Complexity coefficient of Inclined features for part j.
C_{FO}	Complexity coefficient of orthogonal features for part I.
C_M	Manufacturing complexity of product
C_A	Assembly complexity of product
C_{SB}	Relative complexity coefficient for sequence-based attributes.
C_i	Complexity coefficient of attribute I.
$C_{in,f}$	Relative insertion complexity factor
C_{in}	Average insertion complexity factor
C_o	Overall complexity for other attributes
C_{ol}	Other attributes based complexity coefficient.
C_p	Overall part complexity coefficient.
C_{part}	Individual part complexity
C_{pdt}	Merged product complexity
C_s	Complexity for other attributes
D_{oijk}	Number of operation sequences dismissed due to other constraints
DC	Attribute value of changing demand

DMS	Dedicated manufacturing system
F_i	The maximum number of operation sequences
FMS	Flexible manufacturing system
G_i	The total number of possible operation sequences for part i
G_{max}	The max number of possible operation sequences among the available parts
GA	Genetic algorithm
h_{ijk}	Part feature for part i.
I_p	Relative part complexity (without weightages)
N_c	Curved feature attribute index
N_f	Number of features for part i.
N_i	Angular/ inclined feature attribute index
N_j	Jix / fixture type attribute index
N_m	Material type attribute index
N_p	Number of possible operation sequences for part i.
N_s	No. of machines in stage s
N_s	Part shape attribute index
NG_i	Normalized complexity coefficient of G_i
OT_i	Complexity coefficient of part I of the 4 attributes: fixture or jig type, shape, surface treatments, material type
RMS	Reconfigurable manufacturing system
n_i	No. of parts for product i
s_i	Total number of part i's features
$w_a \dots w_z$	Weighted factors for the attributes.

Abstract

In the modern world of competition, having wide variety of products is main challenge, the manufacturing industry is facing nowadays. They mainly focus on customization of products, which increases the complexity in a lot of many ways in manufacturing system. Thus, to tackle this challenge a novel metric is suggested in this work, which mainly focus on product complexity. This includes product manufacturing complexity and products assembly complexity and integrating both complexities to have a combined complexity of a product. The manufacturing complexity is assessed on the basis of nine attributes, which play a significant role in manufacturing of a product and assembly complexity is assessed on the basis of previous work, which focus om handling and insertion attributes. This complexity metric is then proved by applying on an industrial case study which give the perfect results. So, the suggested complexity metric can serve as a tool for decision making during the design selection of a product or comparison between different products. Thus, measuring the complexity is helpful in reduction of complexity which in result reduces production time and production cost.

Chapter 1: An Overview

The idea that variation in the products design and functions can boost sales in a cutthroat market and bring in more profit has always seemed intuitively enticing. Sales first increase as the products offered become more appealing. Product's variety should be according to customer's choice, but the market trends shows that the increase in variety make the cost of the products expensive which not in favors of customer nor client. returns do not keep up with the costs as variation keeps growing. In such cases, the business is required to offer a variety of the product at lower costs and higher quality. One way to fulfil this obligation is by maximizing the external variety is in direct relation with the complexity of product's manufacturing and assembly and overall systems disturbance. Designing and creating product families is a well-known and efficient way to manage product variation for a few market niches. Product family formation can offer a number of advantages in a production system, which can a reduce complexity of the production system and risks involved in development of a product, the ability of a process of upgradation of products design can become better, improvement in manufacturing processes with better flexibility, in addition to that it helps the optimize use of resources of an organization by managing the variety to cost ratio. When a corporation invests in the development of new product families, its primary goal is to offer its consumers a wide enough selection of options while maintaining an acceptable cost-to-delivered-variety ratio within the limits of their manufacturing capacity.

These greater product variants, shifting consumer preferences, and high production rates have significantly altered the manufacturing paradigms. These problems have given rise to a number of novel automated assembly lines that offer a quick change in both structure and software. Additionally, specialized system configurations for a product family—a collection of products that share a number of characteristics—can be created. This family formation can be based on a number of factors, including the assembly of the components and similarity in shape of the components. All production systems, in general, are composed of a wide range of resources, including workers, experts, managers, tools, machinery, and computers. Due to the evolution of the parts being manufactured, their associated product characteristics, forms, etc., these systems get more and more sophisticated with time. Therefore, operation sequences for part manufacture and assembly sequences for product formation serve as the foundation for modern manufacturing systems' flow lines. These systems have complex architectures because of their highly automated nature. To create complex and elaborate products, numerous production phases like material processing, handling, and transportation are interwoven. These systems' complexity tends to rise along with the frequency of disruptive occurrences like equipment failures. It is important to remember that complexity cannot continue to rise indefinitely, just like many other aspects of existence. Above a certain "upper critical threshold," complexity inevitably ends to increase.

One of the most popular approaches to the quick and economical development of various products is the use of scalable systems. By having the ability to produce a wide variety of complicated items, these systems enable manufacturing of the products at a fixed throughput and may be updated for a bigger throughput with a minimal loss in lead time. The number of stages and the number of machines per stage must be adjusted to meet the new production requirements. Conventional methods often concentrate on changing the number of machines per step while maintaining the same number of stages. Additionally, certain product complexity factors have a direct impact on the stage requirements. These elements, when incorporated into a production structure, will not only decrease potential issues but also decrease lead times.

In this thesis, part- and product-based complexity models that are currently in use are first examined. A novel method of determining the degree of complexity in the manufacture and assembly of a product is devised based on their capabilities and limitations. Nine characteristics of Hasan, 2018 have been chosen as the foundation for part segregation from a variety of potential characteristics. These include:

1. Tool approach direction
2. operation sequences
3. number of features
4. feature type: angular inclined features
5. feature type: curved features
6. fixture type
7. material type
8. part shape
9. surface treatments

Based on these attributes manufacturing complexity of product is calculated and integrates with assembly complexity given by (Samy, 2010) then applied on industrial complex products as a case study and so enhancing their capacities.

It should be emphasized that there are three unique methods for assessing complexity: complexity control, complexity reduction, and complexity prevention (Hasan, PhD Thesis, 2018). Because it aids in streamlining production system flow lines, "complexity prevention" is the type of complexity moderation taken into consideration in this work. The capabilities of the suggested paradigm are demonstrated by an industry case study involving goods with various degrees of complexity.

Outline of Dissertation

The following chapters make up the remainder of the dissertation:

Chapter 2: It presents a thorough survey of the literature on research on scalable systems, part/product family creation, and complexity and its variants. The chapter shows prospects for participation in product family construction based on complexity, part-complexity assessment, and development/modification of scalable systems based on product complexity.

Chapter 3: It presents a proposed product manufacturing complexity metric, integration with existing product assembly complexity, and a thorough methodology are covered in this chapter.

Chapter 4: there is given the application of suggested model on an industrial case study which elaborates the useability of proposed complexity metric with better results.

Chapter 5: Conclusions including novelty of work, its applications are detailed.

Chapter 6: Gives the future recommendations regarding the complexity of a system.

Chapter 2: Literature Review (Motivation)

Objective

This chapter is written with the intention to provide a detailed review of relevant research done in the past. The work is focused on:

- *A brief overview of the major Manufacturing systems in practice today.*
- *Need for Reconfigurable Manufacturing Systems (RMS)*
- *Complexity and the need for its proper assessment in the modern industry.*
- *Existing work done in the domain of complexity and its sub features: part, product and system complexity.*
- *Research carried out in product-family formation along governing factors including complexity.*
- *Review of research work on scalable lines / setups with changing products.*
- *Conclusion of research work.*

Manufacturing Systems

Manufacturing is still a crucial aspect of daily life. The conversion of raw materials into completed goods can be interpreted as the definition of manufacturing when expressed in clear, concise terms (Beamon et al, 1998). Manufacturing was automated in the early 20th century (Goldin et al, 2018). Unorganized production can result in unfinished goods, a low production rate, and other problems. As a result, there was a need to coordinate this production, and the idea of manufacturing systems was born. Since the advent of automation, numerous new systems have been developed (Chryssolouris, 2013). These systems can be categorised into three groups:

1. Dedicated Manufacturing System
2. Flexible-Manufacturing System
3. Reconfigurable-Manufacturing System

The following sections offer a quick overview of these systems:

1.1.1 Dedicated Manufacturing System

In the early twentieth century, automated machines were made up of fixed mechanisms that were made to accomplish just one task. Cork fitting, bottle capping, and fundamental assembly procedures are a few examples of them. These equipment pieces made up the production system called as Dedicated-Manufacturing System (DMS) or Dedicated Manufacturing Lines (DML), which was created specially to fulfil a single, unique purpose (Nagel et al, 1991).

DMS is ideal for high production rates because it is built to create a single product with little to no changes. Operating the devices requires only a minimal amount of training and labor expertise. The machines require little maintenance because they have been refined over time for the same product. As a result, the machine is very expensive. The phrase "dedicated manufacturing lines" comes from the fact that the system has a typical rigid structure and that the machines are typically connected by a number of production lines. The system's overall design is very stiff, therefore its potential for improvement is not very promising. The development of any change in the part specifications is severely hampered by this concentration. Due to its incapacity to adapt to changing consumer expectations in the modern era, DMS is progressively becoming obsolete.

Flexible Manufacturing Systems

Flexible-Manufacturing Systems (FMS) were first introduced in the latter part of the 20th century. Currently, FMS is a highly well-liked production system. The foundation of FMS is cellular manufacturing (Thomas et al, 1988). For each sort of activity, a different manufacturing cell is available. For instance, there could be separate cells for milling, finishing the surface, and drilling activities. In this thesis, FMS is restricted to machining processes that result in metal products. FMS has, nevertheless, generally shown to be appropriate for creating a wide range of goods. Figure 1 depicts an illustration of a flexible manufacturing facility.

FMS is flexible enough to accommodate significant product changes (Gerwin, 1993). Only the drilling cell will need minimal alterations to allow the machine to drill the hole in the new place, for instance, if a hole has been moved in a product's design. DMS is unable to perform this function. Therefore, it is simple to create alternative products by altering the surface finish, the locations of the operations on the surface, etc. By rearranging the operation cells, the order of the operations on the part in FMS can also be altered.

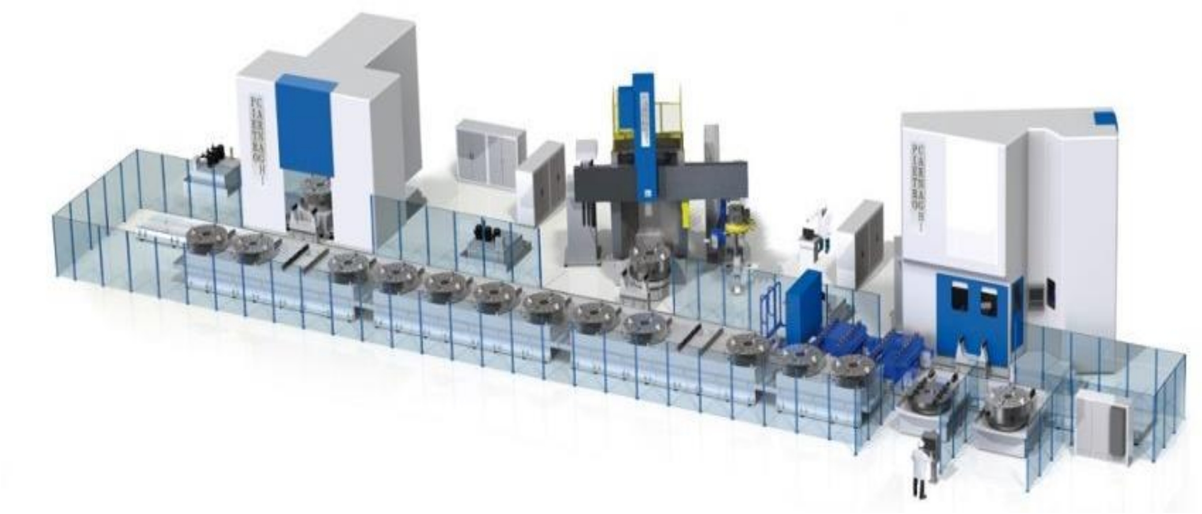

Figure 1: An example of FMS Plant [1].

1.1.2 Reconfigurable Manufacturing System

The idea of Reconfigurable Manufacturing Systems (RMS) developed at the turn of the 20th century (Mehrabi et al, 2000). Using a single platform, this manufacturing system's reconfigurable machines, which have several tool posts and a high degree of freedom, can create a wide range of goods. The primary distinction between RMS and FMS is that the former uses fixed machine architectures while the latter uses a specific set of reconfigurable machines, each of which typically consists of a single unit (see Figure 2). (Manufacturing cells). In the last ten years, the manufacturing industry has evolved a lot of new paradigms (Tao, 2017)

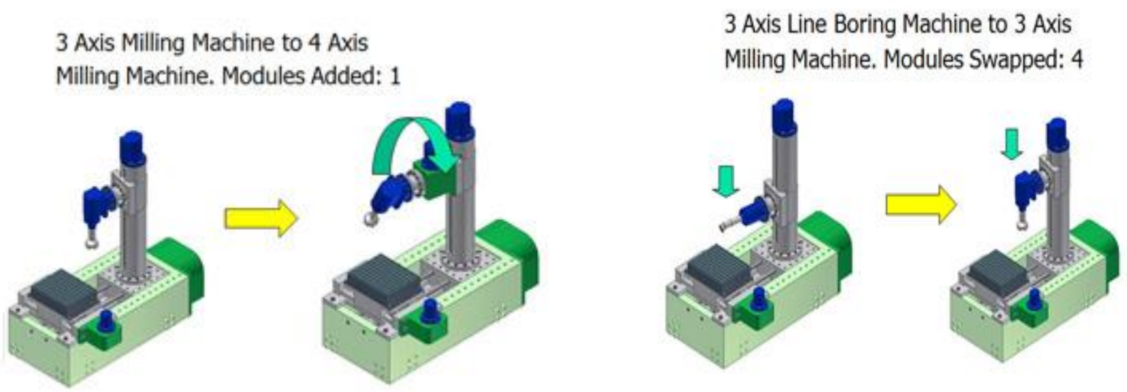

Figure 2: Reconfigurable machines having different capabilities w.r.t. modules attached [2]

[1] http://www.pietrocarnaghi.it/en/42/fms-cell-system.html

[2] http://www.expo21xx.com/automation21xx/15268_st2_university/default.htm

Due to its shorter lead times and flexibility in responding to shifting market trends, RMS is an efficient and effective production method in the modern period where fierce competition and unexpected consumer demands are commonplace (Zheng et al., 2016). By altering the tool posts and sequences, RMS can alter its manufacturing methods from a low quantity single batch production to a large quantity line production (Hu et al., 2011). RMS is primarily intended for automated industries; as a result, two levels of configuration are needed, the first at the system level and the second at the localised machine level, or tooling and tool positioning (Andersen et al., 2015). As a result, RMS also needs two levels of control: software control (Hoffman et al., 2016) at the system level and G&M code (CNC) control (Lesi et al., 2016) at the machine or hardware level. This is started by creating system-level control algorithms (Haddou et al., 2017), and after the system as a whole is configured, the algorithm is transformed into G&M codes that control the CNC machines.

