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Structural Complexity of Manufacturing Systems Layout

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Structural Complexity of Manufacturing Systems Layout

by

Valeria Betzabe Espinoza Vega

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Submitted to the Faculty of Graduate Studies
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Windsor, Ontario, Canada

Structural Complexity of Manufacturing Systems Layout

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DECLARATION OF CO-AUTHORSHIP/PREVIOUS PUBLICATION

This thesis includes one original paper that has been previously submitted for publication in a peer reviewed conference proceedings, as follows:

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ABSTRACT

The layout of a manufacturing facility/system not only shapes material flow pattern and influence transportation cost, but also affects the decision making process on the shop floor. The layout of manufacturing systems determines the information content of its structural complexity inherent in the layout by virtue of its configuration design.

This thesis proposes a methodology which converts the physical system layout to a graphical representation to produce measurable complexity indices. The elements to represent the physical layout are the number of places where decisions are made and relationships within the layout. The structural characteristics of the layout include density, paths, cycles, decision points, redundancy distribution and magnitude, which are captured by the complexity indices. The indices are directly determined by the information content, and the layout complexity index (LCI) combines those individual indices representing the structural complexity of the layout. The LCI is insensitive to the sequence of the complexity index values, which is its main advantage. The methodology is applied to six manufacturing systems layouts. Two layouts from the literature were used for comparison purposes since their complexity was previously assessed. The developed method is used to design the least complex layouts and to compare alternative layouts.

DEDICATION

This thesis is dedicated to all members of my family, each one has taught me something very special. Especially to my parents Sergio Espinoza and Laura Vega who I love so much, and to Waldo Perez, Saul, Ricardo, Cari, and Nora.

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CHAPTER I

INTRODUCTION

This chapter presents an introduction to complexity in manufacturing. It includes the motivation for the research, objectives, and scope. A description of the thesis outline is included at the end of the chapter.

1.1 Motivation

A steady increase of complexity in industry has been observed in the past. Generally, new requirements for an enterprise's complexity management can emerge from each of the four fields shown in Figure 1.1 (Lindemann, Maurer et al., 2009). As indicated by the arrow, the different fields of complexity are mutually linked.

The effects of globalization are one reason for increased market complexity. The effects of globalization combined with a social trend toward individuality has resulted in more requests for product customization. This creates more product variants, decreasing quantities per variant, and increasing overall complexity, which are challenges for the manufacturer (Pine, 1993).
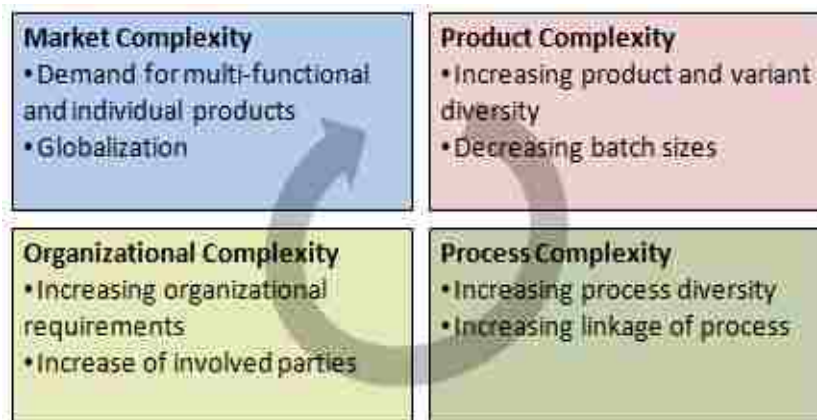
Figure 1.1. Aspects of complexity in manufacturing- adopted from Lindeman et al.(2009)

The design of a manufacturing system not only affects the performance, in terms of productivity, throughput, quality (Huang, 2003), but also the complexity of the system, i.e., the number and type of machines and connections between them (Gabriel, 2007). Manufacturing systems have plenty of components and subsystems with several interactions and relationships, which increase the complexity of the manufacturing system. Quantity is one of the aspects of complexity emphasized by Martin (2004) , complexity is regarded as the amount of uncertainty in the system, where an increase of system components increases that uncertainty. That notion is alternatively expressed by the uncertainty level in Axiomatic Design where, in the second axiom, the complexity of a system is measured by the probability of success of achieving functional requirements (Suh, 2005).

1.2 Complexity in Manufacturing Systems Layout

The manufacturing system layout is an important parameter affecting the complexity of a system. Manufacturing system layouts have evolved from process layouts into the recent paradigm of changeable systems where changes in the layout can be made when needed to adapt to product changes (ElMaraghy, 2005). The layout of any manufacturing system determines the system's information content which increases or decreases the difficulty of decision making during production and, therefore, the system complexity.

The entropy approach (ElMaraghy, Kuzgunkaya et al., 2005) is frequently applied to assess complexity in manufacturing systems. Different types of complexity in manufacturing systems have been identified as, static (Deshmukh, Talavage et al., 1998), dynamic (Sivadasan, Efstathiou et al., 2002), internal, external, product, process (ElMaraghy and Urbanic, 2004), and technology complexity (Tani and Cimatti, 2008).

However, assessing the complexity of manufacturing systems configuration layouts has only been considered on the machine level, where the series, parallel and hybrid configurations of machines and effects of the system operational complexity are analyzed (Koren, 2010).

This research is concerned with quantifying the structural complexity that arises due to the characteristics of manufacturing system layouts. The features of various layouts govern the movement of material between workstations and affect the kind of decisions to be made to ensure smooth flow, minimum travel time, to reduce bottlenecks and downtime, and to guard against workstation starvation. This research presents a new method to measure the structural complexity of manufacturing systems layouts. This method introduces complexity indices based on characteristics of the layout configurations, such as, density, paths, cycles, decision points, redundancy distribution, and magnitude of the decision points. These indices reflect the information content inherent in a manufacturing system layout.

Despite the attention received by researchers in measuring structural complexity of manufacturing systems (Gabriel, 2007, Kim, 1999, Calinescu, Efstathiou et al., 1998) the layout has not been included in the structural complexity assessments. Gabriel (2007) investigated internal static manufacturing complexity (ISMC), based on product line complexity, product structure, and process complexity components. However, his complexity measure did not consider the system layout, arguing that it is difficult to quantify layout complexity because it does not have any evident quantifiable elements. Consequently, no quantifiable element of layout complexity has been identified.

The objective of this research is to assess the structural complexity of manufacturing system layouts by defining a set of system characteristics and patterns that contribute to the information content/complexity and affect on the decision making process. This thesis proposes a methodology, which converts the physical system layout to a graph representation, in order to produce measurable complexity indices, based on the number and locations of decision making points. The resulting complexity index is a useful tool, at the early system design stage. Also, it facilitates comparing and evaluating alternatives and identifying potential structural problems.

1.3 Hypothesis

The material flow patterns in any manufacturing system layouts and the points where decisions have to be made, by operators or system control programs, regarding the next destination and movement path/route to take (for parts, tools, transporters, etc.) directly affect the amount of information and knowledge required to make decisions. Hence, it is hypothesized that the complexity of any system layout, in as much as it is related to information content, is a function of the attributes that characterize a system configuration layout.

1.4 Research Questions

The question to be answered in this thesis is:

How can a manufacturing system layout be assessed in terms of its structural complexity?

The following questions are the focus of the research:

1. How can a system layout be represented graphically ?

2. What are the quantifiable elements that can be extracted from a system layout representation?

3. What are the structural characteristics of layout elements that increase information content?

The first question represents the basic understanding of a facility layout as a unique process converted into a graphic visualization. The second question points to the assumption that it is possible to identify quantifiable elements that can help reduce graphic representation to a form that can be managed computationally. The third question seeks to recognize structural characteristics that increase or decrease a system layout's information content and, hence, complexity.

1.5 Objectives

The objective of this research is to develop a methodology that assesses the structural complexity of manufacturing system layouts.

This will be accomplished by:

- Establishing a methodology that describes how the physicial manufacturing system layout can be translated into a graphical and mathematical representation.

- Defining complexity indices that describe relevant characteristics of the layout representation.

- Combining individual complexity indices together in one complexity index that represents the structural complexity of the system layout.

1.6 Scope of the Research

This research addresses the structural complexity that arises due to the characteristics of a manufacturing system's layout.

Static and structural complexity concepts are used interchangeably in this thesis, because both terms refer to the complexity of the structure of the system and not to the result of the operation. A structural complexity focuses on the decisions made while using the system layout with respect to a system but not with respect to each machine.

This research draws upon definitions of manufacturing systems, layouts, configurations, and complexity in manufacturing. It also, uses definitions from graph theory related to the graphic representation of systems.

This research does not assess the operational complexity. Operational or dynamic complexity is affected by changes during periods of time.

This thesis does not determine how to arrange, locate, and distribute the equipment and support services in a manufacturing facility to achieve multiple objectives.

The proposed methodology is applicable to all manufacturing system layouts. The knowledge generated throughout this research is intended to extend the scientific understanding of characteristics that affect the structural complexity of the manufacturing system layouts.

1.7 Structure of the Thesis

The organization of this thesis is as follows:

Chapter 1 presents a brief introduction to the subject. The research questions and objectives are also presented.

Chapter 2 reviews the literature of different approaches to assess complexity in a manufacturing environment.

Chapter 3 describes the proposed methodology and reviews the significance of the proposed complexity indices.

Chapter 4 exemplifies the application of the proposed methodology to different manufacturing system layouts.

Chapter 5 summarizes the results obtained from the applications and presents the final conclusions and future work.

Finally, the appendix includes comprehensive details about the algorithm used.

CHAPTER II

REVIEW OF LITERATURE

This chapter provides a review of the literature related to manufacturing system, layouts, configurations, and various approaches to measure complexity specifically in manufacturing systems. Graph theory concepts are also reviewed.

2.1 Manufacturing Systems

Cochran et al. (2001) defined a manufacturing system as the arrangement and operation of machines, tools, material, people, and information to produce a value-added physical, informational, or service product whose success and cost is characterized by measurable parameters.

Mehrabi et al. (2000) summarized the major manufacturing system paradigms and their definitions. Traditionally, mass production systems have been focused on the reduction of product cost. Lean manufacturing emphasizes continuous improvement in product quality, while decreasing product costs. Koren et al. (1999) described dedicated manufacturing lines (DML) or transfer lines as based on inexpensive fixed automation that produce a company's core products or parts at high volume. DMLs are cost effective as long as demand exceeds supply and they can operate at full capacity; however, there may be situations in which dedicated lines do not operate at full capacity. In contrast, flexible manufacturing systems (FMS) can produce a variety of products, with changeable volume and mix on the same system. FMS consists of expensive, general-purpose computer numerically controlled (CNC) machines and other programmable automation.

Mehrabi et al. (2000) defined reconfigurable manufacturing (RMS) as a new type of manufacturing system which allows flexibility not only in producing a variety of parts, but also in changing the system itself. An RMS system is designed for rapid adjustment of production capacity and functionality, in response to new circumstances, by the rearrangement of changes to its components. RMS aims to allow extra capacity when required and additional functionality when needed. ElMaraghy (2005) classified manufacturing systems reconfiguration activities into two types: physical (hard) and logical (soft). Examples of physical reconfiguration include adding or removing machines, adding or removing machines modules, and changing material handling systems. Examples of logical reconfiguration include re-programming of machines, re-planning, re-scheduling, and re-routing.

The characteristics of reconfigurable manufacturing system are presented and compared with dedicated and flexible manufacturing systems in Table 2.1 (Koren, 2005).

	Dedicated	RMS	FMS / CNC
System structure	Fixed	Adjustable	Adjustable
Machine	Fixed	Adjustable	Fixed
System focus	Part	Part family	Machine
Flexibility	No	Customized	General
Scalability	No	Yes	Yes
Simultaneous operating tools	Yes	Yes	No
Cost	Low	Intermediate	High

Table 2.1. Characteristics of dedicated, RMS and FMS.

2.2 Layout Configuration

Configuration layouts have an important contribution to the efficient running of production affairs because it increases the speed of in-process work and reduces the manufacturing time.

Manufacturers have traditionally used long serial lines in production. Such lines are associated with low productivity, inflexibility, and the use of buffers to increase productivity. Buffers are not only expensive, but also lead to inventory costs for work in progress. Dramatic reductions in the cost of CNC(Computer Numerically Controlled) machines and gantry robots along with other technological advancements have recently begun to motivate manufacturers to consider configurations other than long serial lines (Slipitalni and Remennik, 2004).

Traditional layout for a job shop manufacturing are considered as process layouts, in which the shop floor is divided into several departments, with each department specializing in some specific operations, for example, lathe machines, drilling machines, grinding machines, or milling machines grouped into different units in the plant. Machines with similar functions are grouped together and placed in the same department. Since material handling often is not automated in the job shop environment, problems like designing flow paths for Automated Guided Vehicles (AGVs) or other automated material handling system rarely exist. As a result, layout methods developed for the job shop environment often do not consider flow path problems. With the development of automation and computer technology and the introduction of new manufacturing philosophies, manufacturing systems have made much progress. Flexible Manufacturing Systems (FMSs) and Cellular Manufacturing Systems (CMS) are two. FMSs were developed to help companies cope with the multiple-product, small-to-medium batch

production environment. On the other hand, a CMS is a direct application of group technology in which a manufacturing system is partitioned into several subsystems. The objective is to have a manufacturing system that has transfer-line like efficiency and job-shop like flexibility (Ho and Moodie, 2000).

In the study of flow of movements in layout, Ho et al. (1993) concluded that a layout that has more in-sequence flow movement usually has better performance in the following areas: less flow distance, easier material handling, and more efficient production. On the other hand, a layout with a lot of backtracking movements usually has greater flow distance, and a more difficult and complex material handling problems than a flow without backtracking flow. They analyzed the flow to achieve a logical layout configuration where the flow movements in the layout will be mostly in-sequence and unidirectional.

Kusiak and He (1997) studied the collective impact of product designs on the product flow in a multi-product assembly system in an agile assembly environment, where a large variety of products are produced. The production of a large variety of products creates difficulties in design and control of agile assembly systems, i.e., line balancing and flow control. In the design of a multi-product assembly line, the flow of products is an important factor to be considered. Ho et al. (1993) discussed four different product flows: repeat operation, serial flow, by-pass flow, and backtracking as shown in Figure 2.1 (a – d). In addition, the branch/merge flow can be observed. Of these five flows, the serial flow is the most desirable because it easier the control of the manufacturing process and material handling. Backtracking is the least desirable flow characteristic since it makes more difficult the flow.

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a) Repeat operation b) Serial flow c) By-pass flow

d) Backtracking flow e) Branch flow

☐ Assembly station

→ Direction of product flow
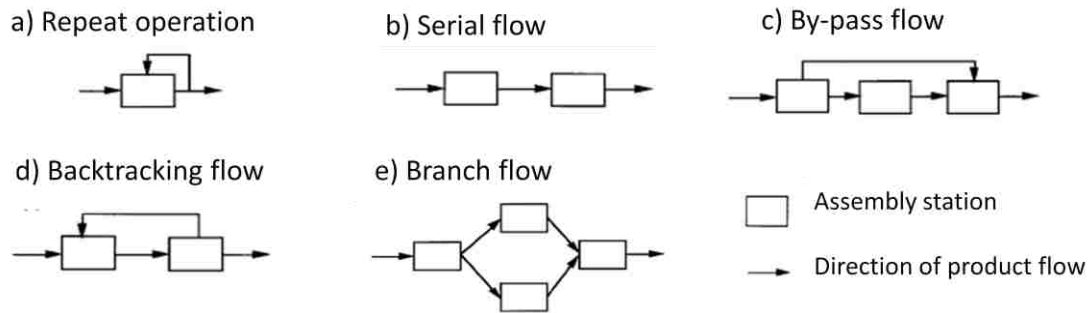
Figure 2.1. Five types of flows.

2.3 Manufacturing System Configurations

Types of manufacturing system configuration include the dedicated line, flexible manufacturing, reconfigurable or responsive manufacturing systems. Spicer et al. (2002) pointed out that the manufacturing system configuration is determined by the arrangement of the machines and the relations (connections) among them. Similar machine arrangements can have different connections; thus, the configurations are different. They compared four systems: pure serial lines, pure parallel lines, short serial lines arranged in parallel, and short serial lines arranged in parallel with crossover. Serial lines in parallel with crossovers allow that parts from one machine to be transferred not only to a specific machine, but also to any other machine in a set of parallel machines. They defined the maximum configuration length when only one machining task is assigned to each operation. This situation creates a very long system that is usually unbalanced. The minimum configuration length is achieved when a maximum number of tasks are assigned to each operation.

Koren (2010) analyzed the number of possible configurations when the daily demand and the total processing time for the part are given. He founded that the number of possible configurations increases exponentially with the number of machines. Koren (2010)

classified the configurations as symmetrical or asymmetrical, based on whether one could draw a symmetry axis through the configuration. A configuration is then evaluated by the machine arrangement and connections. The type of material handling system determines the connections of a configuration. For manufacturing systems, only symmetric configurations are suitable because asymmetric configurations add much complexity and are not viable in real manufacturing lines. Furthermore, Koren classified the symmetric configurations as follows (Koren, 2010):

- Class I. Cell configurations, consisting of several serial manufacturing lines (cells) arranged in parallel with no crossovers, as shown in Figure 2.2.

- Class II. RMS Configurations are configurations with crossovers connections after every stage, as shown in Figure 2-3. The parts from any machine in stage i can be transferred to any machine in stage $(i + 1)$. All machines and operations are identical.

- Class III. Configurations in which there are some stages with no crossovers. This class includes combinations of the previous two classes.

Class I
Serial lines in parallel

Class II RMS
Configuration with
Crossovers

Class III
No Crossovers
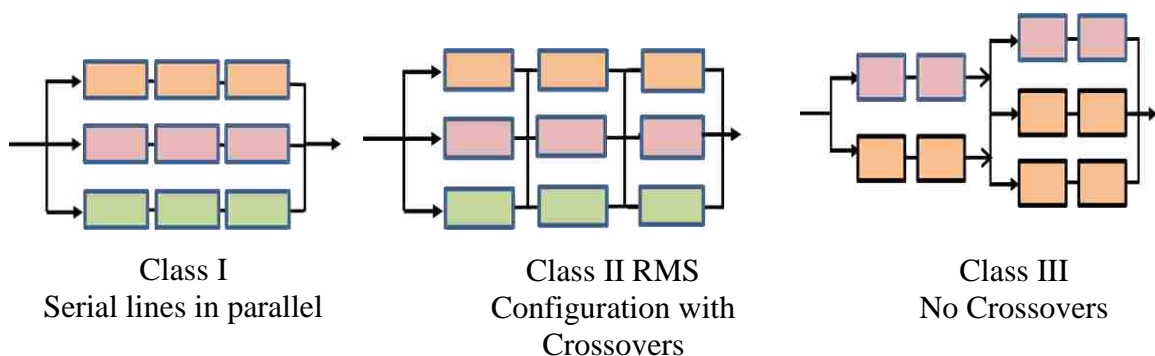
Figure 2.2. Three classes of symmetric configurations.

Koren (2010) also compared parallel lines configuration and RMS configurations. To understand the RMS configuration, the sketch in Figure 2.3 illustrates a practical three-

stage RMS with gantries that transport the parts. A spine gantry transfers a part to a small conveyor; the part moves on the conveyor to a position where a cell gantry can pick it up and take it for processing in one of the machines in its stage. When the part processing is done, the cell gantry returns the part to the conveyor, which moves the part to a position in which the next spine gantry can pick it up for processing in the next stage, and so on.
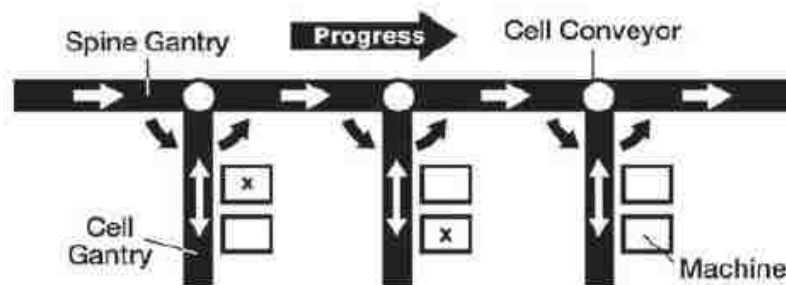
Figure 2.3. Practical Reconfigurable Manufacturing System.

The criteria to compare parallel lines configuration and RMS configuration are: investment cost, line-balancing ability, scalability options, productivity when machines fail. Capital investment is higher in RMS due to the requirements of the part handling devices. Parallel lines provides less flexibility in balancing the system when new products are introduced by contrast in RMS configurations where the number of machines in the various stages of RMS may be adjusted to provide an accurate line balancing and improved productivity.

System scalability of the RMS configuration is better than the parallel line configuration because adding a machine in one of the stages and rebalancing the system adds a small increment of capacity whereas in the parallel line, an additional line must be added to increase the overall system capacity. RMS configuration offers higher productivity than a parallel line configuration if machine reliability is low. In parallel lines, if two machines are down, the entire system is down. Whereas, for an RMS, if two

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machines are down in different stages, the throughput is at 50%. The RMS is a more productive system from a machine downtime perspective. However, if one of the cell gantries in the RMS is down, the entire system is down. Systems with parallel lines do not contain cell gantries and are more reliable from a material handling perspective. The analysis revealed that there is a borderline based on the machine reliability and gantry reliability. In large systems, with a large number of stages and machines per stage, the RMS configuration has higher productivity than the parallel line configuration. If the machine reliability is very high, then the parallel line configuration yields higher productivity than the RMS configuration.

The results from comparing parallel lines and RMS configuration are summarized (Koren, 2010) in Table 2.2.

	Capital investment	Scalability	Line Balancing	Productivity
Parallel lines	Lower			Higher for high machine reliability
RMS Configuration	Higher	Much better	Much better	Higher in complex, large systems

Table 2.2. Comparing parallel lines and RMS configuration.

Youssef and ElMaraghy (2007) proposed an approach to select an RMS configurations in terms of demand requirements and targeting the best system performance level while taking into consideration the smoothness of the anticipated reconfiguration process from one configuration to the next expected configuration.

Zhu et al. (2008) summarized an agreement on the elements to measure complexity in manufacturing: (i) product variety increases the complexity in manufacturing system, and (ii) information entropy is an effective measure of complexity. They studied the impact of a variety on manufacturing complexity in mixed-model assembly system, taking into consideration the characteristics of the assembly system, such as system configuration, task to station assignment, and assembly sequences.

