Harnessing Product Complexity: An Integrative Approach

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ABSTRACT

In today's market, companies are faced with pressure to increase variety in product offerings. While increasing variety can help increase market share and sales growth, the costs of doing so can be significant. Ultimately, variety causes complexity in products and processes to soar, which negatively impacts product development, quality, production scheduling, efficiency and more. Product variety is just one common cause of product complexity, a topic that several researchers have tackled with several sources of product complexity now identified. However, even with such progress, product complexity continues to be a theoretical concept, making it difficult for companies to fully implement advances and fully manage product complexity.

More and more companies are relying on product family design to handle product variety. Broadly, a product family can be defined as a group of products sharing common elements. The advantages for companies using product family strategies can be significant: they enable efficient derivation of product variants, reduce inventory and handling costs, as well as setup and retooling time. The design challenge however, is to select the product platform to generate a variety of products with minimum deviation from individual requirements. Accordingly, the structure of product families makes designing and evaluating them a challenging process. In order to fully embrace the relationships between variety, product complexity, and product families an understanding of product complexity causes and impacts is essential.

This research begins by introducing four main dimensions of product complexity within the context of a generalized definition. Product complexity indicators suitable in product design, development and production are derived. By establishing measurements for the identified indicators and using clustering techniques, a complexity evaluation approach for product family designs is also developed in this research. The evaluation approach is also applied on a component basis, to identify Critical Components that are main sources and contributors of complexity within product families. By standardizing identified Critical Components, product complexity levels and associated costs can be managed. A case application of three product families from a tire manufacturing company is used to verify that this research approach is suitable for evaluating and managing product complexity in product families.

Dedication

To my advisor and my mentor, Professor Janis Terpenny, I wish to express my deepest gratitude for her guidance, patience, inspiration and support. I was truly fortunate to be able to study under such a gifted individual. I am also fortunate to have Professors C. Patrick Koelling, Asli Sahin-Sariisik and Konstantinos Triantis on my committee, and I am very thankful for their encouragement throughout this study and for making it a great learning and growing experience.

To my family, your unconditional love and everlasting support has influenced every part of my life and encouraged me throughout this process. To my son, Youssef Tawfik, you fill our lives with so much love and joy. Finally, and most importantly, I wish to dedicate this work to my husband, Aly Tawfik, who has been my biggest source of motivation and encouragement; thanks for your love, understanding, support and for all you have done to make this venture a success.

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Chapter 1: Introduction

1.1 Background

1.1.1 The Problem with Product Complexity

In order to have a substantial advantage over competitors in today's global market, companies must be able to respond quickly to the rapidly changing wants and needs of today's customers [1]. The proliferation of products entails managing a variety of components, functional requirements, quality standards and production processes all of which are considered main sources of product complexity.

Research has shown many disadvantages associated with product complexity. A complex product typically results in complicated and costly product design and development processes, causing inefficiencies in the product realization phase. Manufacturing of complex products entails less efficiency; higher set-up costs; the need for more raw material, work-in-process and finished goods inventory; less economies of scale; higher quality control requirements; more complex product scheduling; difficulty in balancing assembly lines and will cause various managerial and logistical problems in the supply chain system. In other words, product complexity can cause operational inefficiencies and increases in direct and indirect costs throughout the different stages of the product lifecycle. Accordingly, it is essential to identify the optimum level of product variety, where the benefits of sales growth is greater than the costs of associated complexity, as shown in Figure 1.

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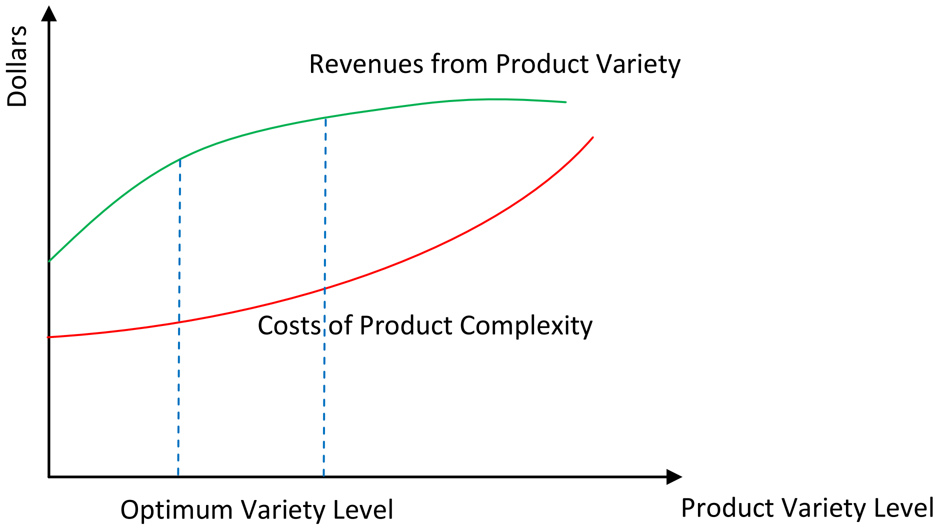