1.1.2.1 Key Characteristics of RMS

Five essential traits of RMS were identified by Y. Koren, and they are still used as a foundation for subsequent research (Koren, 1999). As a result, in order to achieve the design objectives established by the sector, the following important traits are necessary:

1.1.2.1.1 Modularity

All of RMS's components, including its structural parts, axes, controls, software, and tools, are regarded as modular, meaning they can be easily adjusted to meet changing needs (Lameche et al, 2017).

1.1.2.1.2 Integrability

The machine's control modules and the machine itself are built via component integration interfaces. The functional useability of an integrated system can be predicted on the basis of working of its components and the interfaces of both hardware modules and software of a machine.(Farid, 2017).

1.1.2.1.3 Customization

Two separate features of this quality can be distinguished:

- Customized-Flexibility
- Customized-Control

Customized-flexibility refers to giving the linked part family flexibility and designing the machines around it to cut costs.

Using open-architecture technology to integrate control modules that provide the precise functionality required, customized control is made possible (Andersen et al, 2018).

1.1.2.1.4 Convertibility

The capacity to convert configuration in small batches that should be finished in a single day with minimal conversion intervals. To do this, new tools, part-programs, fixtures, and degrees of freedom must be developed (Da Silva et al, 2016).

1.1.2.1.5 Diagnosability

It is critical to swiftly adjust the newly reconfigured system as production systems are modified more frequently and become more reconfigurable. Additionally, quick detection of inferior parts is necessary for this (Sampath et al, 1995).

The reduction in reconfiguration time and effort is a significant benefit of modularity, integrability, and diagnosability. Costs can be cut by customizability and adaptability. These characteristics will be regarded as highly reconfigurable in a system.

1.1.3 **Comparison between DML, FMS and RMS**

Table 1 compares the three manufacturing systems based on a number of characteristics, such as complexity, cost, necessary skill level, production volume, variety, etc., and shows that RMS is generally a better option as a manufacturing system (Koren et al, 2006).

Table 1: Comparison between FMS, DML and RMS.

Factors	**DMS**	**FMS**	**RMS**
Complexity	Low	High	Medium
Initial Cost	High	High	Medium
Training required and Skill level	Low	High	Medium
Integration capacity of new additions	Low	Low	High
Upgradation Potential	Low	Low	High
Structure	Rigid	Rigid	Modular
Product-variety	Low	High–Very High	Medium –High
Production Volume	High	Variable	Variable

Structure of Machine	Fixed	Fixed	Adjustable
Focus of System	Part	Machine	Part Family
Flexibility	No	General	Customized

There is a large quantity of operation sequences and manufacturing methods available to produce any new part that is added to any of the three systems. These can be chosen depending on a variety of criteria, including (but not limited to) the machinery that is available, the needed production rate, and the product quality (tolerance limit). There are many practical designs that can be used for every given production unit that are both within the capability of the currently available machinery and economically viable for the system (Abdi et al, 2018).

Understanding the manufacturing system is a prerequisite for developing process plans (operation sequences). When using computer-aided process planning systems (CAPP) traditionally, the parts of machine are thought of as static and only one process plan is created for the system (dedicated-manufacturing lines). However, much recent research has been focused on creating various process plans and a framework to apply them. Reconfigurable process planning (RPP), the CAPP for RMS, offers a great deal of latitude in this area. Multiple process plans can be created, and from those process plans, various machine configurations can be derived (Baqai, 2009). Figure 3 provides an illustration of this idea.

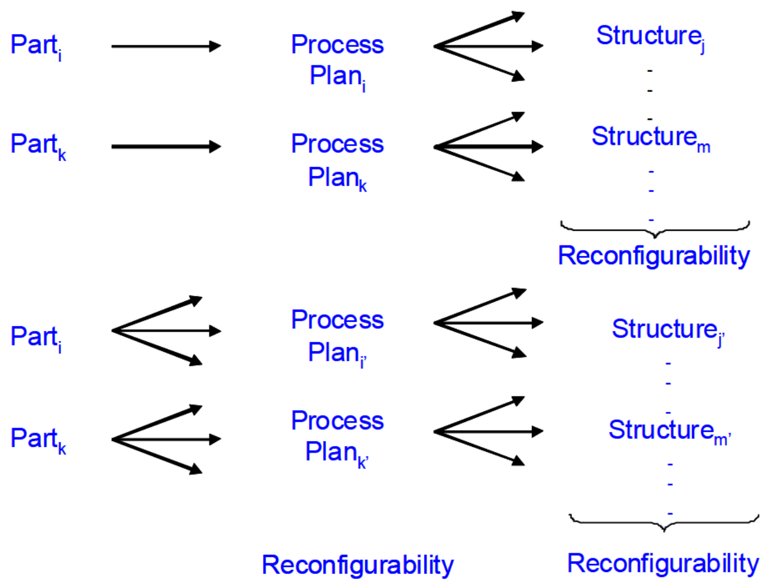

Figure 3: Enhancement of the domain of reconfigurability (Baqai, 2009)

The traditional methods involve creating a single process plan for a single portion, after which there are numerous possibilities for choosing the structure of that single process plan. For a single part, there are various RPP-related process plan options. As a result, the structure's potentialities are increased. Selecting a process strategy is a labor-intensive operation that takes a lot of time. Even so, it is quite uncommon to choose a specific process plan that will be quick, produce accurate results, and just need basic equipment. In light of the selection criteria, various process strategies exist that are appropriate for a single product. A specific process plan might be appropriate, for instance, if the selection criterion is production rate, but it might not be appropriate if the selection criterion switches to quality, and so on.

Review on Reconfigurable Systems

Unexpected changes in consumer demand are transforming items at an accelerating rate. These modifications serve as the foundation for the introduction of novel materials and production techniques. Such modifications have also led to increasing production variations, which have resulted in unanticipated and expensive delays—a characteristic frequently related to the ongoing development in the field of reconfigurable manufacturing systems (RMS). O. Garro created the first reconfigurable machine tool (RMT) in 1992 by suggesting a design methodology for creating machine tools (Garro, 1992). Tollenaere then improved the process by incorporating machining elements and machine equipment (Tollenaere, 1998). The next strategy led to "Machining RMTs," which are machines with multiple spindles and a variety of tools to help the machine perform several "operations" at once. These operations can be used sequentially, concurrently, or as a combination of both. Lead times are shortened by using parallel machining, however complications like reduced accessibility owing to size and vibrations (many spindles) simultaneously arise. On the other hand, sequential processes require more time but are advantageous because the vibrations are generally minimal. Thus, a variety of parameters, including the key ones of the required lead time and tolerance limit, influence the choice of the best mode of operation. In 1993, O. Garro et al. also developed a temporal logic for the mathematical foundation of operation sequencing. Chu et al. offered various methods for the element of process planning that deals with setup minimization (Chu, 1996). In following years, other design tool techniques emerged, with the first one being introduced by Moon and Kota (Moon and Kota, 2002; Moon, 2000).

Koren et al. offered several methods for the machine structure quality analysis (Koren and Katz, 2003; Koren and Moon, 2003). The full analysis of these machine structures was further completed by Bonev (Bonev, 2003), and then by Yousef et al. (Yousef, 2006). Additionally, Ismail et al. suggested combining the ideas of flow lines and RMS (Ismail, 2008). Later, optimization approaches were applied to flow lines as well as part sequencing (Quanwei, 2015), product architectures and machine capability optimization (Asghar, 2018).

Cellular manufacturing's conceptual underpinnings are built on group technology, which groups together parts that are similar based on a variety of characteristics (Groover, 2007). The foundation of part family formation is "Cellular Manufacturing," just like in many other parts of Reconfigurable Manufacturing Systems (RMS). Researchers from many fields have classified parts into part families in literature based on a variety of criteria. These include demand, reusability, modularity, and operational similarity. Yousef et al. created a favourable selection model as a result of optimal machine configuration (Yousef, 2006). Shabaka et al. improved the model by include the idea of minimum machine configuration selection (Shabaka, 2007). Therefore, the emphasis of these strategies was to increase manufacturability while controlling modularity and reconfigurability, thereby lowering complexity. These ideas go beyond what conventional production methods can do. Modern systems should not only be modular (Costa, 2001) (customizable and adaptable to change), but also affordable and capable of high speed (Li, 2017). Such high and complex requirements for part manufacturing introduce "complexity" into the system, resulting in unanticipated backlogs and losses.

1.1.4 **Complexity**

There is no agreed-upon definition of "complexity" and the term itself is ambiguous. Complexus originally meant "entwined" or "twisted together" in Latin. Similar to the meaning of "complex" in the Oxford Dictionary, which is something made up of (often numerous) tightly connected elements (Stanwoski, 2011). A system is deemed more complicated in the field of manufacturing systems if it has a disproportionate number of pieces or components and more connections between them.

One of the main difficulties facing manufacturing sectors in the modern, highly automated world is complexity (Baines et al, 2009). Generally speaking, any manufacturing system is made up of a variety of employees, experts, managers, tools, machines, and computers. These systems get more and more complicated over time. Supervisors and managers should place a high priority on managing complexity (Steger, 2007). Researchers have demonstrated in the past that productivity problems result from disregarding complexity

(Lindemann, 2008). Hubbert et al(Hubbert, .'s 2008) research demonstrated that the Mercedes E-series' sophisticated electric systems had serious issues. Complexity was cited as the main expense driver by managers in an automated industry survey by 64 percent of respondents (Figure 4). (Schleich, 2007). Complexity has evolved into a crucial criterion for product development as a result of similar problems in products in a relatively short period of time (Ulrich, 2003).

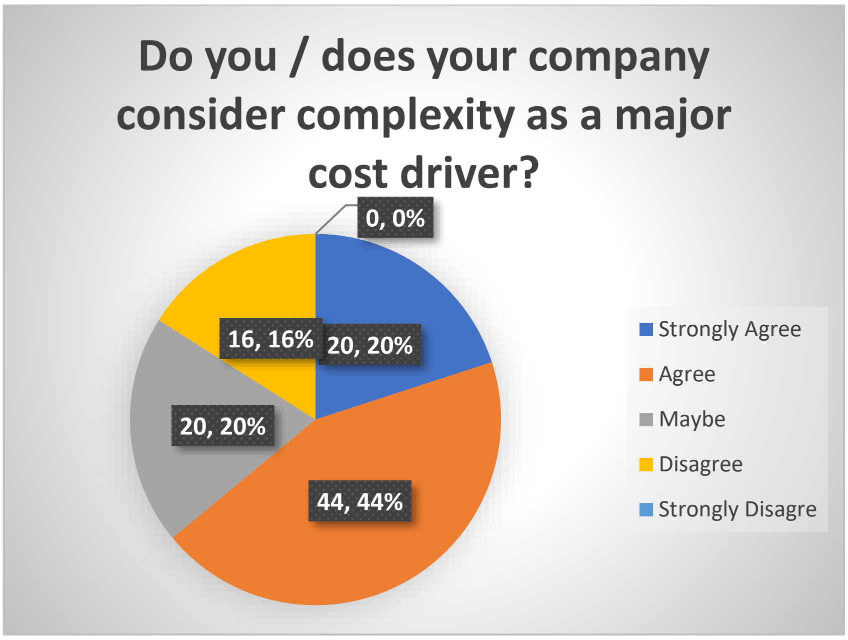

Figure 4: Managers consideration about complexity and cost? (Schleich, 2007)

There are some characteristics that modern manufacturing systems can have in common, such as the abundance of different elements, the shifting interactions between these elements, and technological advancements. Limiting the adoption of new technologies should be done if they are not increasing productivity (Kuzgunkaya, 2006). Since complex systems cannot be simply simplified, the top management must show a real commitment to managing such systems (Steger, 2007). Additionally, proper differentiation between the various approaches addressing complexity, such as complexity prevention, complexity reduction, and complexity control, is necessary for proper complexity management (Figure 5) (Bednar, 2014).

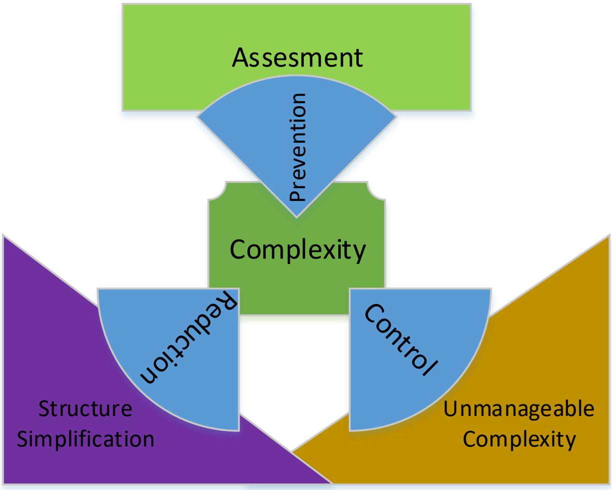

Figure 5: Complexity & its Measures (Bednar, 2014)

Complexity Prevention

The creation of models to evaluate complexity is the main goal of complexity prevention. The models that have already been created can be used at various stages of development, from the conceptual phase to an operational manufacturing setup. The effectiveness of complexity prevention is higher at the conceptual stage, which includes helping to compare various tools, equipment, settings, etc. as well as (in some situations) simplifying manufacturing setups (Blecker et al, 2004).

Complexity Reduction

The goal of complexity reduction is to make structures simpler. It is a temporary measure that, for example, aids in the elimination of unprofitable product versions or the reduction of customer system components (Matt, 2007).