2.4 <u>System Performance Approach</u>

Different configurations in manufacturing are used because products have become more complex and sophisticated and require handling flexibility as society moves towards mass customization. Manufacturing systems configurations are an important, and sometimes overlooked, aspect of the manufacturing system design that can significantly affect a system's performance. Koren et al. (1998) have demonstrated that system configuration has a significant impact on the performance of manufacturing systems including productivity, capacity scalability, and part quality.

Yu (2002) also studied the relation between modifications in system configurations and the system performance. He provided a quantitative method to evaluate the performance of system layout design in terms of complexity and throughput. Network complexity is defined as the structural complexity in a manufacturing network. His measure captures the effect of network shapes, the effect of availability, and working rates of stations. The connection or linkage is about how the events at one station affect events at another station or the whole system. The station state is based upon its working rate. Three examples were described. The first example pointed out the tradeoff between complexity and throughput when parallel machines are introduced. The second example shows that

overall performance can be improved without adding any new resources into the system by repositioning machines according the working resources to reduce the occurrences of bottleneck. The model includes the availability and working rates of stations; only performance metrics are taken into account when evaluating the layout.

Freiheit et al. (2004) examined parallel systems with crossovers between the stages and noted that they are more productive than parallel systems without crossover between the stages, considering the availability of the additional material handling required for the crossover. The flexible material handling required increased flexibility, however, greater complexity and associated potential for breakdowns and a subsequent impact on system productivity arise. The analysis was limited to cell configurations that do not use buffers internal to the cell. They concluded that, without highly available material handling, the significant productivity gains that are achieved from crossover cannot be obtained.

Freiheit et al. (2004a) developed a methodology and analysis to evaluate the effect of systems configurations on productivity. They showed that no synergistic increase in productivity is achieved when a line with no crossover between the operations is added. In a parallel-serial line, adding crossovers it is noted that as the number of machines in a line is increased, there is a greater benefit from adding a crossover. Also there is a diminishing return: each additional line in parallel with crossover adds less additional productivity. Further, the extent of the synergistic productivity gain is dependent on the availability of the machines. Considerably more productivity is gained from crossover when the machine availability is lower than when it is higher.

Freiheit et al. (2004b) analyzed the productivity of pure serial and parallel-serial production lines with standby machines to perform any operation when failures in the

main production line occur. They demonstrated that synergistic productivity improvements can be obtained by providing reserve capacity to serial-type production lines. In serial lines, as the number of machines in the main line is increased, the productivity of the system falls. However, the redundant machines permit lower rates of productivity loss as the main line is lengthened. The productivity performance of parallel-serial machining lines is similar to the pure serial line. They analyzed the importance of buffers and capacity reserve in the manufacturing systems configurations.

Wang and Hu (2010) developed a throughput analysis and compared different configurations, from serial to hybrid and parallel, considering complexity measures and incorporating the operator reaction time and fatigue effects. The results showed that complexity increases from serial to hybrid and parallel configurations. In the case of throughput, the configuration with a higher number of parallel stations has a higher throughput.

The performance of manufacturing systems is also impacted by redundancies. Windt, Hüt et al., (2012) looked at the redundancy inherent in the structure of a manufacturing system due the possibility different paths that a product can take. The main resource elements of the manufacturing system considered were the machines, tools, transport, buffers, and suppliers. The parameters identified to determine the robust functioning of the system were: number and complexity of the variants, number of machines at each stage, connectivity within each stage and among the stages, and number of stages. The approach presented by Windt et all. (2012) analyses the redundancies in the structure of a manufacturing system. The approach suggests a path analysis to investigate the structural

redundancies. They concluded that redundancies can impact the performance of manufacturing systems.

2.5 Summary

This literature review presents the evolution of manufacturing systems from job shops to the new reconfigurable paradigm. The literature review also presents why some manufacturing systems are more suitable for specific production requirements.

The system performance approach emphasizes the importance of the effect of manufacturing system configurations on different performance indicators, such as, productivity, quality, scalability capacity, productivity, and throughput. Authors offered different models to analyze and predict the effect of manufacturing system configurations on the system performance. Parallel-serial configuration, with and without crossover, are used to quantify the productivity. It was shown that significant improvements to productivity can be obtained by placing operations in parallel and there is a synergistic improvement to productivity from having crossover between the operations.

The effect of manufacturing system configurations on system performance has been analyzed in terms of probabilities, machine availability, and working rates; in most cases, the structural characteristics of the manufacturing system configuration layout have been overlooked. No authors have studied the manufacturing system configuration layout at the facility level to analyze the decision making points and the interrelations between them.

2.6 Complexity

In this section, complexity is presented as something taken up in several disciplines. First, the definition and characteristics of complexity are explained. These definitions are used

to explore the relevant content for structural complexity in manufacturing systems. Last, existing metrics that can be used to assess structural complexity, in general, and, more specifically, in manufacturing system configurations, are reviewed.

Commonly, complexity refers to that aspect of a system that consist of "parts or entities not simply coordinated, but some of them involved in various degrees of subordination; complicated, involved, intricate; not easily analyzed or disentangled" Simpson (1989). That said, complexity has many interpretations. Computational complexity refers to the computability of an algorithm (Papadimitriou, 1994); information processing understands complexity as the total number of properties transmitted (Newell, 1990), and physics sees it as the probability of reaching a certain state vector (Heisenberg, 2007). In engineering, complexity generally addresses the high coupling of the entities of a technical system (Maurer, 2007), and software science focuses on assessing program code for its complexity, and, thereby, the risk of introducing errors into the code.

Complexity science originated from Cybernetics, founded by Wiener (1948), and Systems Theory, founded for the most part by Bertalanffy (1950). It was also influenced by Dynamic System Theory, which belongs to the field of applied mathematics for the description of dynamic systems. Complexity often involves the difficulty of handling a system, because it is hard to estimate the outcome of an action. Complexity is sometimes defined as a degree of disorder (Shannon, 1948).

Complexity is characterized (Cardoso, Mendling et al., 2006) by :

- Structure: a complex system is a potentially highly structured system which indicates a structure with variations.

- Configuration: complex systems have a large number of possible arrangements of their parts.

- Interaction: A complex system is one in which there are multiple interaction between many different parts.

- Inference: A system structure and behavior cannot be inferred from the structure and behavior of its parts.

- Response: Parts can adjust in response to changes in adjacent parts.

- Understability: A complex system is one that by design or function, or both, is difficult to understand and verify.

Joel Moses, in his memo "Complexity and Flexibility," emphasizes the complexity of the internal structure of a system (Sussman, 2000). His approach is close to a dictionary definition of 'complicated" - A system is complicated when it is composed of many parts interconnected in intricate ways.

Sussman (1999) defines a system as "complex" when it is composed of a group of related units (subsystems), for which the degree and nature of the relationships is imperfectly known. The overall emergent behavior is difficult to predict, even when the subsystems behavior is readily predictable. Behavior in the long and short-term may be markedly different and small changes in input or parameters may produce large changes in behavior.

To differentiate between complicated and complex, complicated pertains to the perception of the designer, which Suh (2005) has defined as "imaginary complexity", the complexity that arises from the lack of knowledge or understanding of a specific system. Sivadasan et al. (2006) summarized the qualities of a complex system:

- Number of elements or sub-systems

- Degree or order within the structure of elements or sub-systems

- Degree of interaction or connectivity between the elements, subsystems, and the environment

- Level of variety, in terms of the different types of elements, sub-systems and interactions

- Degree of predictability and uncertainty within the system

Elsewhere, the definition of complexity (Suh, 1999) pertains to a measure of uncertainty in achieving the specified functional requirements. Therefore, complexity is related to information content. This is the concept that will be used in assessing the structural complexity of the manufacturing system layout in this thesis.

2.7 Approaches to Measuring Complexity in Manufacturing

2.7.1 Entropy/ Information Approach

Shannon (1949) derived an entropy-based approach to express uncertainty about an information source in terms of probability.

Given a set of n states, E= {e_1, e_2,......., e_n}, and their respective a priori probabilities of occurrence P= {p_1, p_2,......., p_n}, where p_i >= 0 and $\sum_{i=1}^{n} p_i = 1$, entropy (H) is defined as:

$$H = -K \sum_{i=1}^{n} p_i \log_2 (p_i)$$

(2.1)

Frizelle and Woodcock (1995a) defined the notion of static complexity and dynamic complexity in manufacturing systems based on the entropy formula. This definition

considers that complexity management the analysis of the progress of parts through manufacturing operations and the obstacles they encounter, that is, the machines that extend the lead time. This definition is based on three essential assumptions. Firstly, each sub-system is assumed to be an operation process. Secondly, the more complex a process becomes the less reliable will be. Finally, the most complex processes are likely to be bottlenecks (Calinescu et al., 1998).

Deshmukh et al., (1998) defined static complexity as a "function of the structure of the system, connective patterns, variety of components, and strength of interactions".

Static complexity accounts for the structure of the components of a system and the relationships among them whereas dynamic complexity deals with the operational behavior and schedule changes of the system. The static complexity of a system *S* can be measured by the amount of information needed to describe the system and its components, namely:

$$H(S) = -\sum_{i=1}^{M}\sum_{j=1}^{N} p_{ij}log_2\,(p_{ij})$$

(2.2)

where S is a system, M is the number of resources, N is the number of possible states for the ith resource, and p_{ij} is the probability of resource i being in state j.

In equation 2.2, the resource can be any entity within a system for which a schedule can be drawn, such as, machines, people, specific work centers, work-in-progress areas, interfaces or materials. The basic assumption made in calculating the structural complexity is that a schedule exists for a period up to the scheduling horizon. All the

resource states used for defining and calculating the structural complexity are, therefore, planned (Efstathiou, Calinescu et al., 2001). Examples of planned states for a given resource include: running, set-up, maintenance, and idle. The static complexity gives the measure of the intrinsic difficulty of the process of producing the required number and type of products in the required period of time.

Dynamic, or operational, complexity systems from the dynamic nature of system resources cause uncertainty of a system as resources move through time (Deshmukh et al., 1998).

Dynamic) complexity determines the operational behavior from direct observations of the process, in particular on how queues behave (in terms of queue length, variability and composition). The main idea in the entropic approach is that operational complexity is reflected by queues. The investigation of the behaviors of queues will help detect obstacles in the process. Operational complexity can be calculated by internal sources, as the entropic formulation from (Frizelle and Woodcock, 1995b) in equation (2.3),

$$
H_{dynamic}(S) = -P \, log_2 \, P - (1-P)P \, log_2(1-P) - (1-P)(\sum_{i=1}^{M^q} \sum_{j=1}^{N^q} p_{ij}^q \, log_2 p_{ij}^q
$$

$$
+ \sum_{i=1}^{M^m} \sum_{j=1}^{N^n} p_{ij}^m log_2 \, p_{ij}^m + \sum_{i=1}^{M^b} \sum_{j=1}^{N^b} p_{ij}^b log_2 \, p_{ij}^b) \qquad (2.3)
$$

where P represents the probability of the system under control, p^q is the probability of having queues of varying length greater than 1, p^m is the probability of having queues of length 1 or 0, p^b is the probability of having non-programmable states, M represents the number of resources, N_j represents the number of states at resource j, and $N_j = N_j^q + N_j^m + N_j^b$.

The entropic approach considers that the queue length is zero when the machine is idle. The queue length is one when the machine is running and there is no element in the queue. The system is under control when there is at most one element in each queue.

The Meyer and Foley Curley (MFC) method is a framework for the investigation of the management of software development. They consider that the system characteristics are an important criterion in choosing the software development approach. Calinescu et al. (1998) compared entropy approach and (MFC) method in measuring complexity in manufacturing. The main criteria considered in assessing the two methods were: methodology, cost, feasibility, type of information required and type of results they provide. They concluded that the entropic method is more thorough and time-consuming to implement and requires more care to gather, analyze, and interpret the data. However, if compared to the MFC method, it provided more insightful information on the system. The weakness of the entropy method is the high cost of resources. On the other hand, the MFC method is generic, easy to implement, and provided a correct view of some aspects of decision-making complexity. They consider that the two methods complement each other.

Efstathiou et al. (2001) proposes that manufacturing complexity is a system characteristic which integrates several key dimensions of the manufacturing environment including size, variety, concurrency, objectives, information, variability, uncertainty, control, cost, and value.

2.7.2 Complexity in Axiomatic Design

In engineering systems, the goal is to reduce the complexity to achieve functional requirements of the systems. Consequently, complexity theory, based on axiomatic

design principles defines information and complexity only relative to what we are trying to achieve and/ or want to know, meaning the functional domain. Suh (2005) defines complexity as a measure of uncertainty in achieving the specified functional requirements (FR). Therefore, complexity, which is related to information content is defined as a logarithmic function of the probability of achieving the FR. The greater the information required to achieve the FR the greater is the information content, and, thus, the complexity.

Suh (2001) classified complexity into two categories: time-independent complexity and time-dependent complexity as shown in Figure 2.4
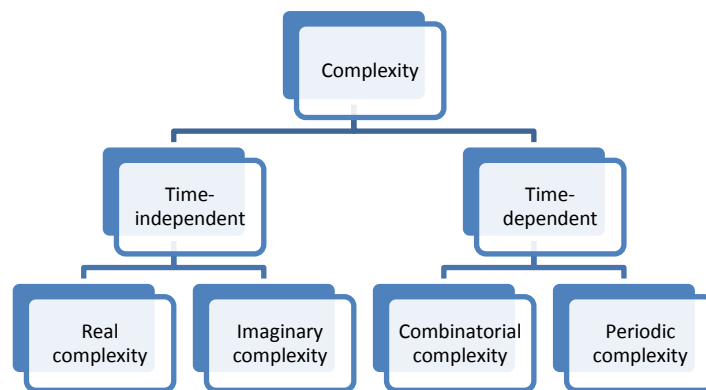
Figure 2.4. Classification of complexity.

Time-independent complexity is related to the real uncertainty coming from variation and imaginary uncertainty introduced from the lack of design knowledge. Real uncertainty results from the difference between the desired probability distribution of the functional requirements (FR) and the actual probability distribution of design parameters (DP). Time-independent real complexity is a result of not satisfying the FR at all times. Real complexity is defined as a measure of uncertainty when the probability of achieving the FR is less than 1.0 because the system range does not lie inside the design range as illustrated in Figure 2.5 (Suh, 2005).
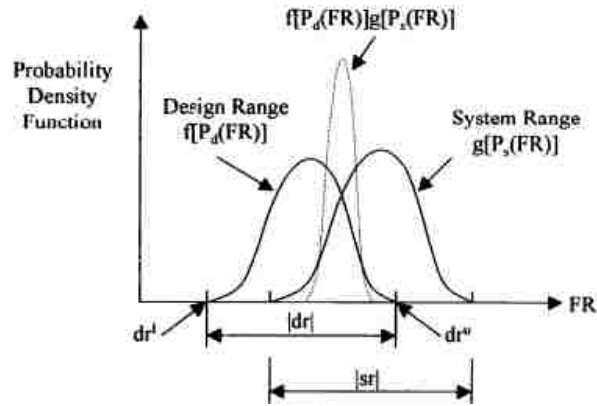
Figure 2.5. Desired probability distribution of the design.

Time-independent imaginary complexity is defined as uncertainty that is not real uncertainty, but arises because of the designer's lack of knowledge and understanding of a specific design itself.

Time-dependent combinatorial complexity arises when the system range moves away from the design range in the course of time because of the unpredictability of several future events. Combinatorial complexity is defined as the complexity that increases as a function of time due to a continued expansion in the number of possible combinations with time, which may eventually lead to a chaotic state or a system failure.

The periodic complexity is defined as the complexity that only exists in a finite time period, resulting in a finite and limited number of probable combinations (Suh, 2005).

The Axiomatic Design approach has advantages and disadvantages similar to entropic approaches since it is based on the information theory. However, it is different from other entropic approaches from the following perspectives:

"Axiomatic Design provides FR and DP, which indicate the kind of probability that should be measured and how they can be calculated. In Axiomatic Design complexity is defined by the information content that is the logarithms of probability of success.

Probability of success is defined as the probability of DPs to meet FRs."(p. 43)(Kim, 1999).

Axiomatic Design suggests that time-dependent combinatorial complexity should be changed to time-dependent periodic complexity to reduce system complexity.

Axiomatic design has been applied in manufacturing systems by researchers (Kim, 2002; Cochran et al., 2000; Lenz, 2000). Cochran et al. (2001) decompose the functional requirements and design parameters for a manufacturing system using the developed axiomatic-based approach to help manufacturing system designers clearly separate objectives from the means of achievement, relate low-level activities and decisions to high-levels goals and requirements, understand the relationships among the different elements of a system design and effectively communicate this information across a manufacturing organization. The system designer must be able to relate low-level activities to high-level system objectives. For example, equipment can greatly influence the way the manufacturing system is designed and operated (Arinez and Cochran, 2000). Thus, it is necessary that the designer understands how the lower-level tactical design solutions achieve higher-level system design goals.

Lower-level decisions not only affect the achievement of higher-level goals, but also interrelate with other lower-levels decisions. For example, equipment selection influences the machine interface; changeover times affect possible run sizes. The manufacturing system design approach must provide a means to understand the interrelationships between design decisions to avoid local optimizations. Manufacturing System Design Decomposition (MSDD) provides a comprehensive view to understand the interrelationships of the manufacturing system and cover many aspects of manufacturing

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systems such as plant layout design and operation, human work organization, equipment design, material supply, use of information technology, and performance measurement that can help to identify causes of complexity.

2.7.3 Heuristic Approach

Heuristic methods have an advantage that they are very easy to be applied to real systems, easy to collect and interpret data. However, for these reasons it has a deficiency of being subjective to an argument whether metrics really reflect the system complexity (Kim, 1999). Kim (1999) used a heuristic approach to quantify system complexity. The proposed series of system complexity metrics were: (a) number of flow paths, (b) number of crossing in the flow paths, (c) total travel distance of a part, (d) number of combinations of products and matching machines, (d) number of elementary systems components, and (e) complexity of each elementary component.

Kim applied those metrics in a case study comparing lean manufacturing and mass production system affected by the increase of product variety. The results confirmed that in lean manufacturing system the number of crossing flow paths, the number of flow paths, and total travel distance of a part were significantly reduced compared to the mass production system.

Those metrics show some characteristics of the layout configuration and proved to be helpful in measuring complexity. However, the relative importance of those individual metrics was not discussed nor were they combined into a single complexity metric for comparison purposes.

2.7.4 Hybrid Approach

ElMaraghy and Urbanic (2003) defined an operation complexity model in manufacturing systems as a function of three basic elements: the absolute quantity of information, the diversity of information, and the information content. A compression factor was applied to the quantity of information represented by an entropy measure: $H = \log_2 (N + 1)$ where N is the total quantity of information. The complexity model in manufacturing environment is a framework that can be used in any design and manufacturing environment by appropriately selecting aspects of the main product influences and process constituents. This model helps reflect the influences of the quantity, variety, and characteristics of the product. ElMaraghy and Urbanic (2003) also defined three types of complexity: product complexity, process complexity, and operational complexity. Product complexity is a function of the material, design and special specifications for each component within the product. For example, mechatronics products are complex due to the multi-disciplinary domains for the design. Process complexity is a function of the product, the volume requirements, and the work environment. The work environment dictates the process decisions such as type of equipment, in-process steps, jigs, fixtures, tooling, gauges, etc. The process complexity is higher in a high volume production due to the number and diversity of features to be manufactured. Operational complexity is a function of the product, process, and production logistics. The performance metrics, scheduling, equipment set-up, running, monitoring, and maintenance tasks of the process are all components of operational complexity.

ElMaraghy and Urbanic (2004) extended the described framework to assess the operational complexity considering the physical and cognitive aspects associated with the tasks related to product and process.

ElMaraghy (2006) developed a code-based structural complexity index for manufacturing systems. This complexity coding system is like Group Technology for coding parts. The complexity index captures the amount and variety of information for the main elements of a manufacturing system, equipment (i.e., machines, material handling, and buffers), and layout. The complexity index is extracted from the complexity code. The system complexity code represents the time-independent structural attributes of the manufacturing system which influence its complexity and operation. The equipment complexity code captures their inherent characteristics and the layout complexity code captures the relationships of individual pieces of equipment in a manufacturing system.

Kuzgunkaya and ElMaraghy (2006) proposed an entropy-based complexity metric index that uses the reliability of equipment to describe its state in the manufacturing system, combined with an equipment complexity code to incorporate the effect of the various hardware and technologies used. The results of the case studies showed that using more reliable machines in a manufacturing system would reduce the overall complexity by increasing the probability of achieving the desired production targets. In addition, using more capable machines decreases complexity by reducing the number of required buffers. The proposed structural complexity metric was shown to be sensitive to changes in manufacturing equipment. A brief description of the layout configuration was presented; however, more comprehensive analysis on layout configuration is required.

Martin (2004) presented a framework to analyze complex systems. The metrics were classified as internal, external, and interface complexity. The complex systems of interest are complex systems embedded in a complex large-scale system. The internal complexity

refers to the complexity of the complex system itself, the external complexity is the complexity of the system environment (i.e., the complexity of the large-scale system in which the system is embedded), and the interface complexity is defined as the interface between the system and its environment. The examples used were two surveillance radars: the first one is Air Traffic control radar and the second is maritime surveillance radar. The internal complexity metrics takes into account the number of links, the number of elements, the function, and hierarchy of the elements. The results highlight the close relationship between the three complexities, the influence of external complexity on internal complexity and the need for a holistic approach to complexity. Interface and internal complexity are approximately linearly related.

Gabriel (2007) investigated mainly the effect on performance of internal static complexity on performance manufacturing complexity (ISMC). In his study, the complexity of a system is determined by the number of elements and relationships, the intricacy of the relationships, and the different states that system elements can have. His quantitative measure consists of three components of internal static manufacturing complexity:

1) Product line complexity is the total number of manufactured items, which accounts for the end items (i.e., product mix) and the manufactured components.

2) Product structure is comprised of the following elements: (1) the weighted average product structure depth, (2) the weighted average product structure breadth, and (3) the component commonality multiplier.

3) The process complexity component is composed of three elements. They are: (1) the weighted average number of routing steps associated with end items, (2) the

total number of work centers in the manufacturing system and (3) the routing

commonality multiplier.

The larger the value of ISMC, the more complex a system's structure. Also, the

differences, or interval, between values for ISMC is important. ISMC is unitless and does

not have a specific interpretation, which is useful for comparison of manufacturing

systems and evaluating management decisions as to how they affect the manufacturing

complexity.