Figure 1: Identifying Optimum Level of Product Variety

Product variety is just one common cause of product complexity, other sources related to the structure, functionality and production of the product can be found in the literature. Many have attempted to classify and categorize product complexity on an application-specific basis, yet it still remains a theoretical concept with no unified and commonly validated approach or measurement; making it difficult for companies to understand and manage. Further, there has been little progress in establishing a quantitative complexity measurement framework; most existing complexity measurements focus on subjective ratings by design and/or production experts. Literature in the area of complexity management has failed to provide approaches to evaluate the validity of existing measurements in controlling product complexity [1].

If understanding complexity in a single product is a daunting process, the difficulty is multiplied when managing product families. The challenge in product family design is to select the product platform that will generate a variety of products with minimum deviation from individual requirements, making product platform and family design a much more complex process than individual product development.

1.1.2 The Situation with Product Family and Product Platform Design

With today's competitive environment, proliferation of niche market and diversified customer needs, many companies have been faced with the challenge of providing as much variety for the market as possible with as little variety between products as possible, making companies more motivated to use product families and platform based product development [2]. A product platform can be defined as the set of all components, manufacturing processes, and / or assembly steps that are common in a set of products, where the set of product variants that share the common product platform is a product family [3].

Research and practice have shown that product platform design can improve product development efficiency, by reducing product development lead time and costs. There are many other cost-savings advantages of implementing platform design in product family development, such as reduction of inventory and handling costs, reduction in setup and retooling time, increased standardization and fewer components to test and qualify within the family [4]. Additionally, product platforms enable the development of different product variants to satisfy the requirements of distinct market segments with reduced effort. Finally, platforms can promote better learning across products and reduce testing and certification of complex products, such as aircraft [5]. The literature has provided several successful cases of implemented product family designs, most popular include Black & Decker and Sony [6]. Volkswagen reportedly saved $1.5 billion per year by using a common platform across its four brands (Volkswagen, Audi, Seat, and Skoda).

Although the many benefits of product platform design are widely known, many companies are still not taking full advantage of this strategy. An important reason is the lack of appropriate methods and useful indices to assess a product family [4]. In comparison to individual product design, product family design is more difficult; as designers need to balance the benefits of commonality across products with the need to differentiate between products to avoid any competition within the product family. Hence, evaluating the design of a product family is a much more complicated process than that of a single product.

In the last decade, research on product family design and platform development strategies has had great attention in both academia and industries. There has been continuous development in research on approaches and methods to address the product family and platform design issues; Simpson [2] provides a good illustration of this development. In 2005, the American Society of Mechanical Engineering International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC/CIE) included a special session on product families and platforms.

Several approaches to evaluate the design of a product family in accordance to different criteria can be found in the literature and are discussed in Chapter 2. However, evaluating the design of a product family and generated product variants in terms of product complexity levels has not been sufficiently addressed.

1.2 Motivation

There are several motivators for this research. Managing product complexity efficiently and effectively can be a daunting organizational task; the implications of having complex or simple product lines are still not fully understood [7]. Most important, the existing gap and lack of a unified approach in research has made it even more difficult for companies to attempt to manage product complexity levels. Accordingly, what is needed is a comprehensive quantitative methodology and decision support tool for designers to evaluate product complexity levels within a product family, identify complexity sources and ultimately manage product complexity.

Research in product complexity has generally failed to give the study of non-assembled products sufficient attention, given the role that non-assembled products play in so many industrial segments and the unique nature of these products and related production processes. Examples of non-assembled products include petroleum products and glass, to name a few. While there exists descriptions of platform methods applied to assembled products, it is difficult to find similar work for non-assembled ones.

Most evaluation tools consider the need to manage product variety through increasing internal (component) commonality, as the main criteria to assess the efficiency and effectiveness of a product family design. In addition to component commonality, this research also considers other important sources of product complexity essential to evaluating product family designs and identifying component platforms that can help improve operational efficiency, reduce costs and manage product complexity throughout the different stages of the product lifecycle.