Complexity Control

The remaining complexity that cannot be minimized by the earlier procedures is the focus of complexity control. Included in this is the complexity brought on by shifting market trends, a wide range of consumer needs, adaptable industry objectives, and so forth.

Complexity prevention was chosen as the intervention for this work for three main reasons: The construction of a model to evaluate complexity at the conceptual/design stage will be aided, ultimately leading to a preliminary simplification. The concept will also be implementable at a later time, giving the business a variety of remodeling options should they be needed. The model will also help in reaching the required throughput with the least amount of additional machine constructions.

Particularly for elaborate items that would otherwise require costly manufacturing setups to be developed, system simplification has a considerable impact on both direct and indirect costs (Brooks et al, 2000). Complexity is treated as a flaw in the system by researchers who are committed to creating methods for dealing with it (Mehra et al, 1996). Therefore, their strategies center on either completely avoiding complexity or drastically reducing it (Nelles, 2013). It should be observed, nevertheless, that rigidity or negativity in the system are not always brought about by complexity. Additionally, the system may become more positive and flexible as a result (Burnwal, 2013). Manufacturing setups will likely change over time to become more capable and adaptable machines since ongoing product variation will have an impact on them. Therefore, benefits of complexity should be utilized whenever available (Zhang et al, 2000).

Complex products are produced by integrating several production phases, such as material processing, handling, and transportation, in today's extremely complex manufacturing systems (Iansiti et al, 2007). As disruptive occurrences like machine breakdowns also start to take place, the complexity of the system is seen to further expand (Cho, 2009). However, there is an upper critical-threshold limit, above which complexity cannot continue to rise indefinitely. The system may be harmed or fail if this limit is exceeded.

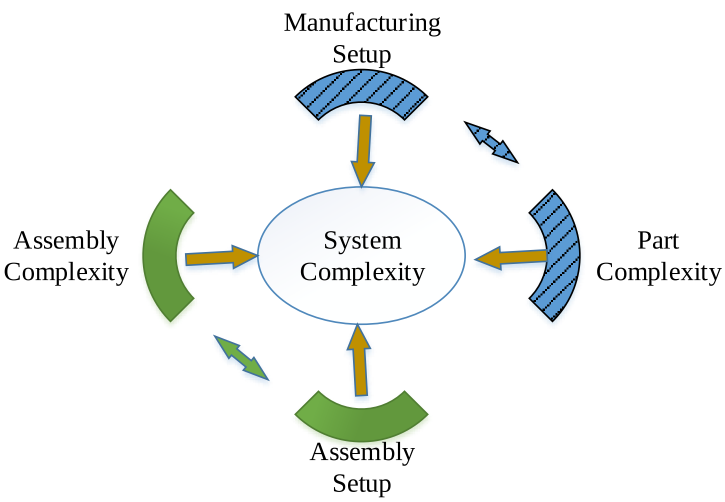

Figure 6: Manufacturing System Complexity

Due to complexity's covert nature, attention has switched to "quantifying" product complexity and the development of product families (Samy, 2010). (Kashkoush, 2015). The resulting algorithms concentrated on assembly system optimization (Al-Geddaway, 2015). Four key areas must be examined in order to actively assess the product's overall complexity: I the complexity of the part's individual parts; (ii) the setups that will produce the part; (iii) the complexity of the part for assembly; and (iv) the complexity of the setups that will assemble the part (see Figure 6). It was noted that the complexity of the portion itself was not thoroughly covered in literature. Additionally, a standard strategy that considers all four of the previously described factors should be developed, as this will not only make it easier to execute complexity assessments but also eliminate many complexity-related problems at the conception and design stages. But given the size of the manufacturing and assembly industries, it is unlikely that a unified strategy will be developed any time soon. Therefore, the research teams' present course entails creating modular mathematical models that may be integrated with other models to increase the functionality of the original systems. Theoretically, this should advance the study toward a cohesive strategy for the entire production and assembly process.

Product Family Formation

For RMS, Abdi et al. (Abdi, 2004) developed an approach based on operational similarities for grouping part families using the Jaccard similarity coefficient (McAuley, 1972). Galan et al. (Galan, 2007) offered a feasible approach by including many features, such as reusability, modularity, compatibility, commonality and demand, as opposed to employing a single criterion. The five coefficients were combined using a weighting technique called the Analytic-Hierarchy Process (AHP) (Vadiya, 2006), and then a clustering method known as average-linkage hierarchal clustering (Seifoddini, 1989) was used to create a binary linkage rooted tree known as a dendrogram (Kashkoush, 2014). Rakesh et al. suggested a modified existing clustering technique on the basis of idea of Jaccard-similarity coefficient (Rakesh, 2010).

A dual criterion based evolutionary genetic algorithm for the establishment of production families was created by Pattanaik et al. taking into account the capability and functionality of RMS (Goyal, 2013). In machining applications and manufacturing, it is usual to arrange items based on the order of processes. To handle numerous products on the same line and minimise the number of reconfigurations necessary, Galan et al. stated that it is crucial to take the operation sequence into consideration while grouping parts (Galan, 2007). Therefore, variety management of items appears frequently in literature (ElMaraghy H., 2013).

1.1.5 **Complexity as a Product Family Formation Criterion**

For the segregation of product into groups, several criteria exist, such as product size, shape, throughput, and so forth, have been utilized in the past. What justifies the formation of product families at the onset of complexity? As we've previously stated, failing to account for complexity during the design phase may result in severe backlogs and delays (Pirmoradi et al, 2014). The Mercedes E-series electric systems might have been sufficiently simplified to avoid the complexity-based concerns if a product family had been created based on complexity (Schleich et al, 2007). Additionally, the intricacy of the product may not contribute as much to its cost.

An improved method for forming product families is to evaluate the level of complexity of the existing modular product families (Weiser, 2016). Multiple elements contribute to the overall complexity of reconfigurable systems (Wang, 2016). (Papakostas, 2009). These consist of things like connectivity between parts, part features, and operation sequences. Elmaraghy (2012) states that while some of these factors affect component manufacturing difficulty, others have an impact on part assembly complexity (Samy, 2010). These elements allow for the computation of the product's total complexity (Wang, 2011), which aids in the creation of product families.

The research revealed that although a number of criteria have been utilised to create product families (Galan, 2007), complexity in combination with the binary rooted trees has not been investigated. Product families can be created based on the rising levels of complexity using the complexity of the individual pieces and the complexity of the overall product. It should be highlighted that one of the considerations for the establishment of product families is complexity (Esmaeilian et al, 2016). Additionally, there is enough of a "gap" to work toward product family creation based on complexity while taking other criteria, like assembly joints, into account (Hasan et al, 2018). This will loosen the bond between complicated and simple items by grouping together the products with similar levels of complexity, minimising disruption in the assembly setup, and helping to resolve some complexity-related concerns. As a result, the subject study proposes a strategy for grouping products into families based on complexity. In the following chapter, the methodology for the approach is explained in depth.

1.1.6 **Product Line Balancing**

The increase in productivity is one of the big challenges facing the industrial industry (Rubmann et al, 2015). A manufacturing system's performance has a direct impact on its productivity (Sundar et al, 2014). The expense and effort necessary to simplify the product cannot be justified if the complexity-based simplification does not reduce costs or achieve throughput requirements (Sagawa et al, 2015). Earlier in the history of manufacturing, it was thought that a optimum production line could offer the highest output (Hasan, 2016). Three key criteria of a balanced production line (Figure 7) include equal mean operation times at all stations, same statistical distributions for all of the mean operation times, and equal variation in mean operation times (Hasan et al, 2016).

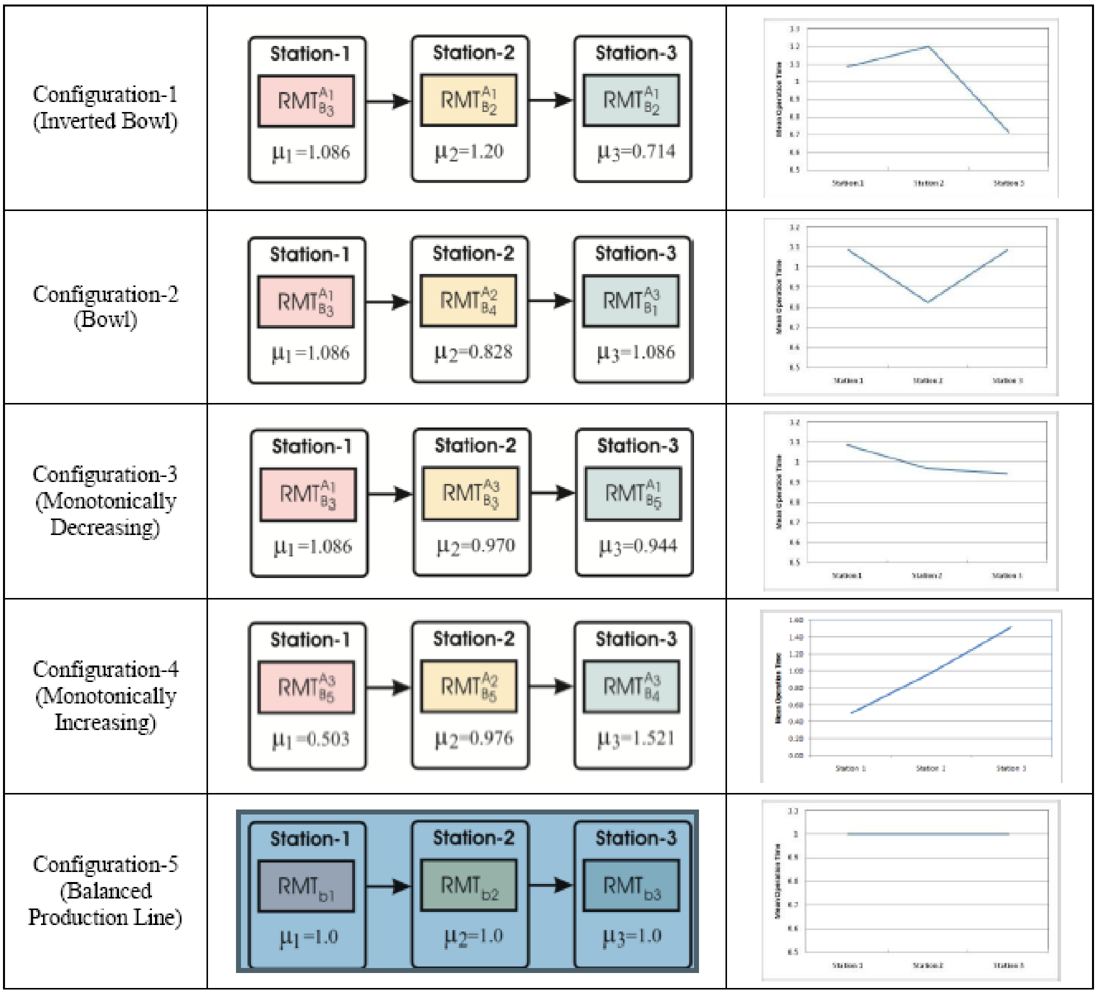

Figure 7: configuration of possible production line along with the mean operation shape (Hasan et al, 2016)

It is typically quite difficult to achieve all three production line balancing criteria because of the variety and complexity of the products. As a result, researchers looked at the effects of shifting the production lines out of balance (Das, 2010). Hiller and Boling (Hiller, 1966; Hiller, 1967) came to the conclusion that, in certain circumstances, a stochastic production line that was purposefully bowl-shaped and intentionally unbalanced (with mean operation-times increasing from the middle to the end of the line) was significantly more productive than a balanced-production line (Hiller, 1967). Other typical production line layouts include monotonically increasing, monotonically decreasing, and inverted bowl (Das, 2010). Additionally, it should be remembered that most production systems are built for a specified capacity based on a demand projection (Tang, 2003). Due to this, the system will find it increasingly difficult to satisfy future demand for new items (Koren, 2010): Stack overflow is a possibility if demand is higher than production capacity on the one hand (Silva et al, 2017). On the other hand, some stations might remain idle if demand is considerably lower than the output capacity. Even when the system is operating at maximum capacity, the duration may occasionally be shorter than the entire product life cycle (Degarmo, 1997). In conclusion, the type of production line chosen will largely depend on the rate of production and the nature / specifications of the particular items. For our efforts, the balanced production line with equal mean operating times during each stage of setup continues to be the main focus.

1.1.7 **Scalable Systems**

The creation of a system with the ability to adjust its capacity in response to demand is one of the answers to the problems covered in the preceding section. Scalability is a more popular term for this quality (Wu et al, 2015). This enables future throughput change based on product demand in a prompt and efficient manner (Koren, 1999; Landers, 2001). Scalable systems have two major characteristics: quick capacity change (just when required) and incremental capacity change (exactly how much increase or reduction needed) (Singh, 2013).

Scalability is a crucial aspect of RMS (Koren, 1999). This relatively new manufacturing system may change machine functionality and capacity to accommodate a wide range of products and production volumes (Elmaraghy H., 2005). Modularity, integrability, convertibility, diagnosability, and customisation are further crucial traits that have already been mentioned. RMTs (Moon, 2002) can be adapted to do a specific, tailored range of tasks, in contrast to standard CNCs, which are general-purpose machines. In the event that a change in production is required, they can also be modified (by switching machine modules) to carry out a different set of tasks. RMT modules can be divided into two categories: basic/essential modules and auxiliary modules (Gadalla et al, 2017). The machines' structural components, such as the sides, beams and columns, beds, housing, etc., are all regarded as basic modules (Scholz et al, 2015). Auxiliary modules include elements that can be changed, such as tool posts, spindles, indexing units, and others. These modules provide the RMTs capability that goes beyond what is offered by typical CNCs. This capacity does (at times) come at the expense of accuracy (Hasan, 2013). As a result, during production, attention must be paid to the tolerances and faults related to part geometry.

The resulting flow line is called as a reconfigurable-product flow line (RPFL) if the RMTs are configured in a way to support the production and/or assembly of a product (Ashraf et al, 2018). This flow line has the flexibility to quickly change its configuration at the outset of product variation and its associated process plans since RMTs are readily available (Hasan, 2013). The RPFL is made up of stations, and each station may have numerous machine sets, just like a traditional flowline. The RMTs' availability of auxiliary modules gives the RPFL the capacity to alter each station's configuration in accordance with the demands of the operation sequence. Generally speaking, there are two primary categories of the product flow line: connected and decoupled (see Figure 8). There are no buffer gaps between stations in coupled flow lines. The stations are reliant on the preceding and next stations in line (Dallery, 1992). A station could be in one of three situations: operating, blocked, or starving. The station is in a working state while it is carrying out any activity or operation on the workpiece. It is advised to create buffer zones between stations to store the job due to these problems. If there are infinitely many buffer stations, it would be ideal for there to be zero blocked and famished stations. The buffers, however, are expensive for the employer and cannot be installed everywhere, making this a less than ideal alternative. To find the best amount of buffers for a setup while conserving cost, an optimum cost analysis is necessary.