Three of the eight individual components of ISMC were correlated to the manufacturing

performance: the breadth of the product structures, the depth of the product structures,

and the number of different end-products in a manufacturing system.

The comparison of the entropy approach and the ISMC, is that ISMC does not predict

performance better than entropy (H); even considering the tightness of due dates and the

mean protective capacity in systems, neither H nor ISMC is clearly superior, is better to

say that both explain little about changes in performance.

2.8 Complexity in Other Fields of Engineering

2.8.1 Complexity in Product Development

Ko, Yu and Pochiraju (2005) applied a system complexity analysis methodology to track

the evolution of information complexity for several design process workflows in product

development. Engineering design consists of three elements which interact with each

other: design problem, design process, and the design artifact. They analyzed the design

process using quantitative measures based on complexity theory considering two aspects:

the size and the link (or interactions). They confirm that the size aspect, such as, the

number of elements or variables, is directly related to the increase of complexity. How

the elements of a system interact with each other also influences the system complexity. These size and link aspects of complexity can describe the complexity of a system and provide a comprehensive picture of the system in terms of complexity. Summers and Shah (2003) suggests that those two aspects of complexity can be viewed as independent measures in a vector form. Ko et al. (2005) use this approach as size and link complexities tend to be independent of each other, e.g., a system can have high size complexity but zero link complexity or a system can have high size and link complexity. In addition to the computation of complexity to provide quantitative values of the design process for comparison purposes they also consider the change of information during the design process or dynamic complexity. Static complexity of a design process is defined as the complexity that is determined by the structure of a given knowledge-base.

2.8.2 Complexity in Computer Science

In computer science researchers have developed software metrics including complexity and quality. Alsmadi (2011) applied structural metrics to measure the complexity of the user interface from testing perspectives. In the Graphical User Interface (GUI), (Tullis, 1988) studied layout complexity and demonstrated it to be useful for GUI usability. He defined arrangement (or layout) complexity as the extent to which the arrangement of items on the screen follows a predictable visual scheme. In other words, the less predictable a user interface the more complex it is expected to be.

Some of the interface complexity metrics are:

- The number of controls in an interface

- The GUI tree depth: The depth of the tree is calculated as the deepest leg or leaf of that tree. Tree depth is directly proportional to the complexity of the GUI.

- The structure of the tree: the more three paths a GUI has, the more number of test cases it requires for branch coverage. Tree paths count is a metric that differentiate a complex GUI from a simple one.

- Choice or edges/ tree depth: the total number of choices in the tree is divided by the tree depth. The edges/tree depth can be seen as a normalized tree-paths metric in which the average of tree paths per level is calculated.

- Maximum number of edges leaving any node: this metric represents the maximum horizontal widths of the tree.

The GUI structure can be transformed to a tree model that represents the structural relations among controls.

Few structural complexity metrics were applied to assess the complexity layout of a Graphical User Interface (GUI) in terms of usability meaning how easy, convenient and fast it is to deal with. The paper considered only single metrics and the combination of metrics was left for future work.

2.8.3 Complexity in Engineering Process Design

Companies have to cope with new products that are of an interdisciplinary character (Kreimeyer, 2009). In a concurrent engineering process, tasks are not put into sequence, with one task waiting for the preceding tasks to finish, but are processed in parallel and interlinked to be synchronized on the go to reduce the cycle time while the individual artifacts within the process are gradually concretized. This process in parallel has created an even greater need for densely network processes, as currently even partial results have to be checked for their mutual dependencies. A deeper look into engineering design process reveals that such networks of a process exist on many levels of process design.

Kremeiyer (2009) developed a methodology to analyze and extract inferences about the process behavior from a process map. Structural characteristics and complexity metrics support the characterization of a structure. The different entities of the process are: tasks, business objects, resources, and organizational units. The interplay of entities involved in the process forms a network-like structure. This interplay takes shapes as certain structure patterns that are referred to as "structural characteristics"; these structures are the basic constellations of a few entities and their relations with other entities. Kremeiyer (2009) applied models and methods of Graph Theory to provide a basis for analyzing structures. The structural metrics proved to be a good means of spotting entities that are of relevance for the network. Also the structural significance of these metrics could be verified for the domains that were reviewed (activities, documents, points in time).

The results indicated that the chosen approach of using structural metrics and structural outliers are able to provide viable results with minimal effort in a systematic manner.

The limitation of this methodology is the interpretation of the metrics; it cannot be derived directly from the metrics, whether a process is "good" or "bad". The approach requires a deep understanding of the principles used to derive the metrics to interpret the results correctly. Therefore, generalizing about each metric's is limited.

Following, Table 2.3 presents a matrix of the reviewed approaches. This matrix helps to visualize the gap analysis of the literature of complexity in manufacturing systems layout.

Approach	Authors	Aspects of complexity	Layout Complexity
Heuristic	(Kim, 1999)	Number of elements and complexity of each element	No
Complexity Model	(ElMaraghy, 2006)	Equipment and layout complexity classification code	Yes, machine level
	(ElMaraghy and Urbanic, 2003) (ElMaraghy and Urbanic, 2004)	Quantity of information, diversity and information content	No
	(Kuzgunkaya and ElMaraghy, 2006)	State of the manufacturing system by reliability, availability and equipment complexity code	Yes, machine level
	(Samy, 2011)	Relationship between assembled products and their assembly equipment and systems.	No
Complex systems	(Martin, 2004)	Number of links, number of elements, function and hierarchy of elements.	No
Structural characteristics	(Ko et al., 2005)	Number of elements and links in product development	No
Structural characteristics	(Kreimeyer, 2009) (Lindemann et al., 2009)	Adjacency, clustering, paths, density, hierarchies in process design	No

Table 2.3. Matrix of literature review.

2.9 Summary of the Literature Review on Complexity in Manufacturing

In this chapter, different approaches to cope with complexity in manufacturing and other related fields have been presented. The entropy approach used to be a common method in manufacturing to describe static complexity and dynamic complexity where the measure of complexity is the probability of an entity being in a determined state. However, the major drawback of this approach is the assumption of independence of the elements, which cannot be the case. The entropy approach does not provide details regarding the states of the entities beside machines. On the other hand, the axiomatic design approach indicates the kind of probability that should be measured and how they can be calculated. In axiomatic design approach complexity is defined by the information content that is the logarithms of probability of success. Probability of success is defined as the probability of design parameters (DP) to meet the functional requirements (FR). Heuristic approach presented by (Kim, 1999) took in consideration relationships between system components, number of elements, and complexity of each element. However the individual metrics were not combined into a single metric. The complexity model proposed by (ElMaraghy and Urbanic, 2003) consist of three elements: quantity ofinformation, diversity of information, and information content and is applied to static complexity (product) and dynamic complexity (process and operational complexity). The advantage of this model is that it can be used in any design and manufacturing environment using appropriate selection of the aspects of the main product influences and process constituents. The classification and coding of elements within the manufacturing system approach, first introduced by (ElMaraghy et al., 2005), offers a new approach to capture the inherent characteristics of the manufacturing system modules and their relationships.

The complexity indices presented by Martin (2004) to analyze complex systems were classified on internal, external and interface complexity. The results highlight the close relationship between the three complexities. The drawback about this approach is that it cannot be generalized to systems whose performances are not comparable. Also, the metrics are based on statistical data and their accuracy depends upon the amount of data collected. Finally, the framework is missing a global approach to analyze complexity in a more holistic, way, indeed more conceptualization and effort will be required.

Gabriel (2007) investigated mainly the effect on performance due to the internal static manufacturing complexity. His study of the complexity of a system was determined by the numerosity of elements and relationships, the intricacy of the relationships and the different states that system elements can have. His internal static manufacturing measure consist of product line complexity, product structure, average number of routings, total number of work centers and routing commonality multiplier. However, the complexity measure did not consider layout complexity arguing that it is difficult to quantify layout complexity because layout complexity does not have any evident numerosity or intricacy elements and no quantifiable element of layout complexity has been identified.

After reviewing the different approaches to assess complexity in manufacturing, the entropy concept has been frequently used to assess complexity especially for dynamic complexity. Assessing structural complexity of manufacturing system configuration and layout has been only introduced on the machine level, where series, parallel and hybrid configurations of machines and effect of the system operational complexity are analyzed.

Chapter 3 proposes a new methodology to assess the structural complexity of manufacturing systems layout. The method introduces new complexity indices that

provide a tool to analyze a layout for the occurrence of relevant patterns among its entities and relationships. These metrics are directly affected by the information content inherent in the system layout.

2.10 Graphs

This section aims to review basic concepts of graph theory to apply in the analysis of the proposed graphical representation of manufacturing systems described in Chapter 3. Graph theory provides some basis to study networks, which are called a graph. A graph is an ordered pair, G= (N, E), where N is a set of nodes (also called vertices) and E is a set of edges (also called arcs); a 2-element subset of N, a graph is, thus, a formal description for "boxes and arrows" when drawing a network on paper.

Graph theory describes networks in a generic way, attributing the following basic properties:

- Graphs can be directed ("diagraph") or undirected, or both ("mixed graph").

- A directed graph or digraph G consists of a vertex set V (G) and an edge set E (G), where each edge is an ordered pair of vertices. A simple digraph is a digraph in which each ordered pair of vertices occur at most once as an edge. The choice of head and tail assigns direction to an edge, which is illustrated by assigning edges as arrows.

- Graphs can have a weight associated to nodes and/or edges ("weighted graph").

- Graphs can have loops ("simple graph") or not.

- An edge can connect a node to itself ("loop").

- Graphs can have multiple edges between two nodes ("multigraph"), one or none, or one edge connecting one node to many others ("hyperdedge").

- Graphs can have edges not associated with any node ("half-edges" or "loose edges").

- Graphs also contain certain basic structures that can be used to describe them.

- Elements in a graph can be "disconnected", i.e., a node has no edge to any other node.

- A graph is "complete" if every pair of nodes is connected by an edge, i.e., if the graph contains all possible edges. Such a graph, in which every node is connected to every other node, is also called a "clique".

- If a graph is "strongly connected", it does not necessarily have any cliques in it, but every node can be reached from every other node.

- A "path" is a set of adjacent edges listed in a specific order; the path can be attributed by its length.

- A "cycle" is a path that starts and ends with the same node.

- If it is a connected graph that has no cycles, it is called a "tree".

- A "spanning" tree is the minimal graph necessary to connect all edges in a graph.

- A "planar" graph is a graph whose edges do not cross each other.

- A "subgraph" is a graph S contained within a graph G: G is the "supergraph: of S.

- "Graph labeling" is used to assign integer labels to nodes and edges; this can be used for the "coloring" of a graph, assigning a color to each node with no tuple of neighboring nodes being of the same color.

Graphs are commonly modeled as "boxes and edges". There are many methods to draw a graph, serving different purposes. A common algorithm is a force-based layout that

arranges the nodes in a way such that nodes arranges which are closely connected as neighbors, repelling less connected nodes (Fruchterman and Reingold, 1991).

Mathematically, graphs can be modeled as an Adjacency Matrix, which is similar to a Design Structure Matrix (DSM). Researchers have used Adjancency Lists to list which nodes that are connected to other nodes.

The models and methods of Graph Theory provide the basis for analyzing structures and provide the basic means of describing large networks in Network Theory.

In regards to a system's entities and relations, the structural characteristics can be understood as an application of Graph Theory.

Kreimeyer (2009) presented a set of structural characteristics from different disciplines of research to analyze complex systems in Table 2.4.

He also, reviewed 52 metrics in detail that can be applied to assess the structure of a process or other complex systems. These metrics are not explained in this thesis. However, the metrics were reviewed to construct the complexity indices in this thesis that capture the information content of the manufacturing system layout.

2.11 Network Theory

Additional means of analyzing large network structures are provided by Network Theory. Network and graph theory are closely related. Whereas Graph Theory is focused on the formal modeling and analysis of the interaction of single nodes and edges of networks of limited size, Network Theory regards global properties of large networks. Network Theory makes extensive use of graphs, but with a different analytic approach mostly based on statistics (Kreimeyer, 2009). Network theory aims at creating viable models for

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large network structures, finding statistical properties to describe the networks, and making predictions about their behavior.

	Structural feature	Meaning
Graph Theory	Adjacency	Immediate neighboring of two nodes
	Connectivity	Integrity of the overall network
	n-partie-ness	Existence of distinct, disconnected groups within the networks.
	Paths	Channels of navigation through the network
	Cycles	Paths that end at their start node
	Reachability	Existence of at least one path to another node
	Planarity	Representation of network with no edges crossing each other
DSM	Sequencing	Ideal sequence of nodes in flow-oriented network
	Tearing	Iterations that inhibit an ideal sequencing
	Banding	Groups of independent nodes
	Clustering	Mutually related nodes
Network Theory	Size	Extent of network
	Small world effect	Existence of shortcuts across network
	Transitivity	Probability of connectedness of neighboring nodes
	Degree distribution	Existence of hubs and spokes in network
	Mixing patterns	Relation of clustering to further attributes of the network
	Navigation	Relevance of shortcuts in small world network
	Centrality	Integration of a node into functioning of the overall network
	Motifs	Fractal patterns across different levels of abstraction

Table 2.4. Combined structural characteristics.

CHAPTER III

ASSESSING THE STRUCTURAL COMPLEXITY OF A MANUFACTURING SYSTEM LAYOUT

This chapter presents a new approach to assess the structural complexity of a manufacturing system layout: six individual complexity indices which include characteristics of the layout, such as, connections, paths, cycles, decision points, and redundancies are defined.

The proposed complexity model incorporates the information content of the system, represented by the characteristics of the manufacturing system layout. This, ultimately, affects the decisions made, expressed in the complexity indices.

3.1 Introduction

This section presents the methodology to assess the structural complexity of manufacturing system layouts. The IDEF0 model is shown in Figure 3.1. The proposed methodology consists of the following steps. First, an analysis of the layout based on the decision making points, and material flow is performed. These will be used as the input to build a diagram representation of the system layout with nodes and arrows representing the decisions made and the direction of the flow respectively. An adjacency matrix is then created to capture the relationships between nodes in the diagram representation. The complexity assessment is based on the quantification of characteristics (i.e., connections, paths, cycles, number of nodes, and number of redundancies) captured in complexity indices. An overall complexity index is then calculated to reflect the information content of the system.
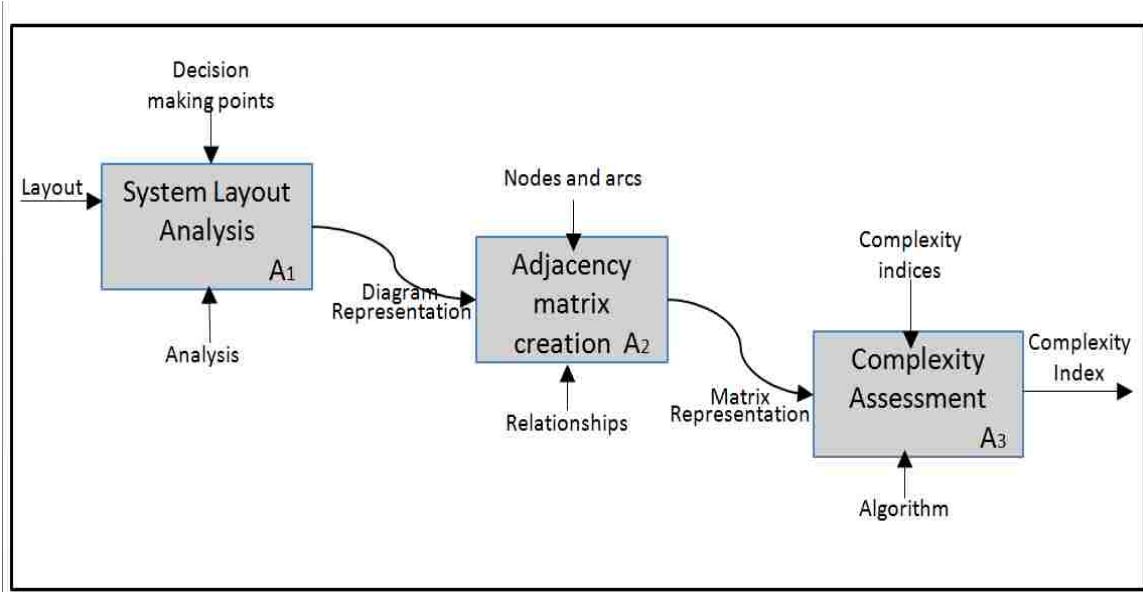
Figure 3.1. Methodology to assess the structural complexity.

3.2 System Layout Analysis

System layout is the arrangement of machines and the connections between them (Spicer et al., 2002). System configuration includes the number and type of modules, their relationships (i.e., machines, workstations, transporters, etc.), and their layout (i.e., locations and connections), which define the flow of work pieces (ElMaraghy, H., 2006). The purpose of the system layout analysis is to identify decision points and directions of the material flow and to represent them by nodes and arrows respectively. The decision points are crucial points where a decision is made regarding the flow of the material.

3.3 Diagram Representation

Diagram representation is a common approach for representing systems and its interactions. Diagrams provide a general idea of how elements interact, do not display quantitative data, but rather relationships and abstract information. The purpose of the diagram representation is to visualize the system layout and to analyze structural characteristics.

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Diagram representations are represented with nodes (input and outputs) and arrows. Nodes in the diagram symbolize a decision needed in the material flow. For example, a product that has several alternative routes for the next process requires a decision to be made regarding which route to take. Then identified and represented in the diagram. Arrows symbolize the direction of the material flow (forward or backward) that exists between nodes. Input nodes of the system symbolize the places where the material flow starts and output nodes symbolize exits for the material. The representation of input and output nodes helps identify a path in the diagram. Figure 3.2(b) shows an example of the construction of a diagram representation from the physical layout in Figure 3.2(a).

a) Physical layout   b) Diagram representation
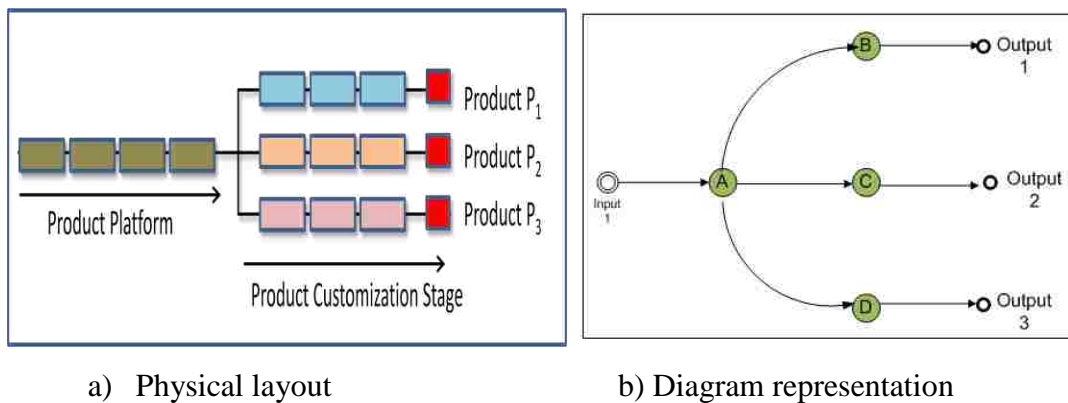
Figure 3.2. Diagram representation of a system layout.

3.4 Adjacency Matrix Creation

A matrix is an information exchange model that represents important system relationships and determine a sensible arrangement for the system being modeled (Kreimeyer, 2009). The purpose of an adjacency matrix is to provide a systematic mapping of system's elements and their relationships.

The adjacency matrix, AM, is created with the nodes of the diagram represented as column and row headings. The values of the matrix correspond to the arrows on the graph

representation. If two nodes are connected, then the value is "1"; otherwise it is "0". The

sequence of the node placement in the matrix commences with the input nodes and ends

with the output nodes. A square matrix of size n x n is created, where *n* is the number of

nodes. An AM is created for the diagram example illustrated in Figure 3.2 as follow.

$$
AM = \begin{array}{c} \\ \text{In} \\ \text{A} \\ \text{B} \\ \text{C} \\ \text{D} \\ 01 \\ 02 \\ 03 \end{array}
\begin{array}{c} \text{In A B C D 01 02 03} \\ \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \end{array}
$$

The adjacency matrix is used as the input for an algorithm (see Appendix A) to calculate

the characteristics related to the proposed indices in the section below.

3.5 Complexity Indices

The proposed manufacturing system layout complexity indices are: density, paths, cycles,

redundancy distribution, and magnitude, as shown in Figure 3.3. The six complexity

indices will be defined and quantified in the next sections.

1. Density index   2. Path index   3. Cycle index

4.Decision point index   5) Distribution Redundancy Index   6) Magnitude Redundancy Index
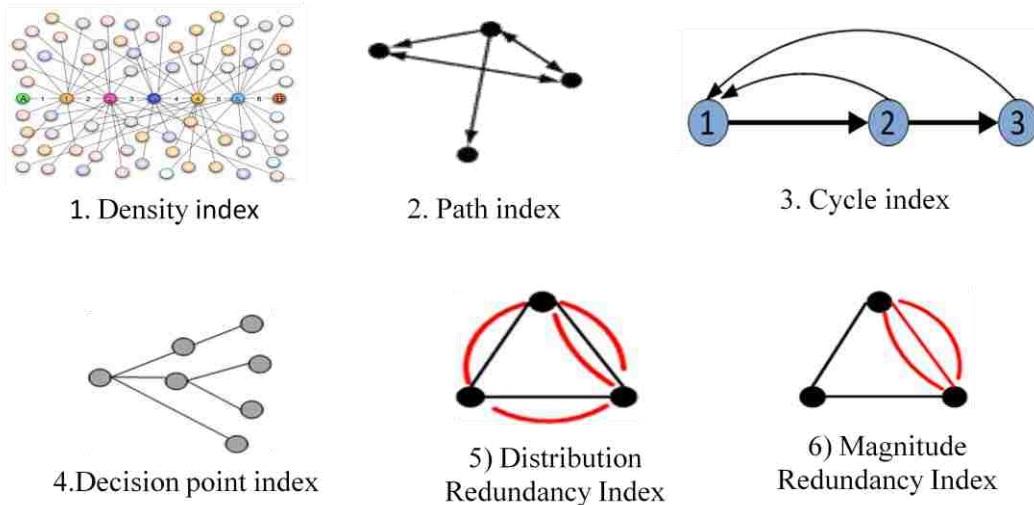
Figure 3.3. Illustration of the proposed six complexity indices.

These complexity indices aim to measure the information content which increases or decreases the difficulty of making decisions regarding the flow of material in the system layout. If the information content increases, then the complexity also increases. The complexity indices are based on concepts of graph theory, such as, connections, paths, and cycles. All indices are normalized to range from 0 to 1. A value of 0 indicates the least theoretical information content and least complexity. A value of 1 indicates the highest theoretical information content and the most complexity.

Table 3.1 presents the complexity indices and the directly related characteristics to measure them.

Structural Complexity Index	Characteristics related to the Index
Density Index	Number of connections Maximum theoretical number of connections
Path Index	Number of paths Minimum theorethical number of paths
Cycle Index	Actual number of cycles Maximum theoretical number of cycles
Decision Points Index	Number of nodes on shortest path Number of nodes on longest path
Distribution Redundancy Index	Number of ocurrences of redundancies between adjacent nodes Maximum theoretical number of ocurrences of redundancies between adjacent nodes
Magnitude Redundancy Index	Total number of redundant parallel arrows Total number of arrows

Table 3.1. Complexity indices.

3.5.1 Density Index

Density is related to the number of connections in a system. The density of a layout graph is the ratio of the number of connections between the nodes of that graph and the number of nodes of that graph.

Density index is the relation between the actual number of connections and the maximum theoretical number of connections (Vanderfeesten I., 2007). The density index is calculated by equation 3.1,

$$D = \frac{k}{n(n-1)} \qquad (3.1)$$

where k is the actual number of connections and n is the number of nodes.

Figure 3.4 and 3.5 show two diagrams with different numbers of connections between nodes (connections between input and output nodes are not counted). Figure 3.4 shows 5 actual connections between nodes. The number of nodes is 4. The maximum theoretical number of connections is equal to 12 given by equation (3.1) as determined by a complete graph with n nodes.
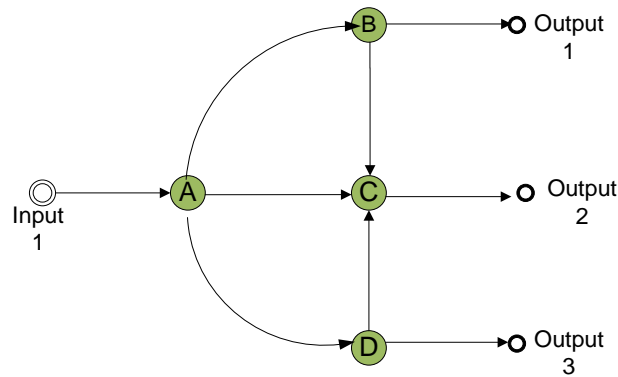
Figure 3.4. Lower density index.

The density index is equal to $\frac{5}{4(4-1)} = 0.41$ in Figure 3.4. Figure 3.5 shows 8 actual

connections between nodes that result in higher density index to $\frac{8}{4(4-1)} = 0.6$.
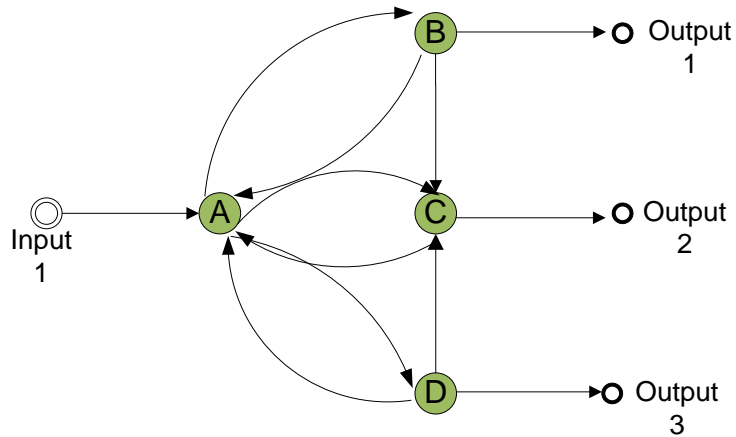
Figure 3.5. Higher density index.

The maximum number of connections in the layout occurs when every nodes has a

connection with all other nodes. A high density index is indicative of a more complex

system because of the increase in the number of connections taken in the system layout.

A low density index in the layout means that there are fewer connections between nodes,

and, consequently, less information content involved.

3.5.2 Path Index

Path in a layout graph is a sequence of nodes that begins from input node through the

arrows to the output node, with at least one different arrow (McCabe, 1976). A path

cannot cross the same node twice. The number of paths is related to the structural

complexity since it increases the number of alternate paths and decisions needed to

control the flow within the system.

Path index is given by equation 3.2,

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$$P = 1 - \frac{p}{N} \quad (3.2) \qquad\qquad (3.2)$$

where p is the minimum theoretical number of paths and N is the number of existing paths. The minimum theoretical number of paths is determined by the number of output nodes. The actual number of paths is the total number of paths between all pair of inputs and outputs node. The diagram in Figure 3.6 shows two output nodes; the minimum theoretical number of paths is equal to 2, and the number of existing paths is equal to 2. Therefore, the path index is $1 - \frac{2}{2} = 0$ by equation (3.2).
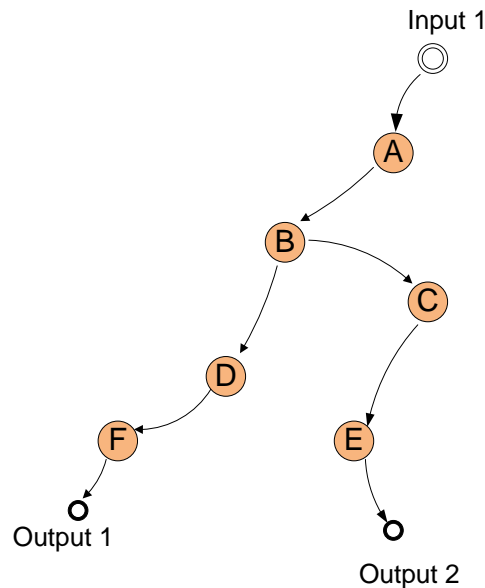
Figure 3.6. Lower path index.

In Figure 3.7, the diagram has two input nodes, which increases the number of existing paths to 5. The minimum theoretical number of paths is equal to 2, thus the path index is $1 - \frac{2}{5} = 0.4$ by equation (3.2). In the layout, a high path index means that there are several alternative paths along the minimum theoretical number of paths. As a result,

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more information is needed to control the flow and, consequently, the complexity increases. Low path index means that there exist few alternate paths beside the minimum theoretical number of paths in the layout system. Thus, less information content and, consequently, less complexity is added to the system.
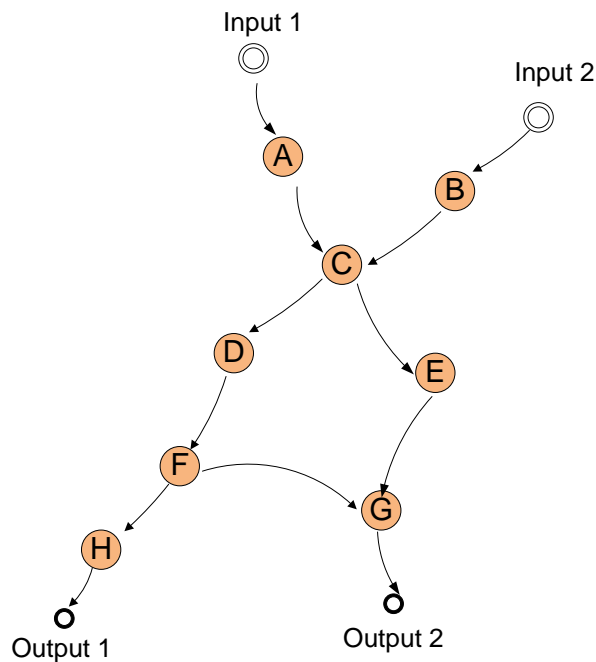
Figure 3.7. Higher path index.

3.5.3 Cycle Index

By definition, a cycle is a path that starts and ends in the same node (Badke-Schaub and Gehrlicher, 2003). The length of the cycle is the sum of the nodes occurring in the loop. A cycle adds structural complexity to the system because the flow does not follow a linear sequence and recurrent flows increase the difficulty of following material travelling across departments.

The cycle index is the ratio of the actual number of cycles and the maximum theoretical number of cycles in the system. The cycle index is calculated by equation 3.3,

$$C = \frac{c}{MC} \tag{3.3}$$

where c is the actual number of cycles and MC is the maximum theoretical number of cycles.

The maximum theoretical number of cycles is the sum of the combination of n nodes starting with two nodes (at least a pairs of nodes is needed to have a cycle), as expressed by equation 3.4,

$$\tag{3.4}$$

$$MC = \sum_{i=2}^{n} C_{(n,i)}$$

where n is the number of nodes and $i = 2$.

Figure 3.8 depicts a diagram with 1 cycle, the maximum theoretical number of cycles is 31 by equation (3.4) thus the cycle index from equation (3.3) is C $= \frac{1}{26} = 0.03$
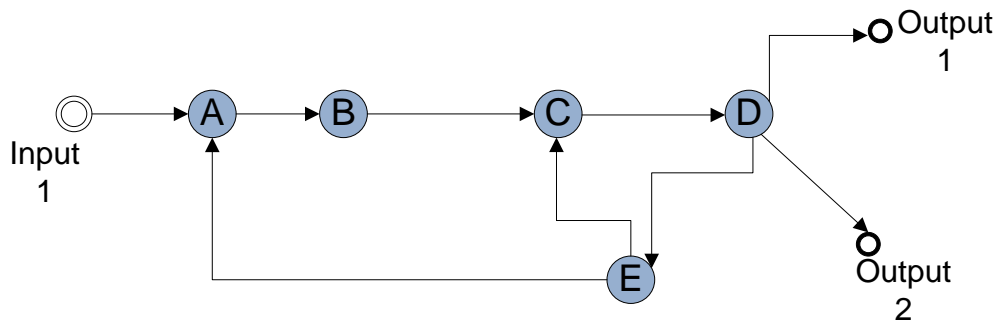
Figure 3.8. Lower cycle index.

Figure 3.9 shows a diagram with 4 cycles, the maximum theoretical number of cycles is 3;1 thus, the cycle index, using equation (3.3), is $\frac{4}{26} = 0.15$. The maximum value of the

index is reached when the actual number of cycles is equal to the maximum theoretical

number of cycles and, consequently, the increase of complexity to follow the flow.
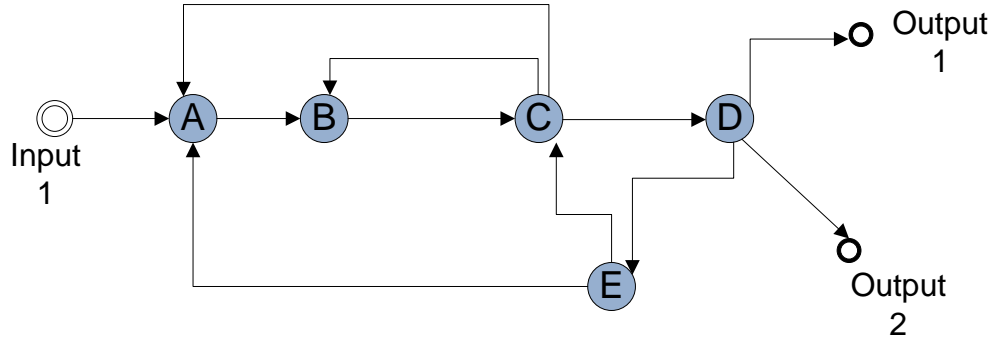
Figure 3.9. Higher cycle index.

3.5.4 Decision Points Index

The decision points index is related to the number of nodes in a path, which is the sum of

all nodes between input and output nodes (Newman, 2003). The number of nodes per

path is related to structural complexity because it increases the number of decisions to be

made along the path. This increases the possibility of errors in the system.

The decision point index is calculated by equation 3.5,

$$DS = 1 - \frac{SP}{LP} \tag{3.5}$$

where SP is the number of nodes on the shortest path and LP is the number of nodes on

the longest path.

Figure 3.10 depicts a diagram with 1 node on the shortest path and 3 nodes on the longest

path. Then, the decision points index, given by equation (3.5), is equal to $1 - \frac{1}{3} = 0.66$
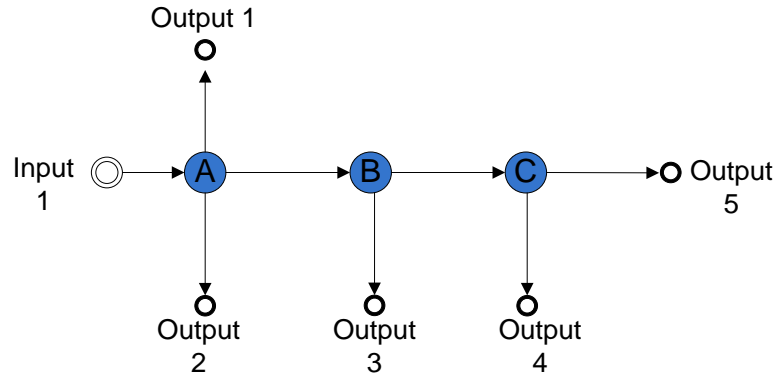
Figure 3.10. Lower decision point index.
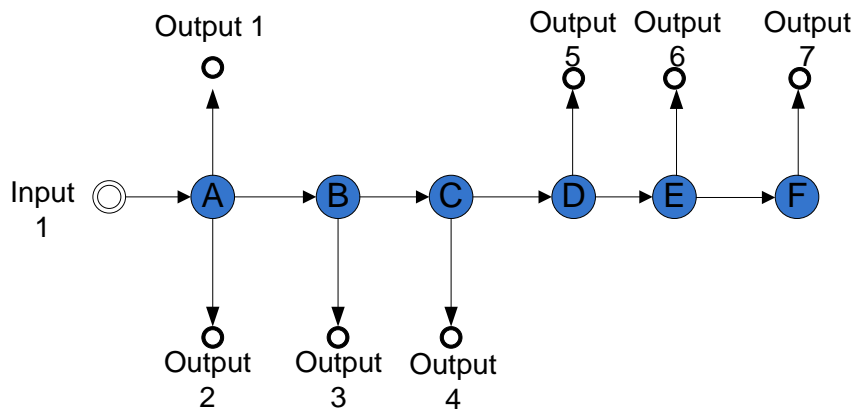
Figure 3.11. Higher decision point index.

In Figure 3.11, the number of nodes on the shortest path is equal to 1 and the number of nodes on the longest path is equal to 6; therefore, the decision point index is equal to $1 - \frac{1}{6} = 0.83$. In the layout, a high decision point index increases complexity due to the increase of number of decisions made per paths. In the layout, 0 in the decision point index means that the number of nodes in the shortest and longest path is equal. Therefore, no complexity is added due to the increase of the number of decisions made in different paths.

3.5.5 Redundancy Distribution Index

Redundancy refers to the repeated or duplicated connections that exist between two nodes. Distribution of redundancy refers to the occurrences of redundancy between adjacent nodes, regardles of the number of redundancy branches. It increases the information content of the layout and, consequently, the complexity.

Distribution of redundancy index is defined as the ratio between the number of ocurrences of redundancies between adjacent nodes and the maximum theoretical number of adjacencies between nodes. The distribution of redundancy index is evaluated from 0 to 1, where 0 means no occurrences of redundancies between nodes and 1 means occurrence of redundancy in all adjacent nodes. The distribution of the redundancy index is calculated by equation 3.6,

$$RD = \frac{r}{a} \tag{3.6}$$

where r is the number of occurrences of redundancies between two adjacent nodes and a is the maximum theoretical number of ocurrences of redundancies between all adjacent nodes.

Figure 3.12 shows a diagram with 2 occurrences of redundancy between adjacent nodes (r) and the maximum theoretical number of adjacencies (a) is equal to 6.
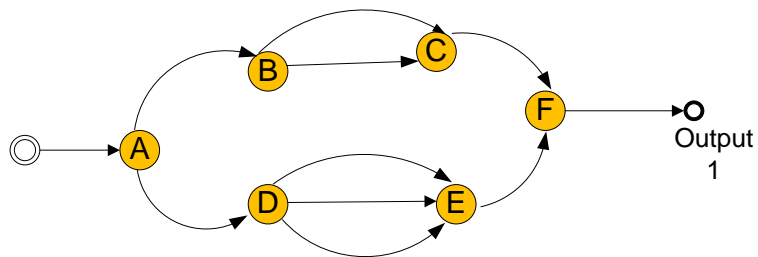
Figure 3.12. Lower redundancy distribution index.
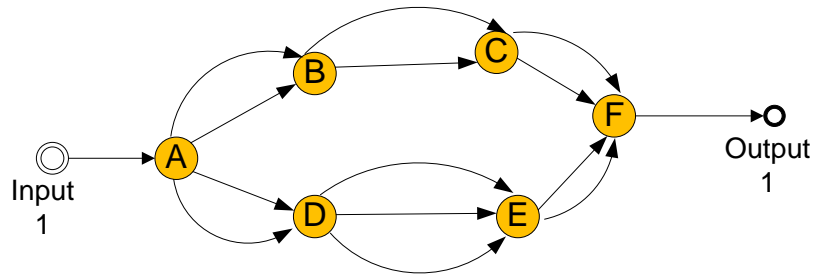
Figure 3.13. Higher redundancy distribution index.

Figure 3.12 shows a redundancy distribution index equal to $\frac{2}{6} = 0.33$. The distribution of

redundancy index reaches the maximum value of the index $\frac{6}{6} = 1.0$ in Figure 3.13, where

the number of occurrence of redundancies and the maximum theoretical number of

ocurrence of redundancies between adjacent nodes are equal. The increased information

content by the ocurrence of redundancies in all adjacent nodes makes the layout in Figure

3.13 more complex than that in Figure 3.12. The minimum value of the redundancy index

is when there is no ocurrence of redudancy in any of the adjacent nodes.

3.5.6 Redundancy Magnitude Index

The redundancy magnitude index accounts for the number of redundant parallel arrows in

the system layout. This is related to structural complexity because as the number of

redundant parallel arrows increases, the information content increases.

The redundancy magnitude index is the relation between the total number of redundant

parallel forward arrows and the total number of forward arrows in the system. The

redundancy magnitude index is calculated by equation 3.7,

$$RM = \frac{pr}{w} = \frac{w - a}{w} \qquad (3.7)$$

whrere pr is the total number of redundant parallel arrows, w is the total number of forward arrows and a is the number of adjacencies.

Figure 3.14 shows 3 redundant parallel arrows, six adjacencies, and the total number of forward arrows in the system is 9. Thus, the magnitude of redundancy index, given by equation (3.7), is equal to $\frac{3}{9} = 0.3$.
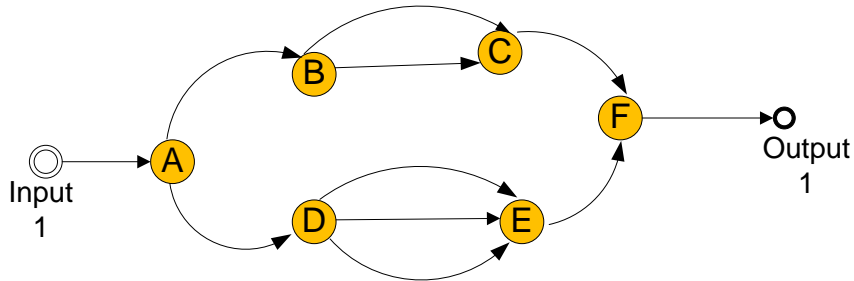
Figure 3.14. Lower redundancy magnitude index.
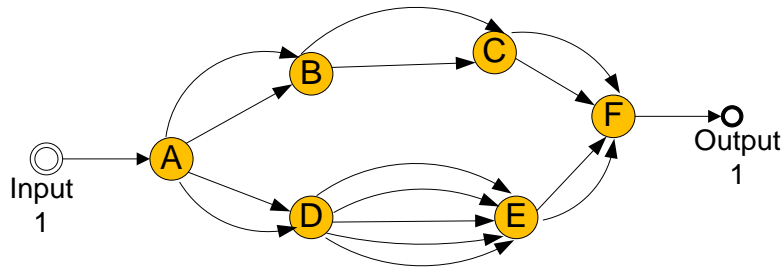
Figure 3.15. Higher redundancy magnitude index.

In Figure 3.15, the total number of redundant parallel arrows is 9, the number of adjacencies is 6, and the total number of forward arrows is equal to 15. Then, the magnitude of redundancy index is equal to $\frac{9}{15} = 0.6$, given by equation (3.7).

The redundancy magnitude index increases the information content due to the increase of the number of redundant parallel arrows and, consequently, increases the layout complexity.

3.6 Layout Complexity Assesment

The assessment of the layout complexity is accomplished by integrating the six complexity indices into an overall measure of structural complexity. Three techniques (average, radar, and vector) for aggregating the individual indices into one are described below and compared to find the best technique to assess the structural complexity of a manufacturing system layout.

3.6.1 Average Value

The average value technique was applied by ElMaraghy (2006) to convert a string code from the complexity clasification for equipment into an overall complexity index. This was done by normalizing the value of each code digit, then calculating the average as given by equation 3.8 (Kuzgunkaya and ElMaraghy, 2006),

$$m = \frac{\sum_{d=1}^{ND} \frac{Vd}{MVd}}{ND} \tag{3.8}$$

where Vd is the value of digit d, MVd is the maximum value of digit d, m is the coeficient that represents the average complexity compared to the most complex value by the proposed code, and ND is the total number of digits in the classification code.

The average value is calculated by equation 3.9,

$$A = \frac{1}{n}\sum_{i=1}^{n} a_i = \frac{a_1 + a_2 + a_3 + \dots + a_n}{n} \tag{3.9}$$

If n numbers are given, each number denoted by a_i, where $i = 1, \dots n$, the average value is the sum of the $a_i's$ divided by n.

The average value aggregation method will be applied to the complexity indices to calculate their normalized value.

3.6.2 Radar Chart

Radar chart is a method used to represent graphically multivariate values taking into consideration the maximum values of each index. The value of the point is represented as the distance from the center of the chart, where the center represents the minimum value and the chart edge is the maximum value. The values are normalized according to the maximum value of the data. The chart connects these points with straight lines forming triangles. The chart is divided into equal segments (based on the number of data point indices).
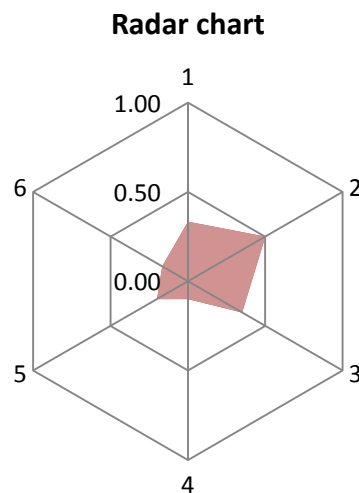
Figure 3.16. Shaded area in a radar chart.