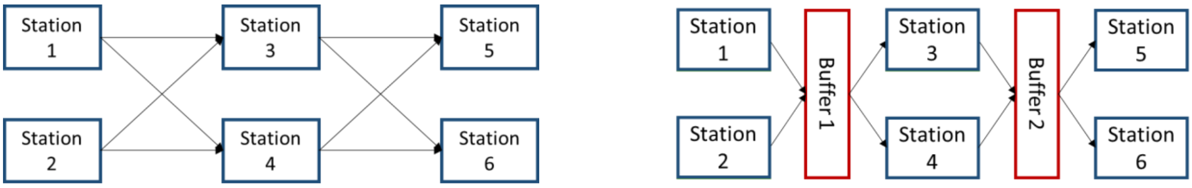

Figure 8: Configurations of flow lines: coupled and decoupled (Dallery, 1992)

Many models have been created in the literature, thanks to the best setup selection (Yousef, 2006; Shabaka, 2007). The variety of RMT machine setups is another element that aggravates the problems. The system becomes more complex as the number of possible configurations grows. Using an algorithm for minimum machine configurations could be a solution (Shabaka, 2007). The amount of parts for the product or the number or kind of stations that will be needed to produce the product are not taken into account by this method, which is instead focused on configuration selection based on product attributes. Another strategy is to build the systems so that they can be scaled up or down with the fewest possible setups or stations (Koren, 2017). Currently, methods are either concentrated on machine level configuration optimization or systems scalability (Wang, 2013; Hasan, 2014). (Bensmaine, 2013; Gadalla, 2017). Thus, it can be concluded that using RMTs to customise configuration level while accommodating complexity goes beyond using traditional methods. In order to avoid complexity-related problems, a production system should not only be modular but also scalable with minimal complexity.

Conclusion of Literature Review

The following are significant deductions from the literature review:

1. Further research is needed on the complexity as selection criteria
2. As a result of its use throughout the design phase, complexity prevention is appropriate for product modelling.
3. There is a lack of a uniform strategy to account for part, product, machine, and setup complexity.
4. There is enough room for research on the creation of product families based on complexity.
5. Complexity-based system modelling has a lot of room for improvement.

A model for the evaluation of part complexity needs to be established in light of these findings. Following that, a system for building product families based on complexity may be developed. The next chapters give the details of methodology for complexity computation.

Chapter 3: A model for the assessment & integration of Product's manufacturing & assembly complexity

Objective:

This chapter is focused on providing the following:

- *Mathematical modeling of part combined complexity*
- *An algorithm and detailed methodology for the proposed complexity metric*
- *Case study of the presented model*

Measuring Part Complexity

In this chapter, an approach to assess the complexity in the production of an individual part is proposed. There are many methodologies available for the calculation of complexity of individual part of a product. complexity of a part is primarily based on many characteristics such as number of features, type of features it include, surface finishing, weights and sizes, along with thickness etc. (Wang et al., 2013). These characteristics can be divided into two main categories: One category, which is related to the complexity of manufacturing of the part and the second category focus on the complexity of assembly of these parts. Different authors worked on different attributes shown in Table_1, but the attributes related to manufacturing of a part are considered by Hasan 2018 who proposed a technique to assess the manufacturing complexity of a product, and S. N. Samy 2010 presented the complexity due to Assembly attributes which is given in the next section of this chapter for the computation of assembly complexity. The flow diagram of the methodology suggested is presented in Figure 9. The first section of this chapter focus on a modified methodology for the computation of complexity of a product during its manufacturing is presented and in the next section assembly complexity of a product (Samy, 2010) is presented and in the last the integration of both manufacturing and assembly complexity is presented which is called combined complexity here.

Measuring Product Manufacturing Complexity

The assumptions made for the manufacturing setup are stated below:

- A reconfigurable or flexible or system is used having the ability to process all the features of considered parts of a product.
- The considered manufacturing system is capable of doing required surface finish.
- There is availability of all tools required for different types of material.

- The considered manufascturing system can have many operation sequences that may be applied according to situation.

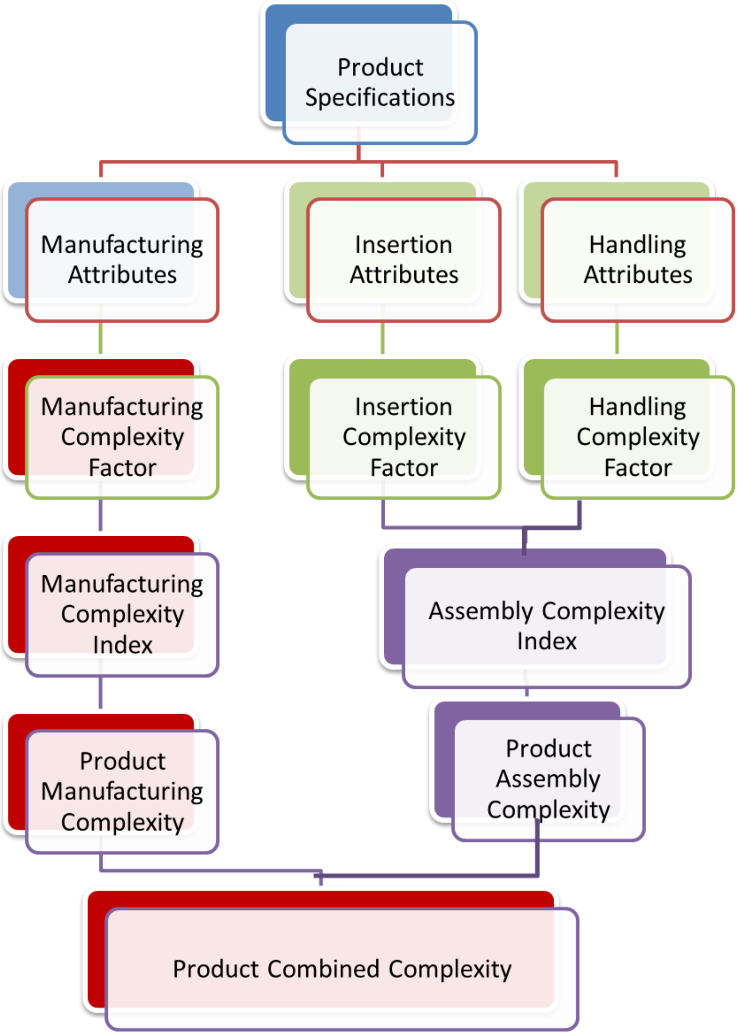

Figure 9: Flow diagram for the suggested methodology of Product Complexity assessment

The attributes which the Hasan, 2018 deemed significant for the computation of manufacturing complexity are listed in **Table *3***. If there is a need by designer for the alteration or addition of new characteristics into the suggested approach, a provision can be provided.

Table 4 presents the numeric values of the nine attributes selected for the computation of products manufacturing complexity. Based on these values factor of complexity of manufacturing is computed at first point then remaining points on the basis of complexity factor.

Table 2: Characteristics considered for manufacturing complexity (Hasan, 2018)

No.	Attribute	Details
1	**Tool Approach Direction (TAD)**	A total of 6 basic TADs exists: +x, -x, +y, -y +z, -z. Higher number of possible TADs for a part add multiple possibilities and thus complexity.
2	**Operation Sequences**	Higher number of Possible Operation Sequences (POS) further complicates the selection process for the appropriate process plan & increases complexity
3	**Feature Type/No of Features**	Higher number/types of independent features add to the complexity of the part.
4	**Angular/Inclined features**	Angular/inclined features like inclined hole(s) require rotation of either the workpiece or the tool, thus further complicating the manufacturing of the part.
5	**Jig/Fixture Type**	Automated fixture types will require additional care for machining.
6	**Material Type**	Harder materials require specialized equipment for their machining.
7	**Part Shape**	Complicated shape will have multiple issues of grasping and induced vibrations.
8	**Surface Treatments**	Additional steps/equipment will be added if any surface treatment is required.
9	**Curved Features**	Curved features like curved slot or tapered holes will further complicate the machining process.

Table 3: Factors considered by other authors for computation of part/product complexity

Authors	**Factors Considered**
Badrous, 2011	Information content, variety, size, dimension, sophistication connectivity, entropy, cognitive complexity, logical complexity, time, TAD, Features, , Operation Sequences
Thome et al, 2016	Component type, , product quantity, product quality. flexibility, steps/ operations , material type, part shape
Genta et al, 2018	Components shape, coupling directions, Forces required, Components alignment, Components geometry, Components size, ratio bt components

Schwabe, 2016	operation , Complexity pattern, cost variance, assemble sequences
Guoliang, 2017	No. of operations, , operation sequences, operation type

Table 4: Attributes for Part *Manufacturing* Complexity (Hasan, 2018)

No.	Aspect	Description	Value	Max. Value	Normalized Value	Sample Value	Sample Normalized Value
A1	TAD	Tool Approach Direction (All)	1-6	6	$T_i = \frac{TAD_i}{6}$	3	0.5
A2	POS	Possible Operation Sequences	G_i	G_{max}	$NG_i = \frac{G_i}{G_{max}}$	10/10	1
A3	Orthogonal features	Feature Type / No of Orthogonal Features	S_i	S_{max}	$C_{FO} = \frac{S_i}{S_{max}}$	5/5	1
A4	Angular / Inclined feature	None	0	2	$C_{FI} = \frac{N_i}{2}$	1	0.5
		Singular	1				
		Multiple	2				
A5	Curved features	None	0	2	$C_{FC} = \frac{N_c}{2}$	1	0.5
		Singular	1				
		Multiple	2				
A6	Jig / Fixture Type	Manual	1	3	$C_{O1} = \frac{N_j}{3}$	3	1
		Semi-Automatic	2				
		Automatic	3				
A7	Material Type	Soft	1	2	$C_{O2} = \frac{N_m}{2}$	1	0.5
		Hard	2				
A8	Part Shape	Simple	1	3	$C_{O3} = \frac{N_s}{3}$	3	1
		Medium	2				
		Complex	3				
A9	Surface Treatment	No Treatment	0	1	C_{O4}	1	1
		Surface Hardened	1				

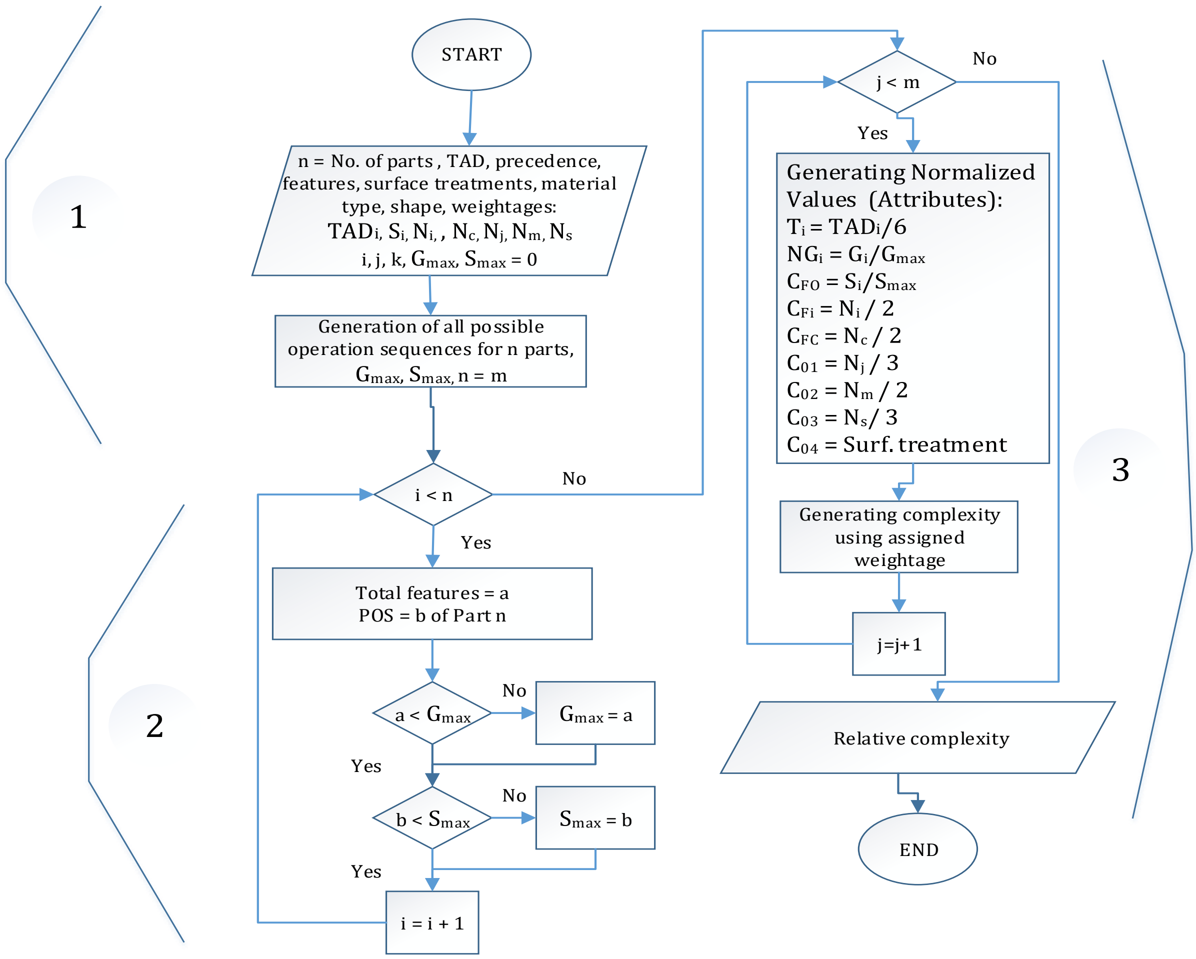

Figure 10: Flow chart for computing the complexity of the part (Hasan, 2018)

Earlier Hasan, 2018 presented a methodology Figure 10 for the computation of part's manufacturing complexity described in Equation *1*, which gives the manufacturing complexity of a part which can be rewritten in more detail in Equation 2 in accordance with their elements as below.

$$C_p = \frac{\sum_{i=1}^{i=f} w_i C_i}{\sum_{j=a}^{w} w_j} \qquad \text{Equation 1}$$

$$C_p = \left(\begin{array}{c} [w_a T_i + w_b NG_i] + \\ \left[w_c \sum_{i=1}^{m} C_{FO}(i,m) + w_d \sum_{j=1}^{n} C_{FI}(j,n) + w_e \sum_{k=1}^{0} C_{FC}(k,o) \right] + \\ \left[\sum_{l=1}^{4} w_l C_{Ol}(l,4) + w_f \sum_{m=1}^{p} C_S(m,p) \right] \end{array} \right) \Big/ \left(w_a + w_b + w_c + w_d + w_e + w_f + \sum_{l=1}^{4} w_l \right)$$

Equation 2

Equation ***2*** gives the elaborated form of Equation *1* describing all the nine attributes and their respective weightages, which can vary according to situations.

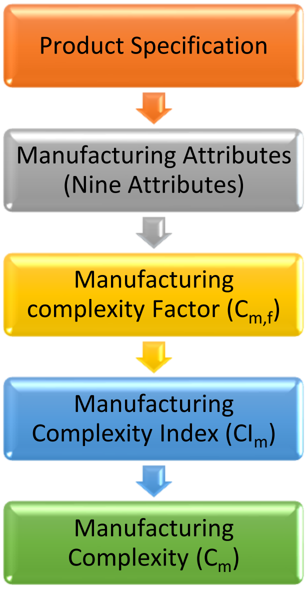

Figure 11: Flow diagram for Product Manufacturing Complexity Computation

In the current research work the methodology is modified from **Figure** ***10*** to **Figure 11** and **Equation** ***2*** is replaced by Equation 3 using the information content definition of complexity by modifying Elmaraghy 2003. The methodology starts with product specification, then based on the nine attributes mention in Table 4 manufacturing complexity factors Equation 4 are computed. These complexity factors then used to compute the manufacturing complexity of a product Equation *3*.

$$C_m = \left(\frac{n_P}{Np} + CI_m \right) [\log_2(Np + 1)]$$ Equation 3

Where C_m is product's manufacturing complexity, n_P is number of unique-parts, Np is total parts numbers in a product and $\mathrm{CI_m}$ is complexity index for manufacturing, which is described in Equation *4*, where $C_{m,f}$ are complexity manufacturing factors, which are calculated from Table 4 by analyzing each part of a product and l is number of attributes.

$$CI_m = \frac{\sum_1^l C_{m,f}}{l} \qquad \text{Equation 4}$$

Case Study: Calculation of manufacturing Complexity of product

Figure 12: Product_1 for computing the complexity of the part

Figure *12* shows a product related to a mechanical industry. It is made up of seven metallic parts which are assembled together to give our product. First of all, we are concerned with the manufacturing of these parts in this stage and will do work on assembly process on later stage. Its manufacturing can be done on automated manufacturing plant, manual manufacturing plant or hybrid manufacturing plant but in our case study all the manufacturing process is being carried out manually, so we will compute the complexities for a manual manufacturing system.

Starting with part_1 as shown in figure, analysis is done to measure the values of complexity related to each attribute (tool approach direction, possible-operation-sequence, orthogonal-features, curved features, inclined features or angular, jig or fixture type, part shape, material type, and surface treatment) listed in the table.

Table 5: Manufacturing Complexities for Part_1 of Product 1

Part Name	Part_1
Number	1
TAD	0.33
POS	0.75
Orthogonal Features	0.19
Angular/inclined	1.00
Curved features	1.00
Jig or fixture type	0.67
Type of Material	1.00
Part-Shape	0.67
Surface-Treatment	0.00

Now Equation *4* is used to calculate the manufacturing complexity index for the given values as follow.

$$CI_m = 0.112208 \qquad \text{Equation 5}$$

In the same way CI_m for remaining parts of the product 1 are computed in table below.

Table 6: Manufacturing Complexities for Part_1 to 7 of Product 1

Part Name	Part_1	Part_2	Part_3	Part_4	Part_5	Part_6	Part_7
Number	1	1	1	1	1	1	1
TAD	0.33	0.50	0.33	0.33	0.50	0.50	0.33
POS	0.75	0.86	1.00	0.70	0.65	0.20	0.20
Orthogonal Features	0.19	0.62	0.79	0.36	0.50	0.60	0.38
Angular/inclined	1.00	1.00	0.50	1.00	0.00	0.00	1.00
Curved features	1.00	0.50	1.00	1.00	0.50	0.50	1.00
Jig/fixture type	0.67	0.33	0.67	0.33	0.33	0.33	0.67
Material Type	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Part Shape	0.67	0.33	0.67	0.33	0.33	0.33	0.33
Surface Treatment	0.00	0.00	0.00	0.00	0.00	0.00	0.00

and the CI_m manufacturing complexity index is computed by using Equation *4*, is given as.

$$CI_m = 0.634 \qquad \text{Equation 6}$$

Now it's time to calculate the C_m the product's manufacturing complexity using Equation *3* as below.

$$C_m = 4.90 \qquad \text{Equation 7}$$

Product's Assembly Complexity

This content is related to the calculation of assembly complexity of the product. The procedure to calculate the assembly complexity of a product is given by S.N. Sammy & H. Elmaraghy 2010. The methodology for the computation of product assembly complexity is shown in the flow chart shown in Figure 13. First step is analyze the attributes considered important for the computation of assembly complexity of a product by Sammy, 2010. The attributes used are grouped into two types handling attributes and insertion attributes which are given in **Table *7***

The procedure for calculating the product assembly complexity is like product manufacturing complexity. Procedure comprised of following steps.

1. Complexity matrix construction based on attributes given in Table 10
2. Handling complexity factor calculation,

$$C_h = \frac{\sum_1^j C_{h,f}}{j} \qquad \text{Equation 8}$$

Where $C_{h,f}$ is the handling-complexity factor and j is the numbers of handling-attributes for each part. Handling complexity factor is calculated by analyzing each part against each attribute and assigned a value according to Table ***7***. The values and attributes considered in this work are for a manual assembly system. For an automated assembly system attributes and respective values are different and can be consulted from S. N. Samy, 2010.

3. Insertion complexity factor calculation

$$C_i = \frac{\sum_1^k C_{i,f}}{k} \qquad \text{Equation 9}$$

Table 7: Attributes for manual Assembly complexity of product by S.N. Samy & H. Elmaraghy 2010

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

where $C_{i,f}$ is the average insertion complexity of each part and k is the numbers of insertion attributes for each part.

4. Based on these factors, calculate the complexity of a part C_{part} given Equation *10* and then compute the complexity index $CI_{product}$ of product shown in Equation *11*.

$$C_{part} = \frac{C_h \sum_1^j C_{h,f} + C_i \sum_1^k C_{i,f}}{\sum_1^j C_{h,f} + \sum_1^k C_{i,f}}$$ Equation 10

$$CI_{product} = \sum_{p=1}^{p=n} x_p C_{part}$$ Equation 11

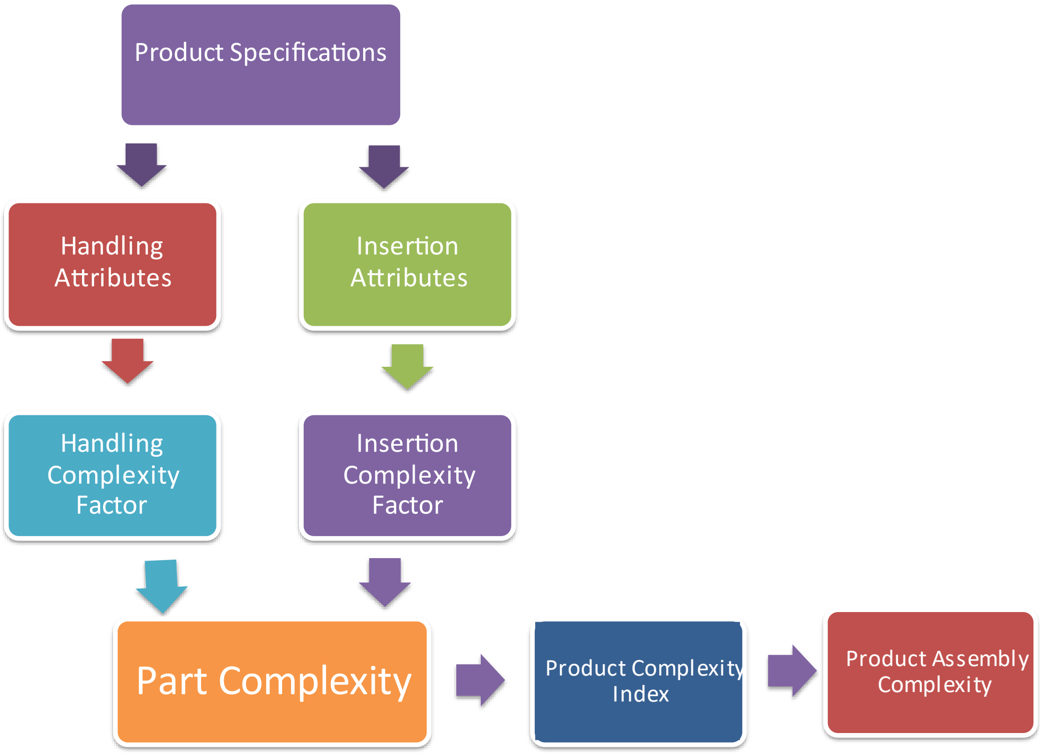

Figure 13: Flow chart for Assembly Complexity Computation (S.N. Samy, 2010)

5. Now using the complexity index Equation 11 we can calculate product assembly complexity using the Equation 12.

$$C_{assembly} = \left(\frac{n_P}{Np} + CI_{product}\right)[log_2(Np+1)] + \left(\frac{ns}{Ns}\right)[log_2(Ns+1)]$$ Equation 12

Case study for the computation of assembly complexity of a product:

Starting with the same product used in the manufacturing complexity is used here for calculation of assembly attributes and related handling complexity factors of part_1 of product 1, which are given in Table 8.

Table 8: Handling attributes of part_1 of product 1

Part name	**Part_1**
Number	1
Symmetry	0.84
Size	0.74
Thickness	0.27
Weight	0.5
Grasping & Manipulation	0.91
Assistance	1
Nesting/tangling	0.58
Optical Magnification	0.8

Next there are given the insertion attributes and related insertion complexity factors of part 1 of product 1 in the Table 9 .

Table 9: Insertion attributes for part_1

Part name	**Part_1**
Number	1
Holding Down	0.54
Alignment	0.86
Insertion resistance	1
Accessibility and vision	0.57
Mechanical Fastening processes	0.42
Non-Mechanical fastening processes	0.58
Non-fastening processes	0.75

Handling complexity factor $C_{h,f}$ for part_1 is presented in Equation *13*

$$C_{h,f} = 2.93 \quad \text{Equation 13}$$

And the insertion complexity factor $C_{i,f}$ for part_1 is presented in Equation 14

$$C_{i,f} = 3.18$$ Equation 14

In the same way we have calculated the following Table 10 values for both insertion and handling attributes and related insertion and handling complexity factors of all parts of product 1.

Table 10: Handling and insertion attributes of all parts

Part name	**Part_ 1**	**Part_ 2**	**Part_ 3**	**Part_ 4**	**Part_ 5**	**Part_ 6**	**Part_ 7**
Number	1	1	1	1	1	1	1
Symmetry	0.84	0.94	0.94	0.94	0.84	0.94	0.7
size	0.74	0.74	0.74	0.74	0.74	0.74	0.74
Thickness	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Weight	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Grasping & Manipulation	0.91	0.91	0.91	0.91	0.91	0.91	0.91
Assistance	1	0.75	1	0.75	1	0.75	0.75
Nesting/tangling	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Optical Magnification	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Holding Down	0.54	1	1	0.54	1	0.54	0.54
Alignment	0.86	1	1	0.86	1	0.86	0.86
Insertion resistance	1	0.87	1	0.87	1	0.87	0.87
Accessibility and vision	0.57	0.57	0.81	0.57	0.57	0.81	0.57
Mechanical Fastening processes	0.42	0	0.42	0	0.42	0	0
Non-Mechanical fastening processes	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Non-fastening processes	0.75	0.75	0.75	0.75	0.75	0.75	0.75

Mean of handling complexity_factor for all parts of product is given in Equation *15*

$$C_h = 4.84$$ Equation 15

And mean of insertion complexity_factor for all parts of product is given in Equation *16*

$$C_i = 4.72$$ Equation 16

By using Equation *10* and then Equation *11* the assembly complexity indexis computed and stated in Equation *17*

$$CI_{product} = 0.665 \qquad \text{Equation 17}$$

So, using the Equation *12*,the assembly complexity of the product 1 computes and stated in Equation *18*. Here n_p is number of unique parts is 7 and N_p the total number of parts is also 7 and n_s the number of unique fasteners is 1 and total numbers of fasteners is also 1.

$$C_{assembly} = 4.99 \qquad \text{Equation 18}$$

Integration of manufacturing complexity and assembly complexity

In literature there are many types of complexities exists as we have studied earlier like manufacturing complexity, process complexity, assembly complexity etc. but here we are presenting a novel complexity metric by integrating the manufacturing complexity and assembly complexity of a product (S.N.Samy & Elmaraghy 2010), which gives us the combined effect of manufacturing attributes, handling attributes and insertion attributes as describe in the Equation *19*

$$C_{product} = \frac{w_a}{w_a+w_m} * \left(\frac{n_P}{Np} + CI_a\right)\left[\log_2(Np+1)\right] + \left(\frac{ns}{Ns}\right)\left[\log_2(Ns+1)\right] + \frac{w_m}{w_a+w_m} * \left(\frac{n_P}{Np} + CI_m\right)\left[\log_2(Np+1)\right] \qquad \text{Equation 19}$$

Here $C_{product}$ is the suggested combined complexity of the product, n_P is the number of unique parts in a product, Np is the total number of parts in the products, CI_a is the assembly complexity index, CI_m is the manufacturing complexity index, and w_a & w_m are weight for assembly and manufacturing respectively which may vary for each product.