For instance, if there are 6 data points, the data points will be spaced 60 degrees apart. The connected points form a shaded area as shown in Figure 3.14. Samy (2011) used a

radar chart representation to calculate a complexity index as the ratio between a shaded

area and the total area of the radar chart. The shaded area is calculated by equation 3.10,

$$a = \frac{1}{2}\left[(C_t * C_1) + \sum_{i=1}^{i=t-1}(C_i * C_{i+1})\right]\sin\left(\frac{360}{t}\right) \tag{3.10}$$

Where a is the shaded radar area, C_i is the normalized value on the radial axis of index i,

and t is the total number of data values in the radar plot.

The total plot area is given by equation 3.11,

$$A = \frac{t}{2}\sin\frac{360}{t} \tag{3.11}$$

where A is the total plot area and t is the total number of data values in the radar plot.

The aggregated complexity index is defined as the ratio between shaded area and the total

plot area, as given by equation 3.12,

$$CI = \frac{a}{A} \tag{3.12}$$

where a is the shaded radar area and A is the total plot area.

The radar chart technique will be applied to the complexity indices to visualize them and

to calculate the shaded area as well.

3.6.3 Vector Method

A vector is a mathematical object that has magnitude and direction. Graphically, a vector is represented by an arrow, defining the direction and the length of the arrow defines the vector's magnitude. The magnitude of a vector is denoted by /V/ or **V**. It can be calculated with Pythagoras' theorem,

$$V = \sqrt{(V_t)^2 + (V_u)^2 + (V_w)^2 + (V_x)^2 + \left(V_y\right)^2 + (V_z)^2} \qquad (3.13)$$

where $V_t, V_u, V_w, V_x, V_y, V_z$ are the components of vector V in six dimensions.

To apply this technique the components must be independent of each other. Using the complexity index values, the independence between them will be verified in Chapter 4.

3.6.4 Summary of the Techniques

The techniques reviewed are summarized in Table 3.2 and applied in the next chapter to asses the structural complexity of the manufacturing system layout in a number of case studies.

Techniques	Data	Limitations	Merits	References applied in manufacturing complexity
Average Value	Input: Individual values with same dimensions. Output: Single metric	Cannot combine values with different dimensions.	Provides a single measure to compare systems.	(Kuzgunkaya and ElMaraghy, 2006) (ElMaraghy, H. et al., 2005).
Radar Chart	Input: Multiple indices of different dimensions. Output: Single metric.	The sequence of the variables is not defined.	Visualizes the variables, provides a single measure.	(Samy, 2011).
Vector Magnitude	Input: Values in different domains. Output: Single metric.	Limited to vector operations. Vectors must be independent	Can be described in two or more dimensions	(Physics, 2011).

Table 3.2. Comparison of Complexity Index Calculation Techniques.

CHAPTER IV

APPLICATIONS OF THE METHODOLOGY

This chapter presents the application of the methodology in six different manufacturing system layouts. The methodology is applied systematically to assess the structural complexity of the system layouts. The manufacturing system layouts presented by Kim will be discussed in Chapter 5.

4.1 ABS Plant Layout

This manufacturing system was presented by Kim (1999). The plant produces anti-lock break system (ABS) units for automotive companies. The presented layout is the machining and assembly area for housing of ABS 5.3. This layout will be compared to an alternate one.

4.1.1 System Layout Analysis

Within the ABS 5.3 family, different features vary according to customer selection. Two variants are built: the anti-lock breaking system (ABS) and an anti-lock braking system with traction control (ASR). This product variation requires flexibility. First, the raw material is stored in a warehouse. Then, parts are moved to the receiving area of the plant. Later, containers are pulled from the machining area for production. Automated Guided Vehicles (AGVs) are used to send the containers to one of the 7 machining cells; see Figure 4.1 (Kim, 1999). After being machined, the parts are moved to one of the 8 deburring machines by AGVs. The deburring operation, which removes burrs from the hydraulic circuits, is done automatically, using a high pressure water jet. Then, the parts are moved by a conveyor belt to the washing and drying machines. Parts are inspected manually after washing and are repacked into containers. These bins are moved to a

buffer area by AGV and bins are retrieved by assembly lines. The assembly tasks are performed in a U-shaped cell. Finished parts are manually taken off the conveyor and sent to the shipping area. A final inspection is performed to return products that do not meet specifications to the start of the assembly line.
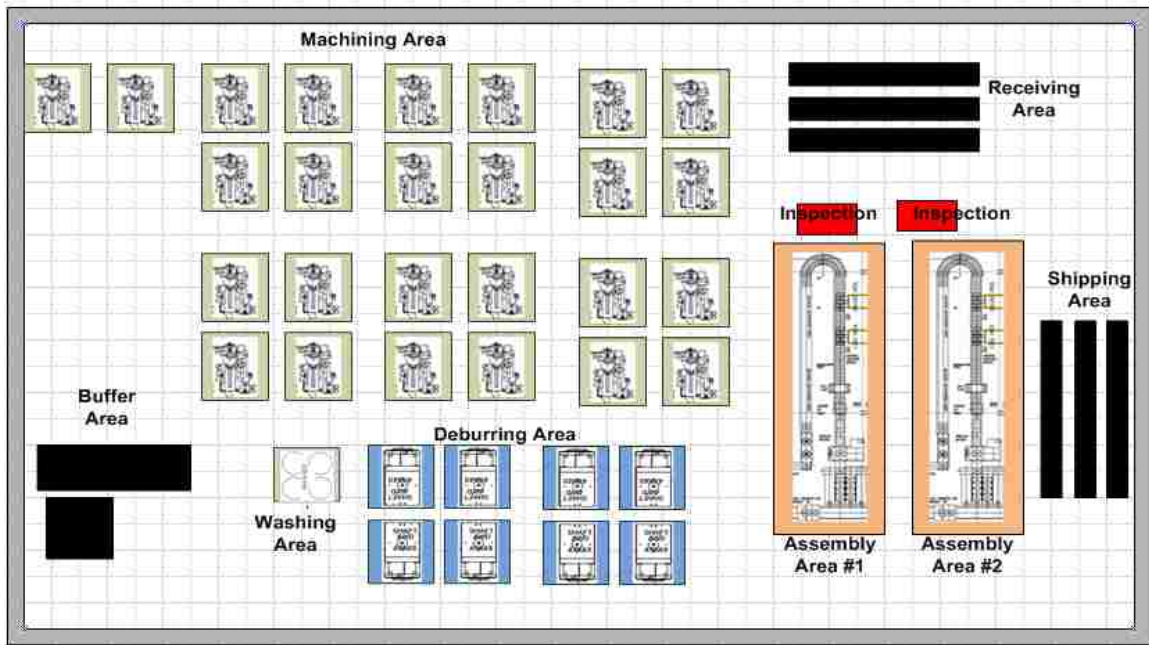
Figure 4.1. ABS plant layout.

4.1.2 Diagram Representation

The physical system layout is analyzed and the decision points and material flow directions are identified. Subsequently, a diagram representation is generated as shown in Figure 4.2.

In the diagram, (Figure 1.12) node A represents the decisions made to send the material to any of the seven machining cells because there are no fixed routes. Node B denotes the decision made to send the material from the machining cells to one of the two de-burring cells. Redundancy is present in the diagram.

Node C expresses the decision to send the material to either one of the two assembly lines. Nodes D and E represent the decision, at the inspection point, to release accepted products or return them to the beginning of the assembly line for re-work.
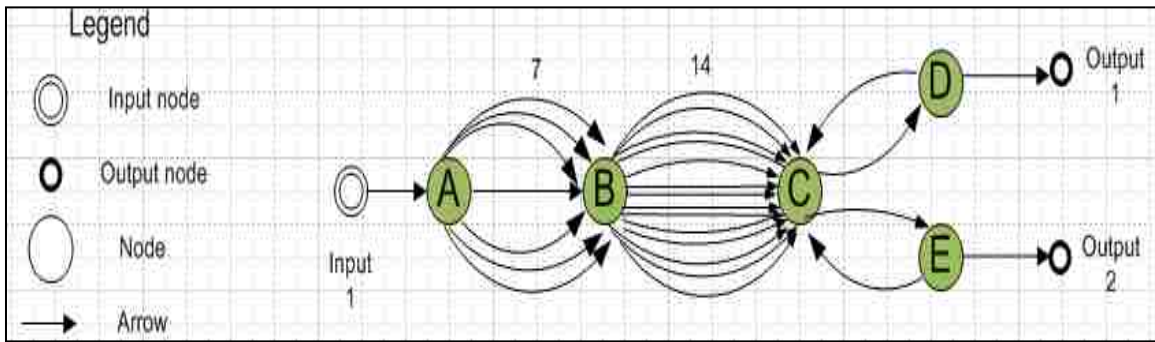
Figure 4.2. Diagram representation for the ABS plant layout.

4.1.3 Adjacency Matrix for ABS Plant Layout

The adjacency matrix is created according to the relationship between nodes in Figure 4.2.

$$
AM = \begin{matrix}
 & \text{In} & A & B & C & D & O1 & O2 & O3 \\
\text{In} & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
A & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\
B & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
C & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
D & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
O1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
O2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
O3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{matrix}
$$

Table 4.1 shows the results of the parameters related to the complexity indices by appying algorithm (see Appendix A) to the adjacency matrix.

The ABS system layout has a low density index, see Table 4.2, which indicates few connections between nodes; a zero path index indicates that there are no alternative paths

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in the graph. A limited number of cycles in the system layout result in a very low cycle index. A zero decision sequence index denotes that the numbers of nodes in the shortest and longest paths are equal. The distribution of the redundancy index indicates that redundancy occurs in half of the connections between nodes. The magnitude of the redundancy index suggests a high number of redundant parallel arrows in the system layout.

ABS Layout	
Number of nodes = 5	Number of nodes on shortest path = 4
Existing connections = 6	Number of nodes on longest path = 4
Maximum theoretical connections = 20	Number of ocurrences of redundancies between nodes = 2
Minimum number of theoretical paths = 2	Maximum number of redundancies = 4
Number of existing paths = 2	Number of redundant parallel arrows = 19
Actual number of cycles = 2	Total number of arrows = 23
Maximum number of theoretical cycles = 26	

Table 4.1. Factors related to indices for ABS layout.

4.1.4 Complexity Indices

Table 4.2 presents the calculated complexity indices.

	Density Index	Path Index	Cyclic Index	Decision points Index	Redundancy Distribution Index	Redundancy Magnitude Index
ABS layout	$\dfrac{6}{20}$	$1 - \dfrac{2}{2}$	$\dfrac{2}{26}$	$1 - \dfrac{4}{4}$	$\dfrac{2}{4}$	$\dfrac{19}{23}$
Results	0.30	0	0.08	0	0.50	0.83

Table 4.2. Complexity Indices of the ABS layout.

4.1.5 System Layout Complexity Assessment

4.1.5.1 Average Complexity Index

The first method to combine the complexity is to obtain the average value of the indices, by equation (3.9).

$$Average\ Index\ Value = \frac{0.30 + 0 + 0.08 + 0 + 0.50 + 0.83}{6} = 0.28\ (3.9)$$

4.1.5.2 Complexity Index Using the Radar Chart

Using the radar chart helps designers to visualize the indices of such layout systems as the one depicted in Figure 4.3 and calculate the shaded area.

ABS Layout
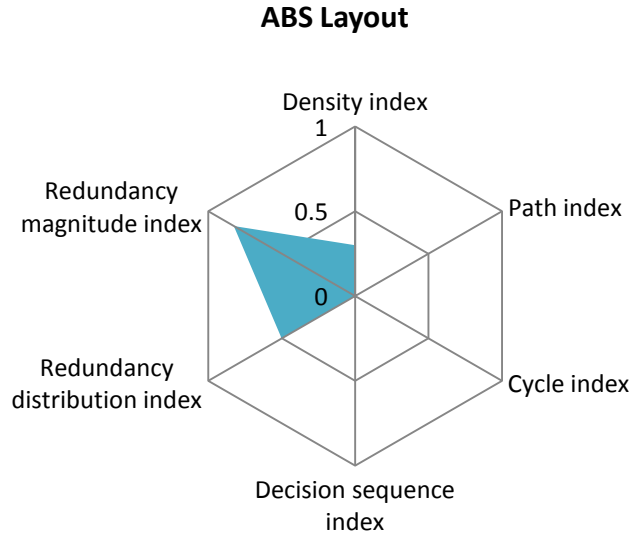
Figure 4.3. Radar chart for the ABS Plant Layout.

The complexity index using the radar chart is calculated by applying equation (3.10).

$$a = \frac{1}{2}\left[(C_t * C_1) + \sum_{i=1}^{i=t-1}(C_i * C_{i+1})\right]\sin\left(\frac{360}{6}\right) = 0.29$$

The differences of the obtained values by the three different techniques will be discussed in Chapter 5.

4.2 ABS Modified Layout

This is a modified layout of the ABS plant, including lean manufacturing concepsts based on cell system or group of products (Kim, 1999).

4.2.1 System Layout Analysis

In the modified layout, the new system has 4 cells; 3 of these cells are for ABS housing and one cell is designed for both ABS/ASR housings. Each manufacturing cell includes

dedicated deburring and washing machines. The new assembly area has 3 lines: 2 of these are for ABS and one line is for both ABS/ASR housings.

The number of equipment is increased to 51 machining centers, 10 deburring machines and 4 washing and drying machines as shown in Figure 4.4. A final inspection is performed to return products that do not meet specifications to the assembly line for re-work.

4.2.2 Diagram Representation

After analyzing the system layout, the decision points and material flow directions are identified. The corresponding graph representation is shown in Figure 4.5.

In the diagram representation, node A stands for the decision made to send the material to one of the two different machining cells, one for ABS and one for ABS/ASR products. Node C stands for the decision made at the machining cell (only ABS) to send material to
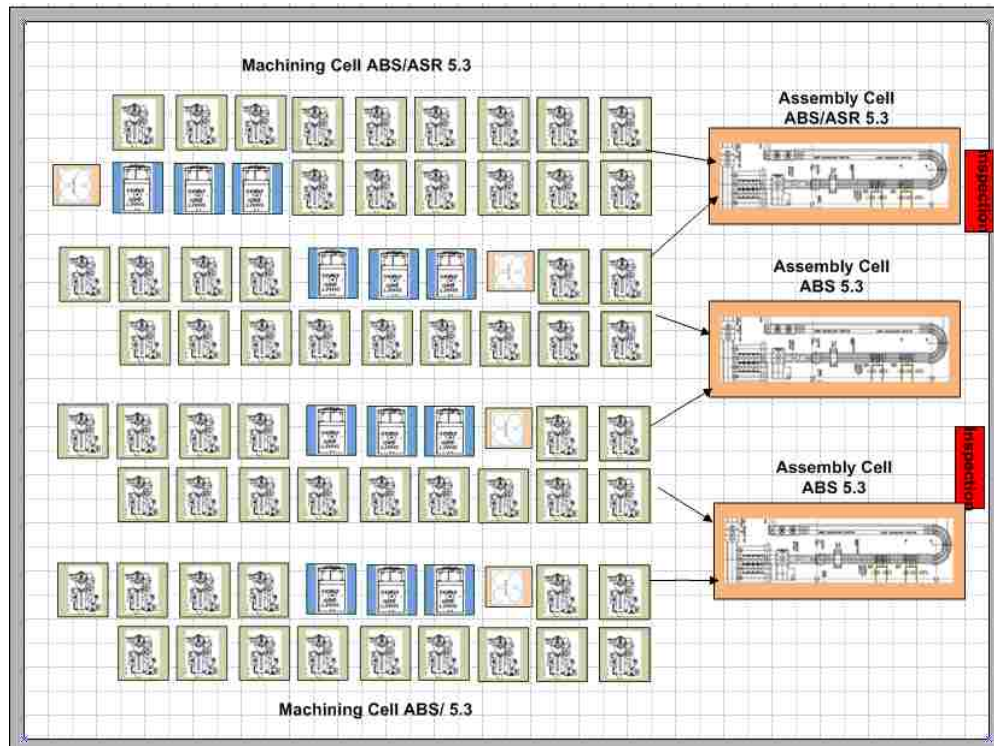
Figure 4.4. ABS modified plant layout.
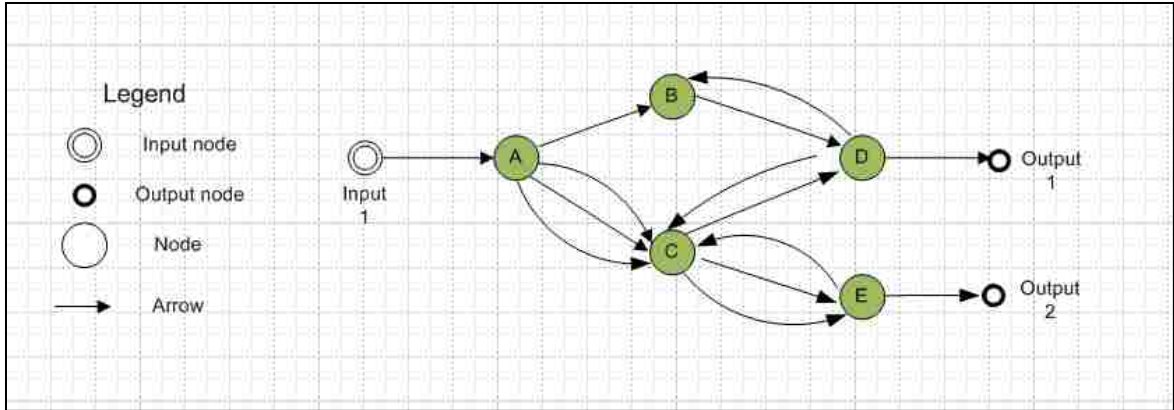
Figure 4.5. Diagram representation for ABS modified plant layout.

one of the two different assembly lines. Node B stands for the decision made when

sending material to the assembly line. Node D and E represent the decision at the

inspection stage to release finished products or return those requiring re-work to the sem

assembly line. Redundancy of machining cells for ABS is represented by the arrows from

input node to node C.

4.2.3 Adjacency Matrix Creation

Subsequently, the adjacency matrix is created according to the relationship between

nodes in Figure 4.4.

$$AM = \begin{array}{c} \\ \text{In} \\ \text{A} \\ \text{B} \\ \text{C} \\ \text{D} \\ \text{E} \\ \text{O1} \\ \text{O2} \end{array} \begin{array}{c} \text{In A B C D E O1 O2} \\ \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \end{array}$$

Table 4.3 shows the results of the parameters related to the complexity indices by

applying the algorithm (see Appendix A) to the adjacency matri.:

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ABS Modified Layout	
Number of nodes = 5	Number of nodes on shortest path = 2
Existing connections = 8	Number of nodes on longest path = 2
Maximum theoretical connections = 20	Number of ocurrences of redundancies between nodes = 2
Minimum number of theoretical paths = 2	Maximum number of redundancies = 5
Number of existing paths = 3	Number of redundant parallel arrows = 3
Actual number of cycles = 3	Total number of arrows = 8
Maximum number of theoretical cycles = 11	

Table 4.3. Factors related to indices of the ABS modified layout.

4.2.4 Complexity Indices

Table 4.4 presents the calculated complexity indices.

The modified ABS layout has a density index value similar to the index of the initial ABS layout. However, the path index increased in the ABS modified layout due to the fixed routes in the system. The decision sequence index is zero, which indicates that the number of nodes on the shortest and longest path are equal. The distribution redundancy index is similar to the initial layout, but the magnitude redundancy index is significantly lower. This reflects a decrease in the number of redundant ocurrences. Finally, cycle index is low for both layouts.

	Density Index	Path Index	Cyclic Index	Decision points Index	Redundancy Distribution Index	Redundancy Magnitude Index
ABS modified layout	$\dfrac{8}{20}$	$1 - \dfrac{2}{3}$	$\dfrac{3}{11}$	$1 - \dfrac{2}{2}$	$\dfrac{2}{5}$	$\dfrac{3}{8}$
Results	0.40	0.33	0.27	0	0.40	0.38

Table 4.4. Complexity indices of the ABS modified layout.

4.2.5 System Layout Complexity Assessment

4.2.5.1 Average Complexity Index

The first method to assess the structural complexity is to obtain the average value of the indices, by equation (3.9),

$$Average\ Index\ Value = \frac{0.40 + 0.33 + 0.27 + 0 + 0.40 + 0.38}{6} = 0.30$$

4.2.5.2 Complexity Index Using the Radar Chart

Using the radar chart helps designers to visualize the indices of such layout systems as the one depicted in Figure 4.6 and calculate the shaded area.

ABS Modified layout
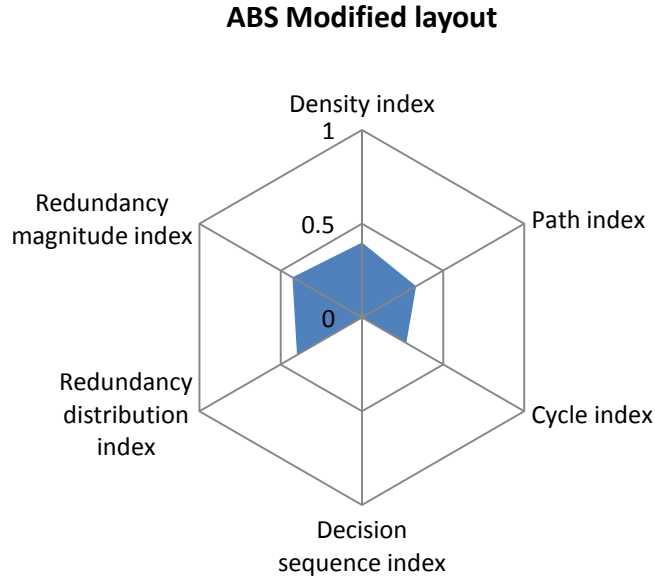
Figure 4.6. Radar chart for the ABS modified plant layout

The complexity index using the radar chart is calculated by applying equation (3.10).

$$a = \frac{1}{2}\left[(C_t * C_1) + \sum_{i=1}^{i=t-1}(C_i * C_{i+1})\right]\sin\left(\frac{360}{6}\right) = 0.23$$

The differences of the obtained values by the three different techniques will be discussed in Chapter 5.