Example:

By using Equation *19* the suggested combined complexity of the product 1 can be computed and presented in Equation *20*, which comes as 4.95 where the values of weights w_a & w_m is equal to 1 for ideal condition. The values of weights can be varied according to situation and can be computed by doing experiments.

$$C_{product} = 4.95 \qquad \text{Equation 20}$$

Normalization of Complexity:

The computed complexity of products can give the better insights for comparison by normalization. It can be done by dividing the obtained complexity with maximum complexity i.e. complexity obtained at value of CI_m, CI_a =1.

$$Cnormalized = Cproduct / Cmax \qquad \text{Equation 21}$$

Conclusion of the chapter

Although a significant number of complexity measures exist in literature that cover a wide range of part / product aspects, but still, a complexity metric assimilating sequence based and feature based attributes of a part for manufacturing and handling based attributes and insertion-based attributes which are important in assembly of a product has not been fully explored. Thus, this chapter suggested an integrated complexity metric which has the following capabilities:

- It can assimilate manufacturing-based attributes comprises of feature-based aspects as and when required by the designer.
- It can assimilate the assembly-based attributes which mainly comprised of handling and insertion attributes.
- It can be incorporated into other strategies that other authors have previously presented.

Chapter 4: Implementation of Proposed Model on an Industrial Case Study

The suggested model for the computation of product combined complexity is elaborated by considering four products manufactures and assembles in a mechanical industry shown in Figure 14 to Figure 17. It can be said that, the subtractive manufacturing and assembly techniques-based industry is the focus of this model. Products were selected on the basis of many characteristics means feature variety types as well as number of features and aspects related to manufacturing techniques and as well as handling and insertion attributes related to assembly aspects.

Figure 14: Specifications of Product 1

The suggested combined complexity for product 1 has been calculated in the previous chapter. In the same way the suggested combined complexity for the other three product will be calculated in this chapter.

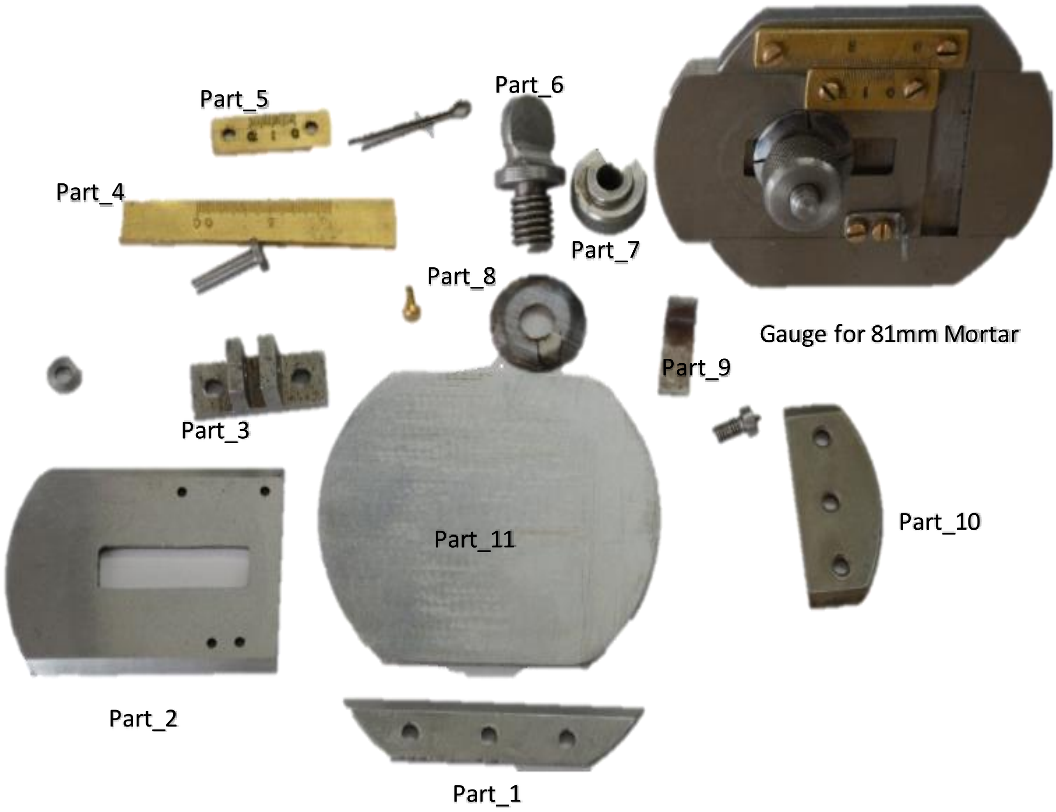

Figure 15: Specifications of Product 2

Figure 16: Specifications of Product 3

Figure 17: Specifications of Product 4 (VPC Socket)

2.1 Working

The product 1 is firing body used in mechanical industry, has seven parts. The values for the all attributes of manufacturing and handling and insertion complexity factors for the product 1 are given in the Table 11 .

Table 11: Manufacturing and Assembly attributes for Product 1

Part name	Part_1	Part_2	Part_3	Part_4	Part_5	Part_6	Part_7
TAD	0.33	0.50	0.33	0.33	0.50	0.50	0.33
POS	0.75	0.86	1.00	0.70	0.65	0.20	0.20
Material Type	0.19	0.62	0.79	0.36	0.50	0.60	0.38
Insertion resistance	1.00	1.00	0.50	1.00	0.00	0.00	1.00
Alignment	1.00	0.50	1.00	1.00	0.50	0.50	1.00
Grasping & Manipulation	0.67	0.33	0.67	0.33	0.33	0.33	0.67
Symmetry	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Assistance	0.67	0.33	0.67	0.33	0.33	0.33	0.33
Optical Magnification	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Curved features	1.00	0.50	1.00	1.00	0.50	0.50	1.00
Non-fastening processes	0.75	0.75	0.75	0.75	0.75	0.75	0.75
size	0.74	0.74	0.74	0.74	0.74	0.74	0.74
Holding Down	0.54	1.00	1.00	0.54	1.00	0.54	0.54

Angular/inclined	1.00	1.00	0.50	1.00	0.00	0.00	1.00
Accessibility and vision	0.57	0.57	0.81	0.57	0.57	0.81	0.57
Nesting/tangling	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Non-Mechanical fastening processes	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Weight	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Orthogonal Features	0.19	0.62	0.79	0.36	0.50	0.60	0.38
Jig/fixture type	0.67	0.33	0.67	0.33	0.33	0.33	0.67
Part Shape	0.67	0.33	0.67	0.33	0.33	0.33	0.33
Thickness	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Mechanical Fastening processes	0.42	0.00	0.42	0.00	0.42	0.00	0.00
Surface Treatment	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The product 2 is bore measuring gauge widely used in an industry has eleven parts. The values for the complexity factors of manufacturing attributes, handling attributes and insertion attributes are all given in

Table 12: Manufacturing and Assembly attributes for Product 2

Part name	**Part _1**	**Part _2**	**Part _3**	**Part _4**	**Part _5**	**Part _6**	**Part _7**	**Part _8**	**Part _9**	**Part_ 10**	**Part_ 11**
Number	2.00	1.00	2.00	1.00	1.00	2.00	1.00	1.00	1.00	1.00	1.00
Symmetry	0.94	1.00	0.94	0.94	0.94	1.00	0.94	0.84	1.00	0.94	0.84
size	0.74	0.74	0.74	0.74	0.74	0.81	0.74	0.81	0.81	0.74	0.74
Thickness	0.27	0.27	0.27	0.50	0.50	0.27	0.27	0.50	0.50	0.50	0.50
Weight	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Grasping & Manipulation	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	1.00	0.91	0.91
Assistance	1.00	0.75	1.00	0.34	0.34	0.34	0.34	0.34	1.00	0.34	0.34
Nesting/tangling	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Optical Magnification	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Holding Down	1.00	0.54	1.00	0.54	0.54	0.54	0.54	0.54	0.54	0.54	1.00
Alignment	0.86	0.86	1.00	1.00	1.00	0.86	0.86	0.86	1.00	1.00	0.86
Insertion resistance	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
Accessibility and vision	0.57	0.57	0.57	0.57	0.57	0.81	0.57	0.57	0.57	0.57	0.57
Mechanical Fastening processes	0.42	0.00	0.42	0.58	0.58	0.58	0.00	0.00	0.58	0.58	0.58

Non-Mechanical fastening processes	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Non-fastening processes	0.75	0.75	0.75	0.00	0.00	0.75	0.75	0.75	0.00	0.00	0.75
TAD	0.50	0.50	0.33	0.33	0.33	0.50	0.33	0.17	0.33	0.50	0.50
POS	0.71	0.79	1.00	0.50	0.50	0.57	0.43	0.43	0.50	0.71	0.43
Orthogonal Features	0.67	0.73	1.00	1.00	1.00	0.25	0.42	1.00	1.00	0.67	0.67
Angular/inclined	0.50	1.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	0.00
Curved features	1.00	0.50	0.00	0.00	0.00	1.00	1.00	0.50	0.00	0.50	1.00
Jig/fixture type	0.67	0.67	0.33	0.33	0.33	0.67	0.67	0.33	0.33	0.67	0.67
Material Type	1.00	1.00	1.00	0.50	0.50	1.00	1.00	0.50	0.50	1.00	1.00
Part Shape	0.67	0.67	0.33	0.33	0.33	0.67	0.67	0.33	0.33	0.67	0.33
Surface Treatment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Similarly, the product 3 is solenoid which is used in a mechanical industry, it has sixteen parts and twenty-one fasteners. The values for manufacturing, handling and insertion complexity factors are all combinedly given in Table *13*.

Table 13: Manufacturing and Assembly attributes for Product 4

Part name	**Part_1**	**Part_2**	**Part_3**	**Part_4**
Number	1	1	1	1
Symmetry	0.7	0.7	0.7	0.7
size	0.74	0.74	0.74	0.74
Thickness	0.27	0.27	0.27	0.27
Weight	0.5	0.5	0.5	0.5
Grasping & Manipulation	0.91	0.91	0.91	0.91
Assistance	0.34	0.34	1	0.75
Nesting/tangling	0.58	0.58	0.58	0.58
Optical Magnification	0.8	0.8	0.8	0.8
Holding Down	0.54	0.54	0.54	0.54
Alignment	0.86	0.86	0.86	0.86
Insertion resistance	0.87	1	1	0.87
Accessibility and vision	0.57	0.57	0.57	0.57
Mechanical Fastening processes	0	0	0.42	0
Non-Mechanical fastening processes	0.58	0.58	0.58	0.58
Non-fastening processes	0.75	0.75	0	0.75
TAD	0.33	0.33	0.33	0.33
POS	1.00	0.02	0.14	0.00
Orthogonal Features	0.53	0.67	0.73	0.75
Angular/inclined	1.00	1.00	0.50	0.00
Curved features	1.00	0.50	1.00	1.00
Jig/fixture type	0.33	0.33	0.33	0.33
Material Type	1.00	1.00	1.00	0.50
Part Shape	0.67	0.67	0.33	0.33
Surface Treatment	0.00	0.00	0.00	0.00

Table 14: Manufacturing and Assembly attributes for Product 3

Part name	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Number	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1
Symmetry	0.84	1	0.7	0.7	0.7	0.7	0.7	1	1	0.84	0.94	0.94	0.7	0.84	0.94	0.7
size	0.74	0.74	0.81	0.81	0.74	0.81	0.74	0.74	0.74	0.74	0.81	0.74	0.74	0.74	0.74	0.74
Thickness	0.27	0.27	0.5	0.27	0.27	0.5	0.27	0.27	0.27	0.5	0.27	0.27	0.27	0.27	0.27	0.27
Weight	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Grasping & Manipulation	0.91	0.91	0.91	1	0.91	1	0.91	0.91	0.91	0.91	1	0.91	0.91	0.91	0.91	0.91
Assistance	1	1	1	0.75	0.75	0.75	0.75	1	1	0.75	1	0.75	0.75	0.75	1	0.75
Nesting/tangling	0.58	0.58	0.58	1	0.58	0.58	0.58	0.58	0.58	0.58	1	0.58	0.58	0.58	0.58	0.58
Optical Magnification	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Holding Down	1	0.54	0.54	1	0.54	0.54	0.54	0.54	1	0.54	1	0.54	0.54	0.54	1	0.54
Alignment	1	0.86	1	1	1	1	0.86	1	1	1	1	1	0.86	1	1	0.86
Insertion resistance	0.87	0.87	1	1	1	1	1	1	0.87	1	1	1	0.87	1	1	0.87
Accessibility and vision	0.87	0.57	0.57	0.57	0.57	0.57	0.57	1	0.81	0.57	0.81	0.57	0.57	0.57	0.81	0.57
Mechanical Fastening processes	0	0	0	0	0	0	0	0.42	0	0	0	0	0	0	0	0
Non-Mechanical fastening processes	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Non-fastening processes	0.75	0.75	0	0.75	0.75	0	0	0.75	0.75	0	0.75	0	0.75	0	0.75	0
TAD	0.50	0.50	0.33	0.33	0.33	0.33	0.33	0.67	0.50	0.33	0.33	0.33	0.33	0.33	0.67	0.33
POS	0.26	0.26	0.07	0.12	0.10	0.07	0.07	1.00	0.33	0.12	0.12	0.24	0.10	0.14	0.24	0.10
Orthogonal Features	0.50	0.67	0.67	0.67	0.75	0.67	0.67	0.79	0.56	0.33	0.67	0.73	0.00	0.67	0.67	0.67
Angular/inclined	1.00	0.50	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.50	0.50	1.00	0.00	1.00	1.00	0.00
Curved features	1.00	1.00	0.50	0.50	0.50	0.50	0.50	1.00	1.00	1.00	0.50	0.00	1.00	1.00	1.00	1.00
Jig/fixture type	0.33	0.33	0.33	0.67	0.33	0.33	0.33	1.00	1.00	0.67	0.67	0.67	0.67	0.67	0.67	0.67
Material Type	1.00	1.00	1.00	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	1.00	0.50	1.00
Part Shape	1.00	1.00	0.33	0.67	0.33	0.33	0.33	1.00	1.00	0.67	0.67	0.67	0.67	0.67	1.00	0.33
Surface Treatment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

In the last, the fourth product is VPC socket, used in industry for electrical devices. It consists of four parts. The manufacturing, handling and insertion complexity factors are all combinedly given in Table *13*

Based on Equation *4* manufacturing complexity index CI_m and using Equation *10* part complexity and using Equation *11* assembly complexity index CI_a are calculated and given in Table 4.5. The values for assembly complexity, manufacturing complexity and combined product complexity are also shown in *Figure 19*

Table 15: Complexity indices for products 1 to 4

No	Name	CI_M	CI_A
1	Product 1	0.63484	0.665268
2	Product 2	0.652319	0.648406
3	Product 3	0.634453	0.741517
4	Product 4	0.593814	0.634773

2.2 Results

In the end the manufacturing complexity C_m of all four products is calculated using Equation *4* and using Equation *12* C_a assembly complexity of product and using Equation *13* the suggested combine complexity is calculated and given in Table *16* . Here the weights are put equal to 1 for the sack of simplicity which can be vary according to situation.

Table 16: Suggested Combined complexities of Products 1 to 4

Values	Firing Body	Gauge	Solenoid	VPC Socket
Absolute	4.950	6.965	7.199	4.060
Max	6.000	8.357	8.491	5.040
Normalized	0.825	0.827	0.846	0.805

Relative	0.214	0.301	0.311	0.175

The Table *16* gives the absolute values of complexities if a product for manufacturing, assembly and suggested combined complexity. These complexities can be normalized by dividing these values by their maximum complexity; thus, it gives the normalized complexity having values ranging from 0 to 1. That means a value closer to 0 is least complex and a product having complexity near to2 is most complex. Here in our case study VPC Socket shows least complex which is 4.14, and the solenoid is most complex one with complexity value equals to 7.25. it is also evident that VPC Socket has four parts which are simple and on the other hand Solenoid has sixteen parts and some parts are very complex to manufacture and assemble. This trend is easily evident in Figure 18.

2.3 **Conclusion**

The results shows that product 3 Solenoid is most complex product among the four products, which is also evident from many other aspects such as number of parts equals to sixteen, and the product 4 VPC socket is the least complex product, it has least number of parts, which are four. Product 1 Firing body ranks at number second in the scale of least complex product, it has seven parts and product 3 Gauge ranks at number third at the scale of least complex product. Below graph explain the scenario in a better way.

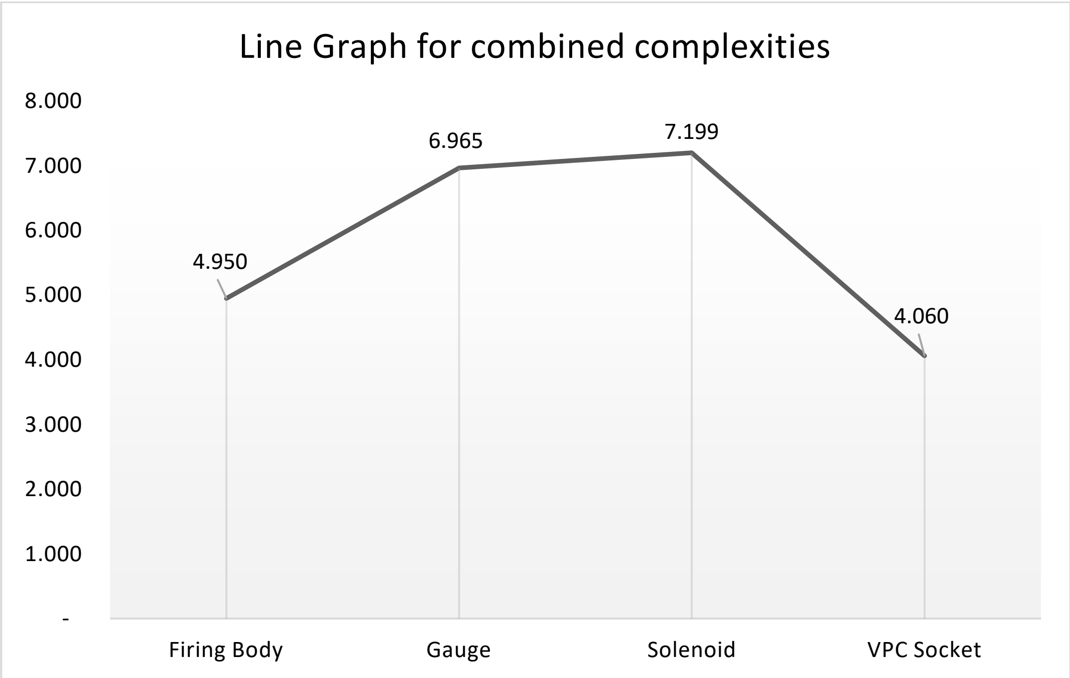

Figure 18: Combined Complexity of four Products

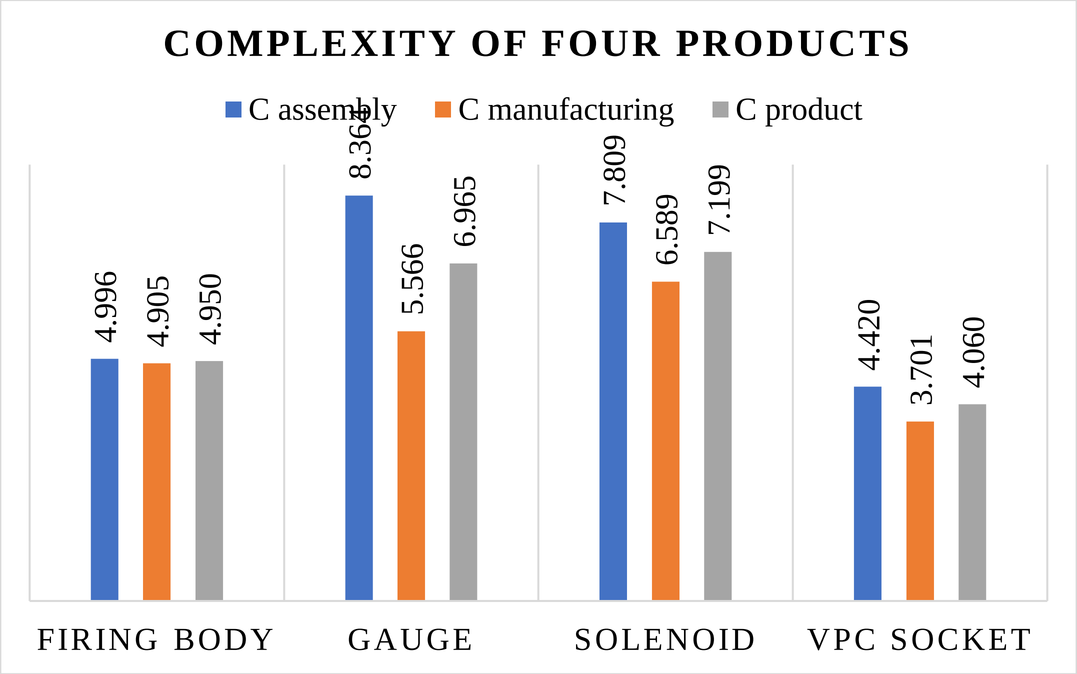

Figure 19: $C_{assembly}$, $C_{manufacturing}$ and $C_{product}$ of four products of case study

In **Figure 19** it can be seen that VPC Socket which is least complex product has smallest value of 3.70 for manufacturing complexity. Which means that among the four products vpc socket is easy to manufacture and solenoid has a value of 7.20 for manufacturing complexity which means that solenoid is difficult to manufacture as compared to other three products. Similarly seeing the assembly complexity of these products VPC Socket has value of 4.59 which is lowest among four mean it is easy to assemble, and Solenoid has a value of 7.60 which, means it id most difficult to assemble. *Figure 20* shows the normalized values of the same products, which also shows the same trend of complexities. Normalized values are achieved by dividing the absolute complexities by the maximum complexities. The overall ranking lies as vpc socket is least complex then firing body and then gauge and, in the end, solenoid is most complex product. Thus, relating these items, a manager can predict that which product takes more time to product and cost expensive. Complexity has direct relation with cost and time, thus by measuring the complexity of a product one can predict the cost and time to produce the product. In early design stage it is very important to check these variables. If there are many variants available of a same product then by implementing the suggested methodology one can measure the complexities of all the available variants, thus it can be predicted that which variant of most suitable to manufacture and assemble according to available manufacturing system. By choosing the best variant a manager can optimize the take time and minimize the cost to produce a product without experimenting to produce the product. Summarizing the whole discussion, by using suggested methodology a best product can be produce having low cost and minimum time to produce by measuring the combined complexity comprising of manufacturing and assembly effects in it. In manufacturing systems where products are produced in the form of batches, or where products are classified in the form of similar products i.e., product family formation, suggested complexity metric can become a base for the products family formation and product similarity co-efficient. Hasan, 2017 did the similar work on product family formation but that id based on assembly complexity, by measuring the product similarity coefficients in the basis on only assembly complexity.

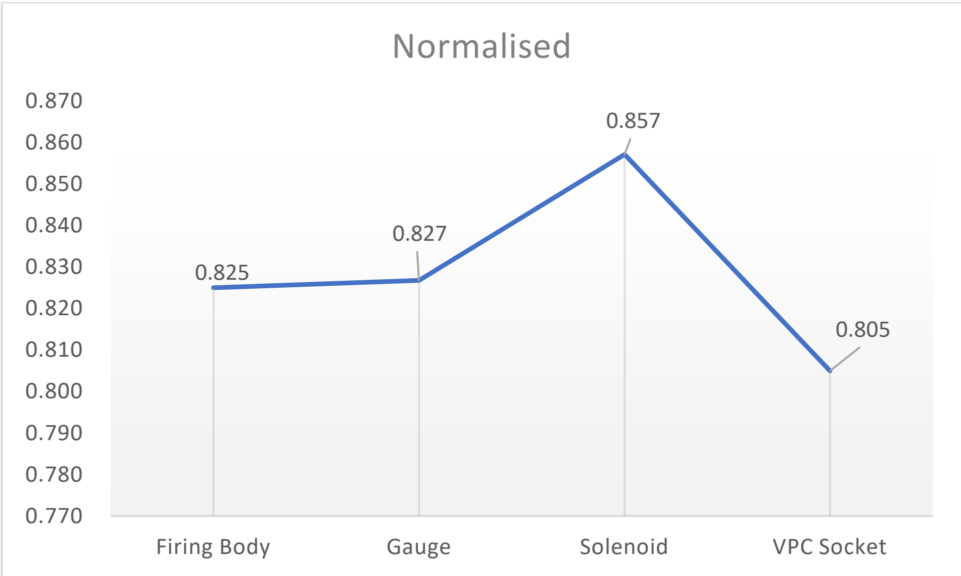

Figure 20: Normalised Suggested Product Complexities of Case Study

Chapter 5: Conclusion

Two models were presented in this dissertation:

a) Product's manufacturing complexity computation model
b) Integrated product manufacturing complexity with assembly complexity

The work initially focused on developing a system to compute product manufacturing complexity by modifying existing two models. Once that was achieved, we moved on to integrating this into product assembly complexity. In the end the integrated complexity model is elaborated by a mechanical industry case study to get the results for comparison. **Novelty** of these models is discussed as follows:

Product complexity model based on both manufacturing and assembly attributes are presented in the chapter three was implemented with on a case study of four products of related mechanical industry, which gives the perfect results and showed that the presented model can figure out the most complex product. First novelty is, existing work for manufacturing complexity model (Hasan, 2018) is improved to be capable of incorporating concept of information content complexity model, which was neglected previously. Secondly the previous manufacturing model was used for only part of a product, not a whole product, but this model gives the complete manufacturing complexity of a product. Thirdly the suggested manufacturing complexity model is integrated with assembly complexity model (S. N. Samy, 2010). Based on that, a combined product complexity model is developed in previous chapter for the computation of complexity.

For product design managers, the suggested models enable the division of products into different groups based on manufacturing complexity and assembly complexity. If, in certain cases, a part is most complex as manufacturing requirements or assembly requirements are significantly higher, then product design can be modified to minimize the complexity. Furthermore, prospective managers can compare products using this model to assess the different designs of a product or different products.

Chapter 6: Future Recommendations

Future Recommendations of this dissertation include the two possibilities:

- The suggested model can serve as a base for a model for the segregation of product into the groups for the ease of batch production.
- As the suggested model starts with the complexity of an individual part, so it can be modified for other production processes such as additive-manufacturing, injection-molding, metal forming, sheet metal cutting, bending, punching as so forth. However, modification may be required to incorporate such production techniques into the suggested method.
- An integration of suggested product complexity can be done with the complexity of the system on which the product is being manufactures and assembles. This can be done by measuring the complexities of machines, buffers and material handling systems on which parts are being manufactured, and products are being assembled

References

Abdi, M.R. and Labib, A.W., 2004. Grouping and selecting products: the design key of reconfigurable manufacturing systems (RMSs). *International journal of production research*, *42*(3), pp.521-546.

Abdi, M.R., Labib, A.W., Edalat, F.D. and Abdi, A., 2018. RMS Value Chain Architecture. In *Integrated Reconfigurable Manufacturing Systems and Smart Value Chain* (pp. 43-58). Springer, Cham.

AlGeddawy, T. and ElMaraghy, H., 2015. Determining granularity of changeable manufacturing systems using changeable design structure matrix and cladistics. *Journal of Mechanical Design*, *137*(4), p.041702.

Andersen, A.L., Brunoe, T.D. and Nielsen, K., 2015, September. Reconfigurable manufacturing on multiple levels: literature review and research directions. In *IFIP International Conference on Advances in Production Management Systems*(pp. 266-273). Springer, Cham.

Asghar, E., uz Zaman, U. K., Baqai, A. A., & Homri, L. (2018). Optimum machine capabilities for reconfigurable manufacturing systems. *The International Journal of Advanced Manufacturing Technology*, 95(9-12), 4397-4417.

Badrous, S.N.S., 2011. *Complexity of products and their assembly systems.* (Doctoral dissertation, University of Windsor (Canada)).

Baines, T.S., Lightfoot, H.W., Benedettini, O. and Kay, J.M., 2009. The servitization of manufacturing: A review of literature and reflection on future challenges. *Journal of manufacturing technology management*, *20*(5), pp.547-567.

Baqai, A., Schmidt, S., Dantan, J.Y., Siadat, A. and Martin, P., 2009, June. Algorithmic Design Methodology for Process Plans and Architectural Configurations of Manufacturing Systems, CIRPMS09. In *42nd CIRP Conference on Manufacturing Systems* (pp. 3-5).