<u>4.3 Modular Layout</u>

This case study presents an example of a modular layout presented by (Benjaafar, Heragu et al., 2002) for a semiconductor plant. The layout consist of different modules. Each module consist of several dissimilar machines connected by a particular flow pattern.

4.3.1 System Layout Analysis

The process has seven departments, which are: diffusion, etching, film deposition, implant, photolithography, metrology, and backend. This layout uses a combination of
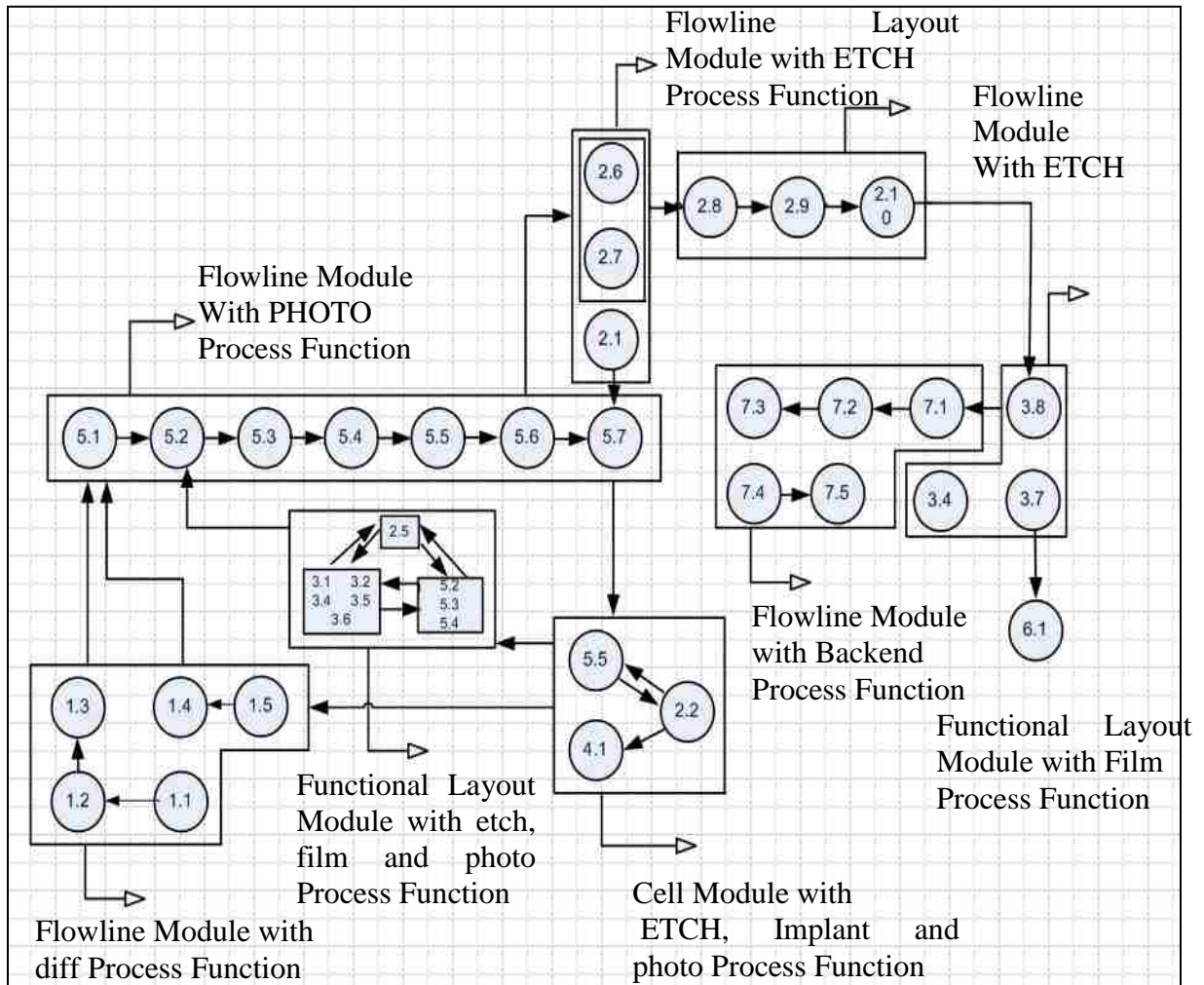
Figure 4.7. Modular layout motorola plant layout.

three traditional layouts (flowline, functional, and cellular layout) to arrange the equipment in different areas of the facility, as depicted in Figure 4.7. In addition, this layout allows some machine duplication, as is usually done for designing a cellular layout for a multi-product manufacturing facility.

4.3.2 Diagram Representation

The physical system layout is analyzed, where the decision points and flow of material are identified. Subsequently, a diagram representation is generated as shown in Figure 4.8.
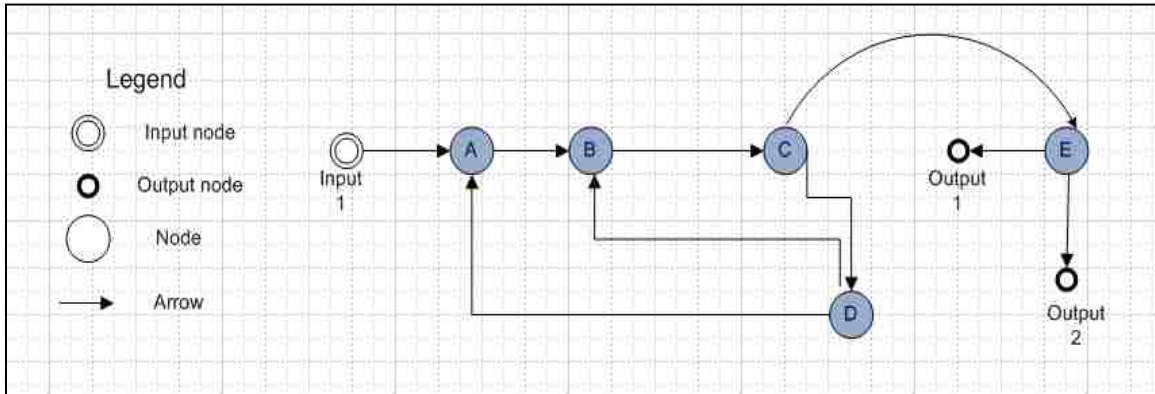
Figure 4.8. Diagram Representation of the modular layout.

In the diagram representation, nodes A and B represent the decision made to send material to the next operation, as well as receiving material from node D. Node C represents the decision to send the material to either a flow line module or a cell module. Node D represents the decision to send material to the flow line module with a different process function or a functional layout module. Node E stands for the decision made to send material to a functional layout module with film process function or flow line module with backed process function.

4.3.3 Adjacency Matrix Creation

Then, an adjacency matrix is created according to the relationship between nodes and arrows in Figure 4.8.

$$AM = \begin{array}{c} \\ \text{In} \\ \text{A} \\ \text{B} \\ \text{C} \\ \text{D} \\ \text{E} \\ \text{O1} \\ \text{O2} \end{array} \begin{array}{c} \text{In A B C D E O1 O2} \\ \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \end{array}$$

The following table shows the results of the parameters related to the complexity indices

by applying the algorithms described in Appendix A to the adjacency matrix:

Modular Layout	
Number of nodes = 5	Number of nodes on shortest path = 4
Existing connections = 6	Number of nodes on longest path = 4
Maximum theoretical connections = 20	Number of ocurrences of redundancies between nodes = 0
Minimum number of theoretical paths = 2	Maximum number of redundancies = 6
Number of existing paths = 2	Number of redundant parallel arrows = 0
Actual number of cycles = 2	Total number of arrows = 6
Maximum number of theoretical cycles = 26	

Table 4.5. Factors related to indices for the modular layout.

4.3.4 Complexity Indices

Table 4.6 presents the calculated complexity indices. The modular layout shows the

following complexity indices, the density index is low, which means few connections

between nodes. The path index indicates there is no altervatives paths in the graph beside

the minimum number of paths. Low cycle index is due to few cycles in the system. The

decision sequence index indicates that there is no difference between the number of

nodes in the shortest and longest paths. Redundancy indices indicate that there is no redundancy distribution or magnitude.

	Density Index	Path Index	Cyclic Index	Decision points Index	Redundancy Distribution Index	Redundancy Magnitude Index
Modular layout	$\dfrac{6}{20}$	$1 - \dfrac{2}{2}$	$\dfrac{2}{26}$	$1 - \dfrac{4}{4}$	$\dfrac{0}{6}$	$\dfrac{0}{6}$
Results	0.30	0	0.08	0	0	0

Table 4.6. Complexity indices of the modular layout.

4.3.5 System Layout Complexity Assessment

4.3.5.1 Average Complexity Index

The first method to combine the complexity is to obtain the average value of the indices, by equation (3.9),

$$Average\ Index\ Value = \frac{0.30 + 0 + 0.08 + 0 + 0 + 0}{6} = 0.06$$

4.3.5.2 Complexity Index Using the Radar Chart

Using the radar chart helps designers to visualize the indices of such layout systems as the one depicted in Figure 4.3 and calculate the shaded area.
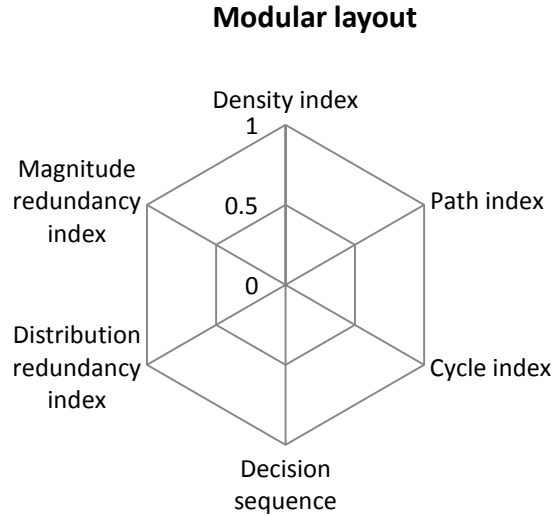
Modular layout

Figure 4.9. Radar chart for the modular layout.

The complexity index using the radar chart is calculated by applying equation (3.10).

$$a = \frac{1}{2}\left[(C_t * C_1) + \sum_{i=1}^{i=t-1}(C_i * C_{i+1})\right]\sin\left(\frac{360}{6}\right) = 0$$

The radar chart indicates that there is no shaded area, despite some non-zero values of the complexity indices. This is the result of the multiplication of complexity indices by zero. This can be understood as the effect of the sequence of the complexity indices in the radar chart.

The differences of the obtained values by the three different techniques will be discussed in Chapter 5.

4.4 Hybrid Serial/Parellel System Layout

This case study demonstrates an example of delayed product differentiation layout (Benjaafar et al., 2002).

4.4.1 System Layout Analysis

The hybrid layout consist of two phases. In the first stage, the plant makes undifferentiated products. In the second stage, the product is customized, based on the actual demand, followed by a check point where the prodduct is accepted or returned to the line for re-work. Figure 4.10 depicts the physical representation for the delayed differentiation system layout (Benjaafar et al., 2002)
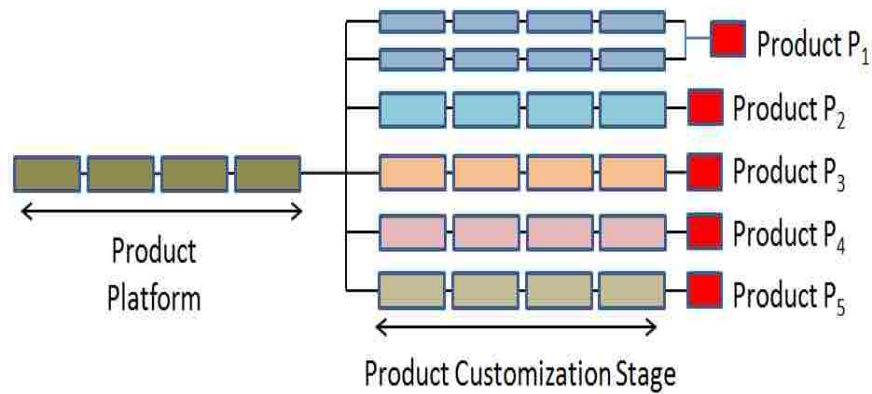
Figure 4.10. Hybrid serial/parallel layout.

4.4.2 Diagram Representation

After the analysis of information of the system layout, the diagram representation is built as in Figure 4.11.
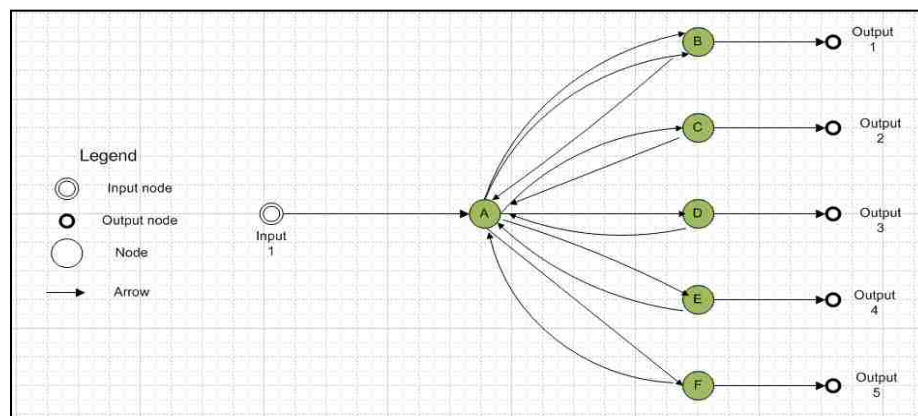
Figure 4.11. Diagram representation for the hybrid layout.

In the diagram representation node A represents the decision made at the product platform to send material to the different product assembly lines. Nodes B, C, D, E and F represent the decision made either to release the material or return it to the product platform.

4.4.3 Adjacency Matrix Creation

An adjacency matrix is created according to the relationship between nodes and arrows in the Figure 4.11.

$$
AM = \begin{array}{c}
\\
In \\
A \\
B \\
C \\
D \\
E \\
F \\
O1 \\
O2 \\
O3 \\
O4 \\
O5
\end{array}
\begin{array}{c}
In\ A\ B\ C\ D\ E\ F\ O1\ O2\ O3\ O4\ O5 \\
\left(\begin{array}{cccccccccccc}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}\right)
\end{array}
$$

Table 4.7 shows the results of the parameters related to the complexity indices by applying the algorithms described in Appendix A to the adjacency matrix.

From Table 4.8 the hybrid layout presents few connections between nodes, resulting in a low density index. Path index is zero because there are no alternative paths beside the minimum number of paths. The cycle index is very low, due to the minimum returning points in the layout. The distribution and magnitude of redundancy is very low because of the duplicated machines in the product differentiation layout.

Hybrid Layout	
Number of nodes = 6	Number of nodes on shortest path = 2
Existing connections = 10	Number of nodes on longest path = 2
Maximum theoretical connections = 30	Number of ocurrences of redundancies between nodes = 1
Minimum number of theoretical paths = 5	Maximum number of redundancies = 5
Number of existing paths = 5	Number of redundant parallel arrows = 1
Actual number of cycles = 5	Total number of arrows = 6
Maximum number of theoretical cycles = 57	

Table 4.7. Factors related to indices of the hybrid layout.

4.4.4 Complexity Indices

Table 4.8 presents the calculated complexity indices.

	Density Index	Path Index	Cyclic Index	Decision points Index	Redundancy Distribution Index	Redundancy Magnitude Index
Hybrid layout	$\frac{10}{30}$	$1 - \frac{5}{5}$	$\frac{5}{57}$	$1 - \frac{2}{2}$	$\frac{1}{5}$	$\frac{1}{6}$
Results	0.33	0	0.09	0	0.20	0.17

Table 4.8. Complexity indices of the hybrid layout.

4.4.5.1 Average Complexity Index

The first method to combine the complexity is to obtain the average value of the indices,

by equation (3.9).

$$Average\ Index\ Value = \frac{0.33 + 0 + 0.08 + 0 + 0.20 + 0.17}{6} = 0.13$$

4.4.5.2 Complexity Index Using the Radar Chart

Using the radar chart helps designers to visualize the indices of such layout systems as

the one depicted in Figure 4.12 and calculate the shaded area.
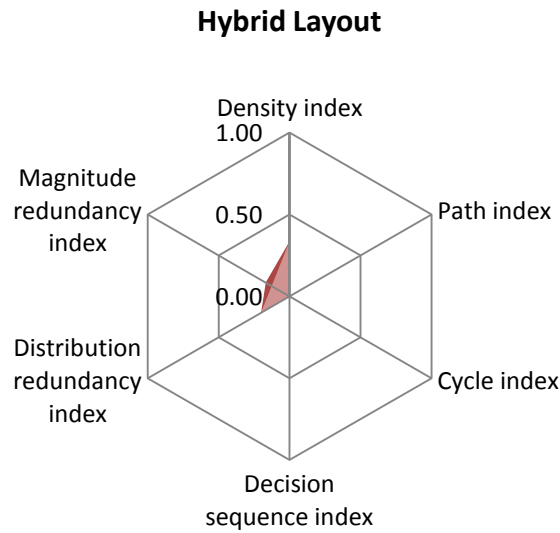
Hybrid Layout

Figure 4.12. Radar chart for the hybrid layout.

The complexity index using the radar chart is calculated by applying equation (3.10).

$$a = \frac{1}{2}\left[(C_t * C_1) + \sum_{i=1}^{i=t-1}(C_i * C_{i+1})\right]\sin\left(\frac{360}{6}\right) = 0.04$$

The differences of the obtained values by the three different techniques will be discussed in Chapter 5.

4. 5 Automobile Engine Piston Assembly Plant Layout

This case study demonstrates an example of an assembly system layout This plant assembles an automobile engine piston in Figure 4.13 (Samy, 2011).

4.5.1 System Layout Analysis

Two types of engine pistons are assembled in the plant. The assembly process starts with a robot gantry that picks the piston head by suction. Parts including the connecting rod, the piston pin, and the snap rings are moved to the indexing table, which feeds the press. Then, the press inserts the pins into the piston head. The next press inserts the snap rings into the piston head. This is followed by an inspection to check the presence of the snap rings, otherwise the subassembly is returned for re-work.

6. Piston rings

1. Piston
3. Piston pin
4. Snap ring
4. Snap ring

Connecting

8. Bearings
Connecting road cap
7. Bolts
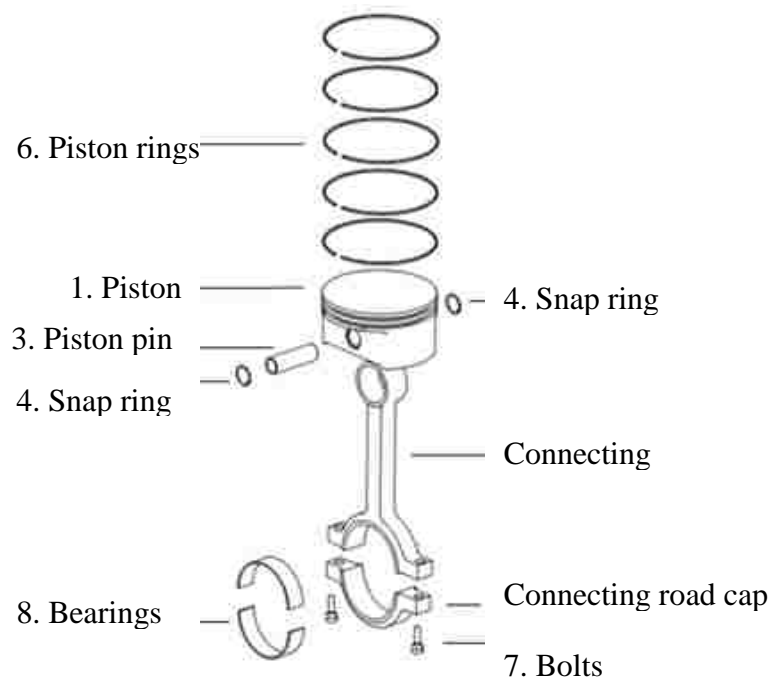
Figure 4.13. Automobile piston engine parts.

After that, the subassembly is placed on an overhead conveyor. The piston rings are located in the cylindrical magazines and inserted into the piston head manually. A nut runner disassembles the connecting rod cap. The bearings are fed into a pick and place device by a conveyor. Later, the bearings are placed in position to be pressed into the subassembly. A robot pick the finished assembly and places it on a pallet on a belt conveyor, as illustrated in Figure 4.14 adapted from Samy (2011).
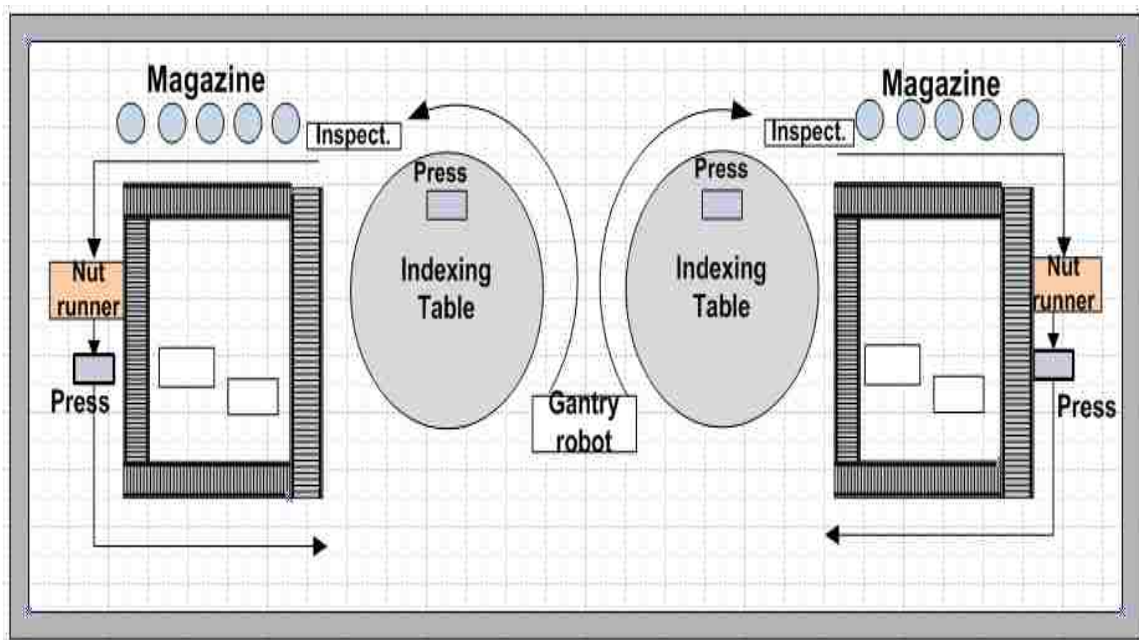
Figure 4.14. Assembly engine piston layout.