Beamon, B.M., 1998. Supply chain design and analysis:: Models and methods. *International journal of production economics*, *55*(3), pp.281-294.

Bednar, S. and Modrak, V., 2014. Mass Customization and Its Impact On Assembly Process' complexity. *International Journal for Quality Research*, *8*(3).

Bonev, I.A., 2002. *Geometric analysis of parallel mechanisms*. Canada: Université Laval.

Brooks, R.J. and Tobias, A.M., 2000. Simplification in the simulation of manufacturing systems. *International Journal of Production Research*, *38*(5), pp.1009-1027.

Burke, L. and Kamal, S., 1995. Neural networks and the part family/machine group formation problem in cellular manufacturing: a framework using fuzzy ART. *Journal of Manufacturing Systems*, *14*(3), pp.148-159.

Burnwal, S. and Deb, S., 2013. Scheduling optimization of flexible manufacturing system using cuckoo search-based approach. *The International Journal of Advanced Manufacturing Technology*, pp.1-9.

Cho, S., Alamoudi, R. and Asfour, S., 2009. Interaction-based complexity measure of manufacturing systems using information entropy. *International Journal of Computer Integrated Manufacturing*, *22*(10), pp.909-922.

Chryssolouris, G., 2013. *Manufacturing systems: theory and practice*. Springer Science & Business Media.

Chu, C.C.P. and Gadh, R., 1996. Feature-based approach for set-up minimization of process design from product design. *Computer-Aided Design*, *28*(5), pp.321-332.

Costa, C.A. and Young, R.I.M., 2001. Product range models supporting design knowledge reuse. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *215*(3), pp.323-337.

Da Silva, R.M., Junqueira, F., Santos Filho, D.J. and Miyagi, P.E., 2016. Control architecture and design method of reconfigurable manufacturing systems. *Control Engineering Practice*, *49*, pp.87-100.

Dallery, Y. and Gershwin, S.B., 1992. Manufacturing flow line systems: a review of models and analytical results. *Queueing systems*, *12*(1-2), pp.3-94.

Das, B., Garcia-Diaz, A., MacDonald, C.A. and Ghoshal, K.K., 2010. A computer simulation approach to evaluating bowl versus inverted bowl assembly line arrangement with variable operation times. *The International Journal of Advanced Manufacturing Technology*, *51*(1), pp.15-24.

DeGarmo, E.P., Black, J.T., Kohser, R.A. and Klamecki, B.E., 1997. *Materials and process in manufacturing*. Prentice Hall.

Dou, J., Dai, X., Ma, X. and Meng, Z., 2008, August. A GA-based approach to optimize single-product flow-line configurations of RMS. In *Mechatronics and Automation, 2008. ICMA 2008. IEEE International Conference on* (pp. 654-659). IEEE.

ElMaraghy, H., Schuh, G., ElMaraghy, W., Piller, F., Schönsleben, P., Tseng, M. and Bernard, A., 2013. Product variety management. *CIRP Annals-Manufacturing Technology*, *62*(2), pp.629-652.

ElMaraghy, H.A., 2005. Flexible and reconfigurable manufacturing systems paradigms. *International journal of flexible manufacturing systems*, *17*(4), pp.261-276.

ElMaraghy, W., ElMaraghy, H., Tomiyama, T. and Monostori, L., 2012. Complexity in engineering design and manufacturing. *CIRP Annals-Manufacturing Technology*, *61*(2), pp.793-814.

Esmaeilian, B., Behdad, S. and Wang, B., 2016. The evolution and future of manufacturing: A review. *Journal of Manufacturing Systems*, *39*, pp.79-100.

Farid, A.M., 2017. Measures of reconfigurability and its key characteristics in intelligent manufacturing systems. *Journal of Intelligent Manufacturing*, *28*(2), pp.353-369.

Galan, R., Racero, J., Eguia, I. and Garcia, J.M., 2007. A systematic approach for product families formation in Reconfigurable Manufacturing Systems. *Robotics and Computer-Integrated Manufacturing*, *23*(5), pp.489-502.

Garro, O., 1992. *Conception d'éléments physiques de systèmes de production. Application aux machines-outils à architecture parallèle* (Doctoral dissertation).

Gerwin, D., 1993. Manufacturing flexibility: a strategic perspective. *Management science*, *39*(4), pp.395-410.

Goldin, C. and Katz, L.F., 2018. The race between education and technology. In *Inequality in the 21st Century* (pp. 49-54). Routledge.

Goyal, K.K., Jain, P.K. and Jain, M., 2013. A comprehensive approach to operation sequence similarity-based part family formation in the reconfigurable manufacturing system. *International Journal of Production Research*, *51*(6), pp.1762-1776.

Groover, M.P., 2016. *Automation, production systems, and computer-integrated manufacturing*. Pearson Education India.

Haddou Benderbal, H., Dahane, M. and Benyoucef, L., 2017. Flexibility-based multi-objective approach for machines selection in reconfigurable manufacturing system (RMS) design under unavailability constraints. *International Journal of Production Research*, *55*(20), pp.6033-6051.

Hasan, F., Jain, P.K. and Kumar, D., 2016. Scalability of reconfigurable manufacturing systems based on bowl phenomenon: an implication of modular machines. *International Journal of Industrial and Systems Engineering*, *22*(1), pp.73-95.

Hasan, S.M., Baqai, A.A., Butt, S.U. and Uz Zaman, U.K., 2018. Product family formation based on complexity for assembly systems. *The International Journal of Advanced Manufacturing Technology*, *95*(1-4), pp.569-585.

Hasan, S.M., 2018. Complexity Framework of Adaptive Scalable Manufacturing Systems *PhD Thesis CEME, NUST*

Hoffman, A.J. and Basson, A.H., 2016. IEC 61131-3-based holonic control of a reconfigurable manufacturing subsystem. *International Journal of Computer Integrated Manufacturing*, *29*(5), pp.520-534.

Hu, S.J., Ko, J., Weyand, L., ElMaraghy, H.A., Lien, T.K., Koren, Y., Bley, H., Chryssolouris, G., Nasr, N. and Shpitalni, M., 2011. Assembly system design and operations for product variety. *CIRP Annals-Manufacturing Technology*, *60*(2), pp.715-733.

Ismail, N., Musharavati, F., Hamouda, A.S.M. and Ramli, A.R., 2008. Manufacturing process planning optimisation in reconfigurable multiple parts flow lines. *Journal of achievements in materials and manufacturing engineering*, *31*(2), pp.671-677.

Kashkoush, M. and ElMaraghy, H., 2015. Knowledge-based model for constructing master assembly sequence. *Journal of Manufacturing Systems*, *34*, pp.43-52.

Kashkoush, M. and ElMaraghy, H., 2016. Product family formation by matching Bill-of-Materials trees. *CIRP Journal of Manufacturing Science and Technology*, *12*, pp.1-13.

Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, G. and Van Brussel, H., 1999. Reconfigurable manufacturing systems. *CIRP Annals-Manufacturing Technology*, *48*(2), pp.527-540.

Koren, Y. and Katz, R., The Regents of the University of Michigan, 2003. *Reconfigurable apparatus and method for inspection during a manufacturing process*. U.S. Patent 6,567,162.

Koren, Y., Moon, Y.M. and Kota, S., The Regents Of The University Of Michigan, 2003. *Reconfigurable multi-spindle apparatus*. U.S. Patent 6,569,071.

Koren, Y., Wang, W. and Gu, X., 2017. Value creation through design for scalability of reconfigurable manufacturing systems. *International Journal of Production Research*, *55*(5), pp.1227-1242.

Lameche, K., Najid, N.M., Castagna, P. and Kouiss, K., 2017. Modularity in the design of reconfigurable manufacturing systems. *IFAC-PapersOnLine*, *50*(1), pp.3511-3516.

Lesi, V., Jakovljevic, Z. and Pajic, M., 2016, September. Towards plug-n-play numerical control for reconfigurable manufacturing systems. In *Emerging Technologies and Factory Automation (ETFA), 2016 IEEE 21st International Conference on* (pp. 1-8). IEEE.

Li, S., Liu, F. and Yin, K., 2017. Real-time acquisition of machining task progress based on the power feature of workpiece machining. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *231*(2), pp.257-267.

Lindemann, U., Maurer, M. and Braun, T., 2008. *Structural complexity management: an approach for the field of product design*. Springer Science & Business Media.

Matt, D.T., 2007. Achieving operational excellence through systematic complexity reduction in manufacturing system design. In *Key Engineering Materials* (Vol. 344, pp. 865-872). Trans Tech Publications.

McAuley, J., 1972. Machine grouping for efficient production. *Production Engineer*, *51*(2), pp.53-57.

Mehra, A., Minis, I. and Proth, J.M., 1996. Hierarchical production planning for complex manufacturing systems. *Advances in Engineering Software*, *26*(3), pp.209-218.

Mehrabi, M.G., Ulsoy, A.G. and Koren, Y., 2000. Reconfigurable manufacturing systems and their enabling technologies. *International Journal of Manufacturing Technology and Management*, *1*(1), pp.114-131.

Mehrabi, M.G., Ulsoy, A.G. and Koren, Y., 2000. Reconfigurable manufacturing systems: Key to future manufacturing. *Journal of Intelligent manufacturing*, *11*(4), pp.403-419.

Moon, Y.M. and Kota, S., 2002. Design of reconfigurable machine tools. *Journal of Manufacturing Science and Engineering*, *124*(2), pp.480-483.

Moon, Y.M., 2000. *Reconfigurable machine tool design: Theory and application* (Doctoral dissertation).

Nagel, R.N. and Dove, R., 1991. *21st century manufacturing enterprise strategy: An industry-led view*. Diane Publishing.

Nelles, O., 2013. *Nonlinear system identification: from classical approaches to neural networks and fuzzy models*. Springer Science & Business Media.

Papakostas, N., Efthymiou, K., Mourtzis, D. and Chryssolouris, G., 2009. Modelling the complexity of manufacturing systems using nonlinear dynamics approaches. *CIRP Annals-Manufacturing Technology*, *58*(1), pp.437-440.

Pirmoradi, Z., Wang, G.G. and Simpson, T.W., 2014. A review of recent literature in product family design and platform-based product development. In *Advances in product family and product platform design* (pp. 1-46). Springer, New York, NY.

Rakesh, K., Jain, P.K. and Mehta, N.K., 2010. A framework for simultaneous recognition of part families and operation groups for driving a reconfigurable manufacturing system. *Advances in Production Engineering & Management*, *5*(1).

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P. and Harnisch, M., 2015. Industry 4.0: The future of productivity and growth in manufacturing industries. *Boston Consulting Group*, *9*.

Sagawa, J.K. and Nagano, M.S., 2015. Modeling the dynamics of a multi-product manufacturing system: A real case application. *European Journal of Operational Research*, *244*(2), pp.624-636.

Sampath, M., Sengupta, R., Lafortune, S., Sinnamohideen, K. and Teneketzis, D., 1995. Diagnosability of discrete-event systems. *IEEE Transactions on automatic control*, *40*(9), pp.1555-1575.

Samy, S.N. and ElMaraghy, H., 2010. A model for measuring products assembly complexity. *International Journal of Computer Integrated Manufacturing*, *23*(11), pp.1015-1027.

Samy, S.N., 2011. Complexity of products and their assembly systems. *PhD Thesis. Paper 4775*.

Sankaranarayanasamy, K., Arunachalam, S., Page, T. and Dhanalakshmi, V., 2005. A Novel Approach to Part Family Formation in Cellular Manufacturing Using Fuzzy Analysis in CAD.

Schleich, H., Schaffer, J. and Scavarda, L.F., 2007, July. Managing complexity in automotive production. In *19th International Conference on Production Research* (Vol. 100). Valparaiso Chile.

Seifoddini, H.K., 1989. Single linkage versus average linkage clustering in machine cells formation applications. *Computers & Industrial Engineering*, *16*(3), pp.419-426.

Shabaka, A.I. and ElMaraghy, H.A., 2007. Generation of machine configurations based on product features. *International Journal of Computer Integrated Manufacturing*, *20*(4), pp.355-369.

Singh, A., Kumar, P. and Singh, S., 2013. Vision, Principles and Impact of Reconfigurable Manufacturing System. *International Journal of Engineering and Advanced Technology (IJEAT)*, *3*, pp.2249-8958.

Stanowski, M. (2011). Abstract complexity definition. *Complicity: An International Journal of Complexity and Education*, 8(2).

Steger, U., Amann, W. and Maznevski, M.L., 2007. *Managing complexity in global organizations* (Vol. 5). John Wiley & Sons.

Tao, F., Cheng, Y., Zhang, L. and Nee, A.Y., 2017. Advanced manufacturing systems: socialization characteristics and trends. *Journal of Intelligent Manufacturing*, *28*(5), pp.1079-1094.

Thomas E.. Vollmann, William L.. Berry and Whybark, D.C., 1988. *Manufacturing planning and control systems*. Irwin.

Tollenaere, M., Aoussat, A. and Le Coq, M., 1998. Conception de produits mécaniques: méthodes, modèles et outils. *Hermes*.

Ulrich, K.T., 2003. *Product design and development*. Tata McGraw-Hill Education.

Vaidya, O.S. and Kumar, S., 2006. Analytic hierarchy process: An overview of applications. *European Journal of operational research*, *169*(1), pp.1-29.

Wang, H., Zhu, X., Wang, H., Hu, S.J., Lin, Z. and Chen, G., 2011. Multi-objective optimization of product variety and manufacturing complexity in mixed-model assembly systems. *Journal of Manufacturing Systems*, *30*(1), pp.16-27.

Weiser, A.K., Baasner, B., Hosch, M., Schlueter, M. and Ovtcharova, J., 2016. Complexity Assessment of Modular Product Families. *Procedia CIRP*, *50*, pp.595-600.

Wu, D., Rosen, D.W. and Schaefer, D., 2015. Scalability planning for cloud-based manufacturing systems. *Journal of Manufacturing Science and Engineering*, *137*(4), p.040911.

Yousef, A.M. and ElMaraghy, H.A., 2006. Assessment of manufacturing systems reconfiguration smoothness. *The International Journal of Advanced Manufacturing Technology*, *30*(1-2), pp.174-193.

Zhang, Z. and Sharifi, H., 2000. A methodology for achieving agility in manufacturing organisations. *International Journal of Operations & Production Management*, *20*(4), pp.496-513.