4.5.2 Diagram Representation

The physical system layout is analyzed, where the decision points and flow of material are identified. Subsequently, a diagram representation is generated as shown in Figure 4.15.
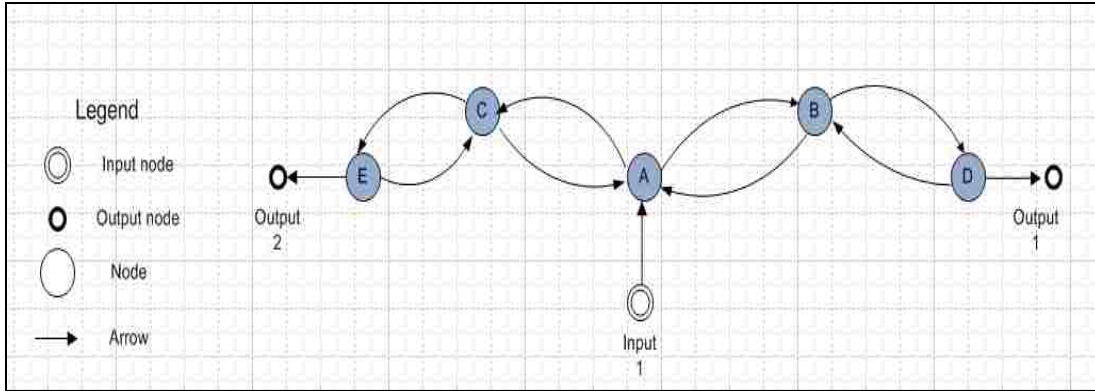
Figure 4.15. Diagram representation for the engine layout.

In the assembly layout for the piston engine, node A represents the decision made to send the piston head to one of the two indexing tables. Node B and C represent the decision made on the inspection point to move the material forward or returned it. Nodes E and D represent the final decision to release the material or return it to the magazine table.

4.5.3 Adjacency Matrix Creation

The adjacency matrix is created according to the relationship between nodes and arrows in Figure 4.15.

$$
AM = \begin{array}{c} \\ \text{In} \\ \text{A} \\ \text{B} \\ \text{C} \\ \text{D} \\ \text{E} \\ \text{O1} \\ \text{O2} \end{array}
\begin{array}{c} \text{In A B C D E O1 O2} \\ \left(\begin{array}{cccccccc}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}\right) \end{array}
$$

Table 4.9 shows the results of the parameters related to the complexity indices by applying the algorithm described in Appendix A, to the adjacency matrix:

Engine Assembly Layout	
Number of nodes = 5	Number of nodes on shortest path = 2
Existing connections = 8	Number of nodes on longest path = 2
Maximum theoretical connections = 20	Number of ocurrences of redundancies between nodes = 2
Minimum number of theoretical paths = 2	Maximum number of redundancies = 4
Number of existing paths = 2	Number of redundant parallel arrows = 0
Actual number of cycles = 4	Total number of arrows = 4
Maximum number of theoretical cycles = 26	

Table 4.9. Factors related to indices for the assembly engine layout.

4.5.4 Complexity Indices

Table 4.10 presents the calculated complexity indices.

	Density Index	Path Index	Cyclic Index	Decision points Index	Redundancy Distribution Index	Redundancy Magnitude Index
Assembly layout	$\dfrac{8}{20}$	$1-\dfrac{2}{2}$	$\dfrac{4}{26}$	$1-\dfrac{2}{2}$	$\dfrac{0}{4}$	$\dfrac{0}{4}$
Results	0.40	0	0.15	0	0	0

Table 4.10. Complexity indices of the assembly engine layout.

The assembly layout presents a medium density index; a zero path index indicates no alternative paths in the layout. Few returning points in the system layout results in a low

cycle index. There is no difference between number of nodes in the shortest and longest path resulting in a zero decision sequence index. It is shown that there is no redundancy in the process which is reflected by the distribution and magnitude redundancy index.

4.5.5 System Layout Complexity Assessment

4.5.5.1 Average Complexity Index

The first method to combine the complexity is to obtain the average value of the indexes, by equation (3.9).

$$Average\ Index\ Value = \frac{0.40 + 0 + 0.15 + 0 + 0 + 0}{6} = 0.09$$

4.5.5.2 Complexity Index Using the Radar Chart

Using the radar chart helps designers to visualize the indices of such layout systems as the one depicted in Figure 4.16 and calculate the shaded area.
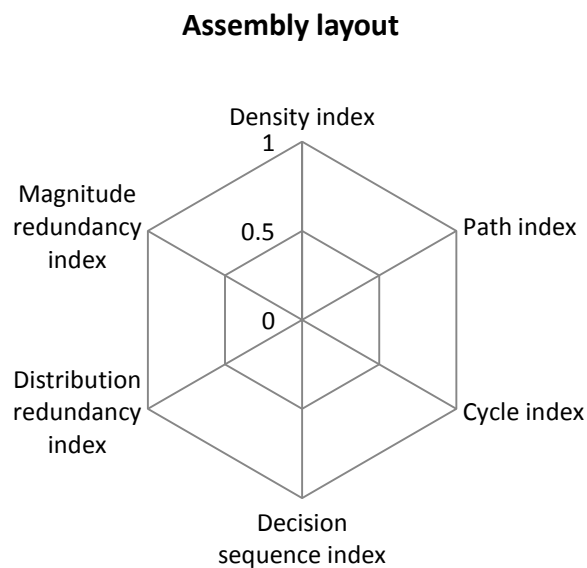
Assembly layout

Figure 4.16. Radar chart for the assembly layout.

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The complexity index using the radar chart is calculated by applying equation (3.10).

$$a = \frac{1}{2}\left[(C_t * C_1) + \sum_{i=1}^{i=t-1} (C_i * C_{i+1})\right] \sin\left(\frac{360}{6}\right) = 0$$

The differences of the obtained values by the three different techniques will be discussed in Chapter 5.

4.6 American Axle & Manufacturing (AAM) Plant Layout

This case study is carried out in an assembly and manufacturing plant of a multinational company. AAM is an automotive supplier of driveline and drivetrain systems, components, chassis systems, and metal formed products. The facility assembles two models of rear axles (7.6 and 8.6 in of ring diameter), see Figure 4.17 (Heincke, 2006), and machining of driveline components (i.e., gear sets, differentials, and carrier differentials). The focus of this case study is the gear machining and axle assembly.
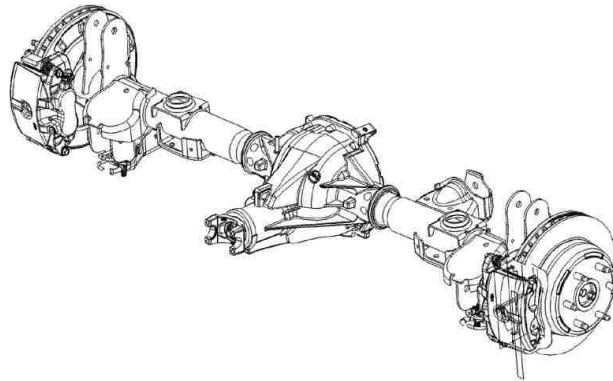
Figure 4.17. Sketch of a rear axle 8.6.

4.6.1 System Layout Analysis

The facility layout consists of two main sub-processes: machining and assembly areas. The machining process consists of three machining components: pinion gears, ring gears, and carrier differential, and one heat treatment area.

The machining process of the gears is divided into phases: soft and hard processes. Soft processes are the operations performed before the heat treatment and hard process the operations performed after it. Soft operations of the ring gear are: turning back face, boring, stamping, drilling, taping, and teeth cut. Soft operations for the pinion gear are: blank pinion, roll splines, and teeth cut. Hard operations, for the the ring gear are the straightener, and thread annealing. Hard operations for the pinion gear are the straightener, thread annealing, and shot peening.

Once the machining operations are finish, the matching of pinion and ring gears takes place. Then, the gear set is sent to be washed, tested, and to the lubrite process.

At the end of the lubrite process, the parts are placed in a container and moved to the sub-assembly line by a fork lift. The sub-assembly line joins the differential carrier and the gears set. During the assembly process parts that do not meet specifications will be rejected and returned to their corresponding area.

In the final assembly line, tubes, brackets, and other final components are assembled to the sub-assembly carrier differential. Finally, the parts are unloaded using a crane. Figure 4.18 depicts the AAM plant layout.

4.6.2 Diagram Representation

The physical system layout is analyzed, where the decision points and flow of material are identified. Subsequently, a diagram representation is generated as shown in Figure 4.19.

In the AAM assembly layout, node A represents the decision to send material to either one of the two models. Node B and C represent the decision to move the material
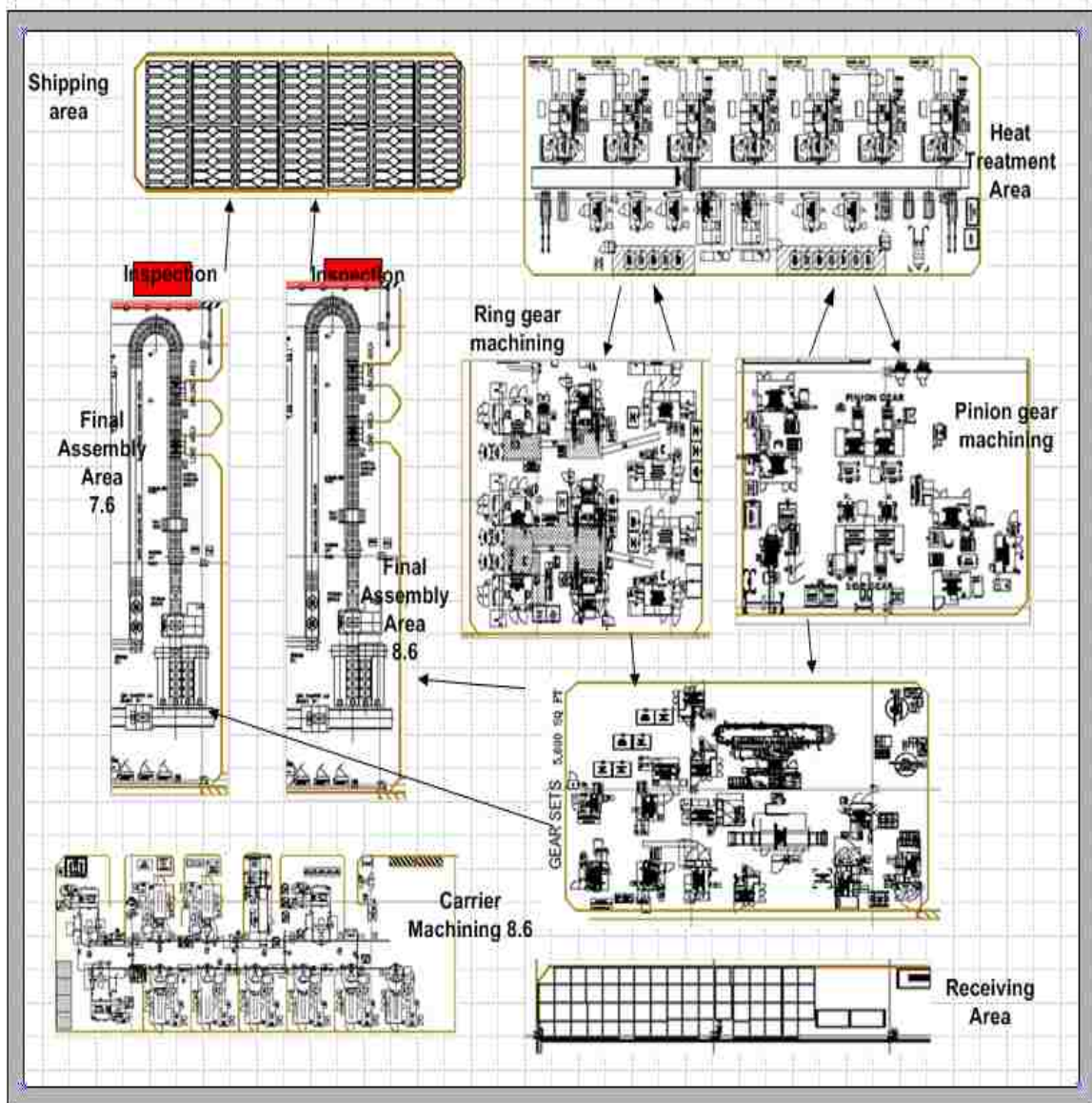
Figure 4.18. American axle & manufacturing plant layout.
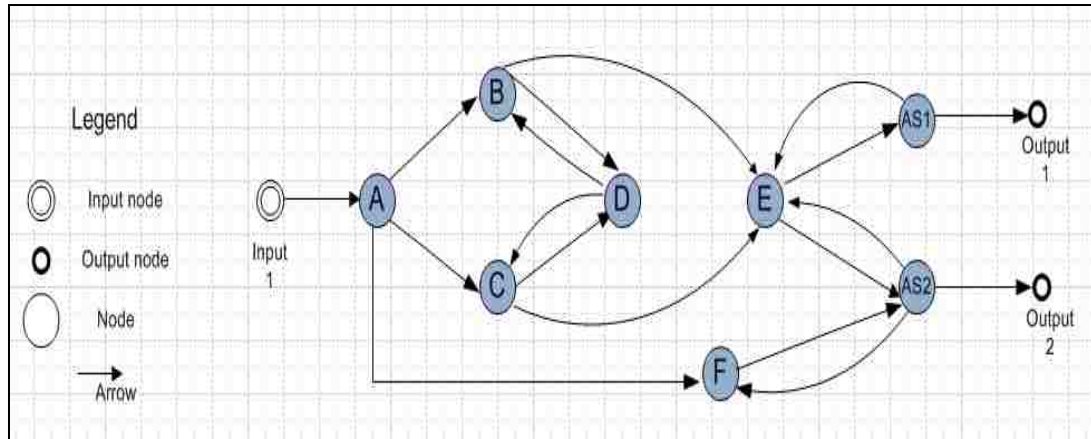
Figure 4.19. Diagram representation for AAM layout.

to the heat treatment area or to the matching area. Node D represents the decision to return material to the hard process. Node E denotes the decision to send material to one of the two assembly lines. Node F represents the decision point to send material to the assembly line or to re-work components.

4.6.3 Adjacency Matrix Creation

The adjacency matrix is created according to the relationship between nodes and arrows in Figure 4.19.

$$
AM = \begin{array}{c} \\ \text{In} \\ \text{A} \\ \text{B} \\ \text{C} \\ \text{D} \\ \text{E} \\ \text{F} \\ \text{AS1} \\ \text{AS2} \\ \text{O1} \\ \text{O2} \end{array}
\begin{array}{c} \text{In A B C D E F AS1 AS2 O1 O2} \\
\begin{pmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\end{array}
$$

Table 4.11 shows the results of the parameters related to the complexity indices by appying the algorithm described in Appendix A to the adjacency matrix.

AAM Assembly Layout	
Number of nodes = 8	Number of nodes on shortest path = 3
Existing connections = 15	Number of nodes on longest path = 6
Maximum theoretical connections = 56	Number of ocurrences of redundancies between nodes = 0
Minimum number of theoretical paths = 2	Maximum number of redundancies = 10
Number of existing paths = 5	Number of redundant parallel arrows = 0
Actual number of cycles = 5	Total number of arrows = 10
Maximum number of theoretical cycles = 247	

Table 4.11. Factors related to indices for the AAM layout.

4.6.4 Complexity Indices

Table 4.12 presents the calculated complexity indices.

	Density Index	Path Index	Cyclic effect Index	Decision sequence index	Distribution Redundancy Index	Magnitude Redundancy Index
AAM layout	$\dfrac{15}{56}$	$1 - \dfrac{2}{5}$	$\dfrac{5}{247}$	$1 - \dfrac{3}{6}$	$\dfrac{0}{10}$	$\dfrac{0}{10}$
Results	0.27	0.60	0.02	0.50	0	0

Table 4.12. Complexity Indices of the AAM layout.

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The AAM layouts has a low density index, which indicates few connections between all nodes. The path index is high indicating that there are several alternative paths in the system layout; nevertheless, it shows a low cycle index. The decision sequence index is high, which means a difference between the number of nodes on the shortest and the longest paths. The distribution and magnitude values of the redundancy indices are zero.

4.6.5 System Layout Complexity Assessment

4.6.5.1 Average Complexity Index

The first method to combine the complexity is to obtain the average value of the indices, by equation (3.9).

$$Average\ Index\ value = \frac{0.27 + 0.60 + 0.02 + 0.50 + 0 + 0}{6} = 0.22$$

4.6.5.2 Complexity Index Using the Radar chart

Using the radar chart helps designers to visualize the indices of such layout systems as the one depicted in Figure 4.20 and calculate the shaded area.
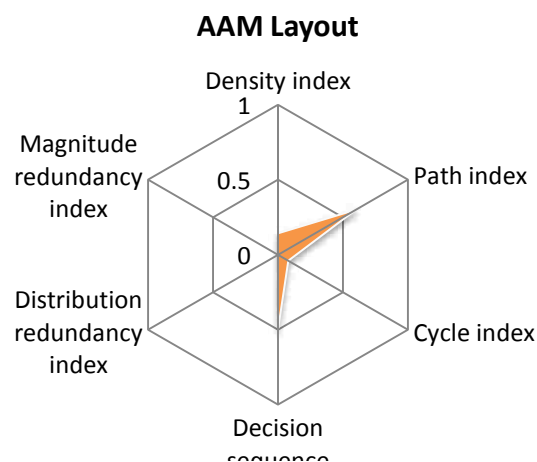
Figure 4.20. Radar chart for complexity indices of the AAM layout

The complexity index using the radar chart is calculated by applying equation (3.10):

$$a = \frac{1}{2}\left[(C_t * C_1) + \sum_{i=1}^{i=t-1}(C_i * C_{i+1})\right]\sin\left(\frac{360}{6}\right) = 0.08$$

The differences of the obtained values by the three different techniques will be discussed in Chapter 5.

4.7 Independence of the Complexity Indices

A correlation of the complexity indices will be find it to determine if there is a dependence between the indices. The correlation coefficient from statistics refers to relationships between random variables or two sets of data, involving dependence. The most common correlation coefficient is the Pearson correlation coefficient, which is sensitive only to a linear relationship between variables (which may exist even if one is a nonlinear function of the other).

The Pearson's correlation is obtained by dividing the covariance of the variables by the product of their standard deviations. The population correlation coefficient $\rho x,y$ between two random variables X and Y with expected values μx and μy and standard deviations σx and σy is defined as:

$$\rho x, y = corr\ (X,Y) = \frac{cov\ (X,Y)}{\sigma x\ \sigma y} = \frac{E\ [(X - \mu x)(Y - \mu y)]}{\sigma x\ \sigma y} \qquad (4.1)$$

The correlation will always be between -1.0 and +1.0. If the result is +1.0 this means a perfect positive correlation, whereas -1 means a perfect decreasing (negative) linear relationship (anticorrelation).

This correlation coefficient is applied to the complexity indices using the values obtained in this Chapter.

Table 4.13 presents the complexity indices obtained from the analysis of the manufacturing system layouts.

Layout	Density	Path	Cycle	Decision	Distribution	Magnitude
ABS	0.3	0	0.08	0	0.5	0.83
ABS modified	0.4	0.33	0.27	0	0.4	0.38
Hybrid	0.3	0	0.08	0	0	0
Modular	0.33	0	0.09	0	0.2	0.17
Engine	0.4	0	0.15	0	0	0
AAM	0.27	0.6	0.02	0.5	0	0

Table 4.13. Complexity indices for six layouts.

The correlation coefficients of the complexity indices for the different manufacturing system layouts were calculated using excel software. Table 4.14 shows the results of the correlation coefficients.

	Density	Path	Cycle	Decision	Distribution	Magnitude
Density	1					
Path	-0.22823	1				
Cycle	0.887503	-0.05312	1			
Decision	-0.56397	0.855413	-0.53848	1		
Distribution	0.152248	-0.13557	0.410142	-0.40301	1	
Magnitude	-0.03194	-0.2104	0.179463	-0.34135	0.946113	1

Table 4.14. Correlation coefficients

As the results in Table 4.14 demonstrate, 0.94 is the strongest correlation between two indices, the distribution redundancy index and the magnitude redundancy index. Two other strong correlations are shown. Density and cycle index with a correlation coefficient of 0.88 and path and decision sequence indices with a correlation coefficient of 0.85. Weak correlations are identified between distribution and cycle index (0.41) and distribution and decision sequence index (0.40).

To conclude, the *distribution* and *magnitude redundancy indices* show a strong coefficient of correlation, which suggest that they are not independent of each other. This dependency between indices does not allow using the vector summation method, where the independence of elements is required. Therefore, only average and radar chart technique were used in calculating the systems layout complexity.

CHAPTER V

STRUCTURAL COMPLEXITY LAYOUT ASSESSMENT

This chapter summarizes the results of the complexity indices obtained from the application of the manufacturing systems layouts in Chapter 4. This chapter also provides a solution for the integration of complexity indices to assess the structural complexity of manufacturing systems layout. Discussion and conclusions are presented at the end of the chapter.

5.1 Summary of the Complexity Indices

The complexity indices obtained from the different system layouts are summarized in Table 5.1.

	Name	Density Index	Path Index	Cycle Index	Decision Sequence Index	Distribution Redundancy Index	Magnitude Redundancy Index
1	ABS Layout	0.30	0	0.08	0	0.50	0.83
2	ABS Modified layout	0.40	0.33	0.27	0	0.40	0.38
3	Modular layout	0.30	0.00	0.08	0	0	0
4	Hybrid layout	0.33	0	0.09	0	0.20	0.17
5	Assembly engine layout	0.40	0	0.15	0	0	0
6	AAM Layout	0.27	0.60	0.02	0.50	0	0

Table 5.1. Summary of the complexity indices of the facility layouts.

The interpretation of each individual complexity in the manufacturing system layout was presented in chapter 4.

Table 5.2 presents the complexity indices obtained from the different methods to integrate the complexity indices and ranks from 1 to 6, where "1" indicates which manufacturing system layout is the most complex. The least complex system layout is ranked with "6".

No.	Name	Average Complexity Index	Rank	Radar chart Complexity Index	Rank
1	ABS Layout	0.28	2	0.29	1
2	ABS Modified layout	0.30	1	0.23	2
3	Modular layout	0.06	6	0	5
4	Hybrid layout	0.13	4	0.04	4
5	Assembly layout	0.09	5	0	6
6	AAM Layout	0.22	3	0.08	3

Table 5.2. Summary of methods and ranks.

From Table 5.2, is observed a difference of the ranks obtained from the complexity indices. The difference of the complexity indices is the result of the difference of the index aggregation techniques. The average complexity index value is a function of the complexity indices and is highly sensitive to changes. Conversely, the radar chart technique calculates the area, which is affected by the positions of the complexity indices in the radar chart.

To solve the problem of the sensitivity of the overall index value to the sequence/position of complexity indexes in the radar chart, we will calculate the number of vectors position permutations. In the radar chart, we have six positions. It will be (n-1) elements to choose from. Then, $(n - 1)! = 5! = 120$. This number represents the different sequences of the position of the indices in the radar chart. The different sequence of complexity indices in the radar chart will be tested to test the variability of the results.

The values of the complexity indices were plotted in a radar chart in 120 different sequences. Following, the shaded area was calculated for those sequences. The area values were ranked from 1 to 6, where "1" indicates which manufacturing system layout is the most complex. The least complex system layout is ranked with "6".

Now, analyzing the obtained ranks from the area values, we found that 10 different sequences of positioning the complexity indices were repeated. Table 5.3 shows the ranks obtained and the number of repetitions of sequences of complexity indices in the radar chart.

From Table 5.3, can be observed that the system layout ranked most as first is the modified ABS layout. The system layout ranked more times in second place is the ABS layout. However, from this table, it can be concluded that there is no consistent sequence of complexity indices in the radar chart that will produce the same ranks. Therefore, another solution is required.

5.2 Sensitivity of the Radar Chart

To illustrate the sensitivity of the radar chart to the positions and sequence of the indices Figure 5.1 shows an example of three indices in a radar chart.

The number of possible combinations is (3!) 6.

The values of the indices are: $X_1=0.30$, $X_2=0.68$, $X_1=0.90$

	Modular	Hybrid	ABS	ABS Modified	Assembly	AAM	Number of Repetitions
1	5	4	2	1	6	3	42
2	6	4	2	1	5	3	16
3	5	4	1	2	6	3	14
4	5	4	3	1	6	2	12
5	6	4	1	2	5	3	8
6	6	5	3	1	4	2	8
7	6	4	3	1	5	2	8
8	6	3	2	1	5	4	4
9	6	3	2	1	4	5	4
10	5	3	2	1	6	4	4
						Sum	120

Table 5.3. Ten ranks repeated from different 120 sequence of indices.

The areas of the formed triangles in the different radar charts are calculated and shown in Figure 5.1. It is shown that different area values are obtained by rotating the position of the indices in the radar chart.
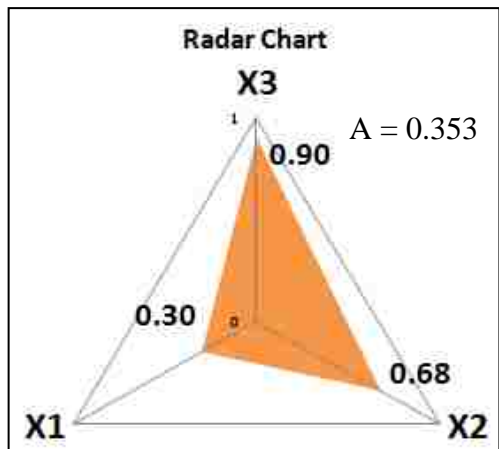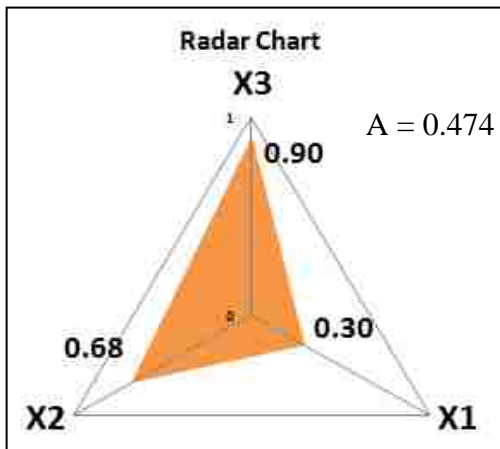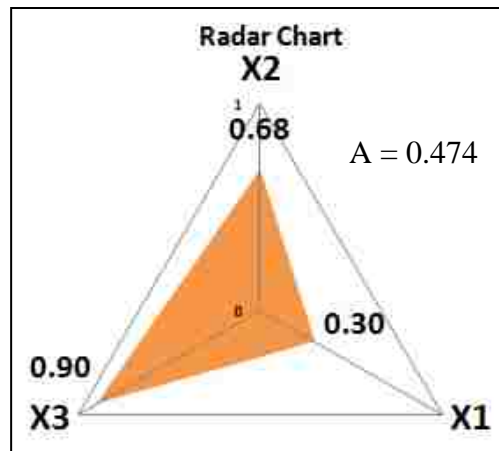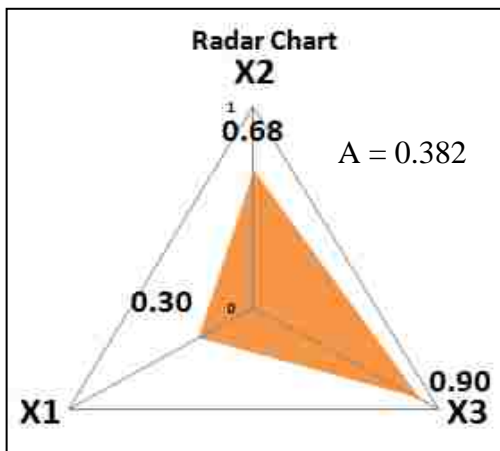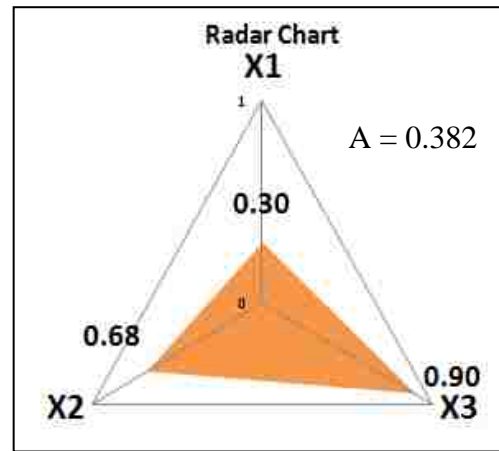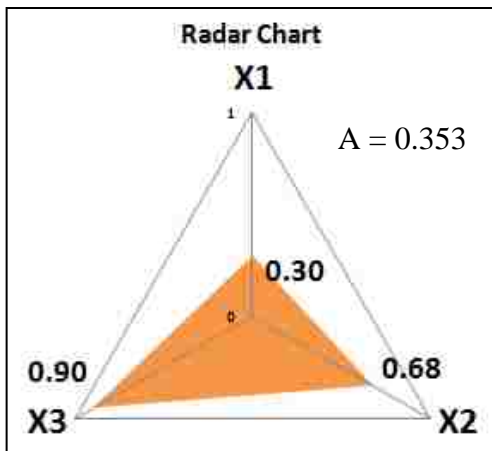
Figure 5.1. Combination of positions of three indices in a radar chart.

5.3 Layout Complexity Index (LCI)

Due to the sensitivity of the radar chart explained in the previous section is required to develop a new measure to integrate the indices. The proposed measure, Layout Complexity Index (LCI) is not sensitive to changes in the sequences in which individual indices are plotted in a radar chart. To explain the LCI, supose that we have a triangle in Figure 5.2.
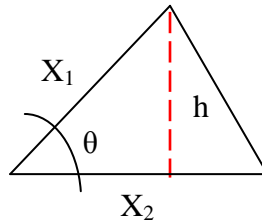
Figure 5.2. Triangle

The area of the triangle is calculated given by equation (5.1),

$$A = \frac{b * h}{2} \tag{5.1}$$

Where b is the base and h is the height.

$$b = X_2$$

$$h = X_1 \, Sin \, \theta$$

$$A = \frac{Sin \, \theta}{2} \, X_1 X_2 \tag{5.2}$$

The general formula to expresses the area of a triangle is:

$$A = \frac{Sin \, \theta}{2} \, X_i X_j \tag{5.3}$$

Suppose that in the first position of the triangle X_i is fixed and the other indices are rotating $X_{i+1} \ldots X_n$. Illustrated in Figure 5.3 we have (n-1) triangles, where n is the number of indices.
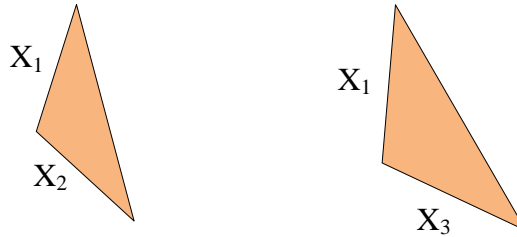
Figure 5.3. Representation triangles with X_1 in a fixed position.

Now, for the same triangle, the first position is fixed for X_2 is fixed and the other indices are rotating, as illustrated in Figure 5.4.
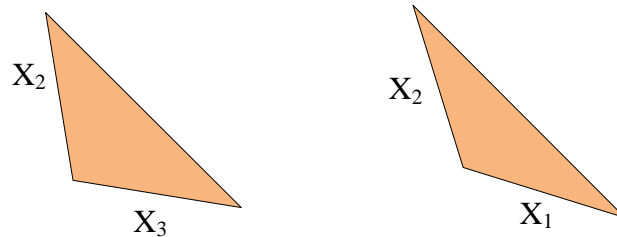
Figure 5.4. Representation of triangles with X_2 in a fixed position.

Figure 5.5 illustrate two triangles formed when the X_3 index is fixed in the first position and the other indices rotating.
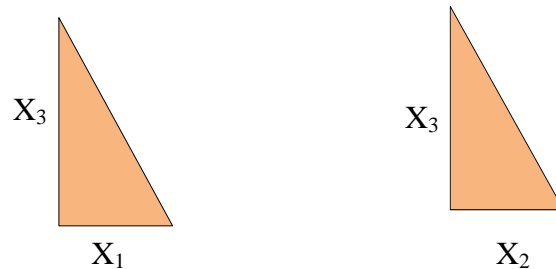
Figure 5.5. Representation of triangles with X_3 in a fixed position.

The area of the all triangles created by fixing one index and rotating the other positions is the average of the area of all these triangles as expressed in equation (5.4),

$$A = \frac{\sin\theta}{2}\frac{X_1X_2}{2} + \frac{\sin\theta}{2}\frac{X_1X_3}{2} + \frac{\sin\theta}{2}\frac{X_2X_3}{2} + \frac{\sin\theta}{2}\frac{X_2X_1}{2} + \frac{\sin\theta}{2}\frac{X_3X_1}{2} + \frac{\sin\theta}{2}\frac{X_3X_1}{2}$$

$$A = \frac{\sin\theta}{4}[X_1(X_2 + X_3) + X_2(X_1 + X_3) + X_3(X_1 + X_2)] \tag{5.4}$$

The area of all triangles in the radar chart is also expressed as equation (5.5),

$$A_{avg} = \frac{\sin\theta}{2(n-1)}\sum_{i=1}^{n}X_i * \left(\sum_{\substack{j=1 \\ j\neq i}}^{n}X_j\right) \tag{5.5}$$

where X is the value of the individual complexity indices, $j \neq i$, and n is the number of indices in the radar chart.

Equation (5.5) can be also expressed in equation (5.6) using the same counter, as follows:

$$A = \frac{\sin\theta}{2(n-1)}\sum_{i=1}^{n}X_i * \left(\sum_{j=1}^{n}X_j - X_i\right) \tag{5.6}$$

$$A = \frac{\sin\theta}{2(n-1)}\left(\sum_{i=1}^{n}X_i * \sum_{j=1}^{n}X_j\right) - \sum_{i=1}^{n}X_i * X_i \tag{5.7}$$

Now, the shaded area formula has been modified to obtain the Layout Complexity Index (LCI) directly using the values of the individual complexity indices, without plotting a radar chart. The final equation is (5.8),

$$LCI = \frac{\sin \theta}{2(n-1)} \left(\sum_{i=1}^{n} X_i \right)^2 - \sum_{i=1}^{n} X_i^2$$

(5.8)

where n is the number of complexity indices and X is the value of each index.

The value of LCI calculated by Equation 5.8 is independent of the sequence of the individual indices.

5.3 Layout Complexity Index for System Layouts

The complexity indices obtained from the manufacturing system layouts in Chapter 4 are used to calculate the Layout Complexity Index (LCI), given by equation (5.8) as follows:

Modular layout

$$LCI = (0.30 + 0.08)^2 - (0.30^2 + 0.08^2) = 0.05$$

Hybrid layout

$$LCI = (0.33 + 0.09 + 0.20 + 0.17)^2 - (0.33^2 + 0.09^2 + 0.20^2 + 0.17^2) = 0.43$$

ABS layout

$$LCI = (0.30 + 0.08 + 0.50 + 0.83)^2 - (0.30^2 + 0.08^2 + 0.50^2 + 0.83^2) = 1.87$$

Modified ABS layout

$LCI = (0.40 + 0.33 + 0.27 + 0.40 + 0.38)^2 - (0.40^2 + 0.33^2 + 0.27^2 + 0.40^2 + 0.38^2) = 2.53$

Engine assembly layout

$LCI = (0.40 + 0.15)^2 - (0.40^2 + 0.15^2) = 0.12$

AAM layout

$LCI = (0.27 + 0.60 + 0.02 + 0.5)^2 - (0.27^2 + 0.60^2 + 0.02^2 + 0.5^2) = 1.24$

Table 5.4 compares the ranks of three integration techniques applied to the manufacturing system layouts, where "1" indicates the most complex manufacturing system layout and "6" is the least complex system layout.

As observed from Table 5.4, the ranks from the layout complexity index correspond to the same ranks obtained from the average complexity index. This shows the inconsistency of the obtained values for the complexity index using the radar chart formulation due to the sensitivity of this method positioning the various indices.

The assessment of the structural complexity layout of the two ABS plant layouts according to the proposed layout complexity index indicates that the modified ABS layout is more complex than the initial ABS.

The layout complexity index formulation has the main advantage of being insensitive to changes of sequences of the complexity indices in the radar chart.

	Name	Average Complexity Index	Rank	Area Complexity Index	Rank	Layout Complexity Index	Rank
1	ABS Layout	0.28	2	0.29	1	1.87	2
2	ABS Modified layout	0.30	1	0.23	2	2.53	1
3	Modular layout	0.06	6	0	6	0.05	6
4	Hybrid layout	0.13	4	0.04	4	0.43	4
5	Assembly layout	0.09	5	0.00	5	0.12	5
6	AAM Layout	0.23	3	0.08	3	1.24	3

Table 5.4. Comparison of complexity indices.

5.4 Analysis and Discussion

5.4.1 Discussion From Previous Assessment

The ABS system layouts were presented and compared by Kim (1999). In his assessment, the ABS Modified metrics indicated a significant improvement of the complexity values. Kim's metrics for assessing the complexity of manufacturing systems were based on the relationships between system components, number of elements, and the complexity of each element (i.e. reliability, quality, and cycle time), which reflects more operational rather than structural complexity. The case study concluded that the modified layout was less complex. According to the structural layout complexity index presented in this thesis,

the modified ABS layout is more complex. A direct comparison is not possible because Kim's metrics rely on reliability, quality outputs, and cycle time. In fact, only one of the Kim's metrics considers the structural system layout complexity, regarding the number of components, which has increased in the modified ABS layout.

In summary, Kim's metrics combined both structural and operational complexity measures. However, the structural complexity metric did not impact his final recommendation.

The main difference between the metrics developed by Kim and the complexity indices proposed in this thesis is the information content approach of capturing structural characteristics (connections, paths, cycles, decision points, and redundancies) of the manufacturing system layout.

5.4.2 Discussion From the Case Study Results

The results of combining the complexity indices show a difference in the ranks obtained from the average complexity index and radar chart complexity index. It was found that the shaded area from the radar chart is sensitive to the changes in the positions of the complexity indices. To test the sensitivity of changes of positions, different sequences were tested. It was shown that there is no consistent sequence of indices to obtain a consistent result. However, the layout complexity index (LCI) formulation was found to be insensitive to changes of positions of the complexity indices.

5.5 Hypothesis and Research Questions

This research was guided by the hypothesis:

The complexity of any system layout is related to its information content and is a function of the attributes that characterize a system configuration layout.

It has been shown that the increase of information content of characteristics such as density, paths, cycles, decision points, redundancy distribution and magnitude increases the structural complexity of a manufacturing system layout.

The core finding of these case studies suggests that the information content of the density, paths, cycles, decision points, redundancy distribution and magnitude impacts the structural complexity. Decision points and connections between them are the core elements to look in a manufacturing system layout, which are represented by nodes and arrows, respectively. Base on these elements, six complexity indices are defined as a function of different parameters.

There is no determined specific configuration that is more complex than others without analyzing its individual characteristics: density, paths, cycles, decision points, redudancy distribution and magnitude that assess the Layout Complexity index.

The number of connections between decision points will affect the density index; the number of decision points and location is a critical element that impacts the path index. Configurations where many cycles exist will increase the cycle index. The number of nodes on the shortest and longest path will impact the decision points index. The number of occurrences of redundancies will impact the distribution and magnitude index.

The questions addressed by the research are:

How can a system layout be represented graphically ?

What are the quantifiable elements that can be extracted from a system layout's representation?

What are the structural characteristics between layout elements that increase information content?

The questions were answered by defining how to convert a physical system layout into a graphic representation. The elements defined represent flow decision points and connections represented by nodes and arcs, respectively. These elements can be quantified into complexity indices related to other relevant characteristics that affect the level of difficulty of the decisions made during the manufacturing process and, hence, its complexity. Finally, the assessment of the structural complexity of the manufacturing system layout is achieved by combining the complexity indices in a consistent manner.

5.6 Conclusions

A new approach to assess the structural complexity of a manufacturing system layout was developed. Six individual complexity indices, which include characteristics of the layout, such as, connections, paths, cycles, decision points, and redundancies, were defined.

These indices provide an insight into the information content inherent in the system layout. They are useful at the early system design stage when developing the work stations layout configuration and selecting connections, paths, cycles and redundancies in the process. They can also be used to compare different system configurations layout characteristics.

The individual complexity indices are combined into an overall layout structural complexity index (LCI) as a measure to compare system layout alternatives and make decisions to select the least complex layout. The layout complexity index was formulated based on the calculation of the shaded area in a radar chart. The developed index is not sensitive to the sequence of the complexity index values, which is its main advantage.

The methodology aims to assess the structural complexity in manufacturing system layouts, which needed further attention. The complexity indices help to identify structural characteristics that significantly stand out from the rest of the system.

The results of system layout complexity assessments were compared with earlier assessment of complexity in manufacturing. The differences were discussed.

5.7 Contributions to Knowledge

The main contributions of this thesis are as follows:

1. The analysis to convert the physical system layout into a graphic and mathematical representation was defined.

2. Relevant layout's characteristics that affect the structural complexity were defined.

3. Complexity indices were defined to capture the information content which is a function of the system layout characteristics.

4. A layout complexity index (LCI) was formulated and compared with existing techniques.

5. A new methodology was developed to systematically assess the structural complexity of a manufacturing system layout.

The knowledge generated throughout this research is intended to extend the scientific understanding of the characteristics that affect the structural complexity of manufacturing systems layout.

APPENDICES

Appendix A

The adjacency matrix AM represents all the paths of length 1. That is, each entry indicates whether there is a 1-length path between corresponding nodes or not. It also tells us how many 1-length paths are there between two nodes.

Based on the property of adjacency matrix (Zeqian 2007), if we multiply the adjacency matrix by itself, the resulting matrix will show the number of paths of length 2 between each node. If we multiply the resulting matrix by the adjacency matrix one more time, the resulting matrix will show the number of paths of length 3 between each node; therefore, the matrix $A_l = A^l$ will give us the number of paths of length l between the nodes described by the adjacency matrix A.

The elements of our interest in the matrix are the elements that relate the inputs and the outputs of the manufacturing system. The element a_{ij} of the adjacency matrix A gives the number of paths between the node i and the node j. If we create the matrix starting with input nodes ending with output nodes, given a manufacturing system with m inputs and r outputs, the elements a_{eo} where $e = 1,2,\dots,m$ and $o = n, n-1, n-2,\dots,n-r+1$ are the elements that indicates the number of paths between the input and output nodes.

The algorithm allows users to specify the maximum path length k. The algorithm will count length paths up to k.

The minimum number of paths, w, the total number of paths, p, and the length, l, of those paths can be calculated by the following procedure:

Initialize the total number of paths and the minimum number of paths.

$$p = 0 \qquad\qquad\qquad\qquad\qquad\qquad (A.1)$$

$$w = 0 \tag{A.2}$$

Define maximum path length, k.

Calculate the new adjacency matrix with paths of length 1

$$A_l = A^l \text{ where } l = 1 \tag{A.3}$$

Count the number of elements of interest, a_{eo}, where $a_{e0} > 0$, to determine the number of paths of length l.

Increase the paths counter

$$p = p + a_{eo} \tag{A.4}$$

Increase the minimum number of paths, if there is a path between the input e and the output o.

$$w = w + 1 \tag{A.5}$$

Increase the size of the path ($l = l + 1$) .

Calculate the new adjacency matrix.

$$A_l = A^l$$

Repeat equations A.3 to A.5 until $l = k$

Algorithm for Calculating Cycles

The number of cycles and the nodes in the cycle can be determined with the adjacency

matrix property as follows:

Initialize the number of cycles

$$c = 0 \qquad\qquad\qquad (A.6)$$

Calculate the new adjacency matrix with paths of lengths 2

$A_l = A^l$ where $l = 2$

Calculate matrix B by multiplying each element of the matrix A_l with each element of the

Identity matrix I of size (n x n).

$$B = A_l.* I \qquad\qquad\qquad (A.7)$$

where ".*" denotes element multiplication in the matrix.

The elements $b_{ij} \neq 0$ represent a cycle.

Counting the number of non-zero elements in the matrix B, where $b_{ij} > 0$

If x $= l$ we have found a cycle with x nodes.

 Increase the number of cycles.

$$c = c + 1 \qquad\qquad\qquad (A.8)$$

Repeat equations A.6 to A.8 until $l = k$

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