1.3 Research Problems and Questions

As described in sections 1.1 and 1.2, the impact and costs of product complexity can be reflected throughout the product's life cycle and managed through product family redesign. Additionally, while a platform design is used to effectively and efficiently manage product variety through increasing internal commonality, which is the common criterion used to evaluate a product family, validated tools to evaluate a product family's design by considering other criteria and sources of complexity do not exist. Accordingly, an important problem to address is:

Problem 1: *How can design and development engineers be supported in evaluating product family design and managing the associated impact of product complexity?*

This problem can be addressed through a comprehensive overview of product complexity and its impact on product design, development and production. An understanding of the sources, causes and impacts of product complexity can help identify indicators to be used in a complexity measurement framework and evaluation approach. Additionally, by identifying and standardizing components that are main contributors to the product family's complexity levels, which will be considered as Critical Components in this research, product complexity and related costs can be managed. Accordingly, to solve the above problem, the following questions need to be answered:

Question 1.1: *What sources and indicators of product complexity should be considered when evaluating a product family design?*

Question 1.2: *How can the identified indicators (from Q1.1) be quantitatively represented in a complexity measurement framework?*

Question 1.3: *How can a product complexity measurement framework be used to evaluate product family design?*

Question 1.4: *How can measurement and evaluation results be used to manage the impact of product complexity?*

As previously mentioned, this research considers the impact that non-assembled products, have on product complexity and on evaluating product families. This raises a new problem and set of questions that need to be addressed:

Problem 2: *How does the nature of non-assembled products impact product complexity?*

Question 2.1: *What are the product complexity sources for non-assembled products?*

Question 2.2: *How can product complexity for non-assembled products be incorporated in the complexity measurement framework?*

1.4 Research Objectives

This research explores product complexity in product design, development, manufacturing and supply chain. Associated objectives include the following:

- develop a product complexity measurement framework and evaluation methodology for product families,
- provide a comprehensive product complexity measurement framework,
- identify sources and indicators of product complexity,
- understand the product complexity associated with non-assembled products, and
- develop a new approach to identify platform component to support product complexity management attempts.

1.5 Overview of Approach and Methodology

In order to identify the sources and indicators, a product complexity definition is set forth by identifying the system being analyzed and the impact complexity has on that system. A product complexity measurement framework is established to provide a quantitative representation of identified indicators.

Using clustering techniques, the product complexity measurement framework is applied across product families to evaluate product complexity levels. The evaluation methodology is also applied within product families to identify Critical Components as main contributors to complexity levels. Identifying Critical Components is the first step to try to manage product complexity through standardization.

The approach in this research is only appropriate when product and product family design is known. An important assumption in this research, is that in a product family, components of products with insignificant difference across specific design attributes (such as geometry, memory space…etc.) can be grouped and standardized into a platform module. It is also assumed that standardizing identified Critical Components to establish platform modules can help manage and reduce the costs of complexity. Furthermore, it is assumed that redesigned products will have the same production process and resources and that collected design information is accurate and complete.

1.6 Research Contribution

This research contributes to four important areas of product family design and product complexity. The first main contribution of this research is the development of a new methodology in evaluating product family design, which is achieved through:

- Establishing new product complexity definition
- Identifying product complexity indicators
- Developing product complexity measurement framework

Second, the research puts forward a new approach to identifying possible platform components in the product family design, and hence, an approach to manage the impact of product complexity. Third, unlike other literature on product complexity, the research also considers the impact of non-assembled products on complexity.

Fourth, a Complexity Management Tool is developed, with required steps to measure and evaluate complexity levels. Critical Components are also identified and standardization possibilities are highlighted through the tool.

1.7 Overview of the Dissertation

Figure 2 provides an overview of the chapters in this dissertation. Chapter 1 provided the foundation and introduced the research. Chapter 2 provides the literature review of related research, which can be divided into three main research areas. The first area is Product Complexity, where existing complexity approaches and measurements found in the area of product design, production and supply chain management are discussed. Approaches to product family design and evaluation tools are also discussed in this chapter, followed by a review of research in the area of Grey Theory and clustering techniques.

The research approach is presented in Chapter 3. The approach is applied to evaluate three product families in a tire manufacturing company. Accordingly, an introduction to the case study and tire products is presented in Chapter 4. The application results are presented in Chapter 5.

Chapter 6 is the final chapter in the dissertation and contains a summary of the dissertation, emphasizing the answers to the research questions and resulting research contributions. This chapter also discusses limitations in this research and possible future work.

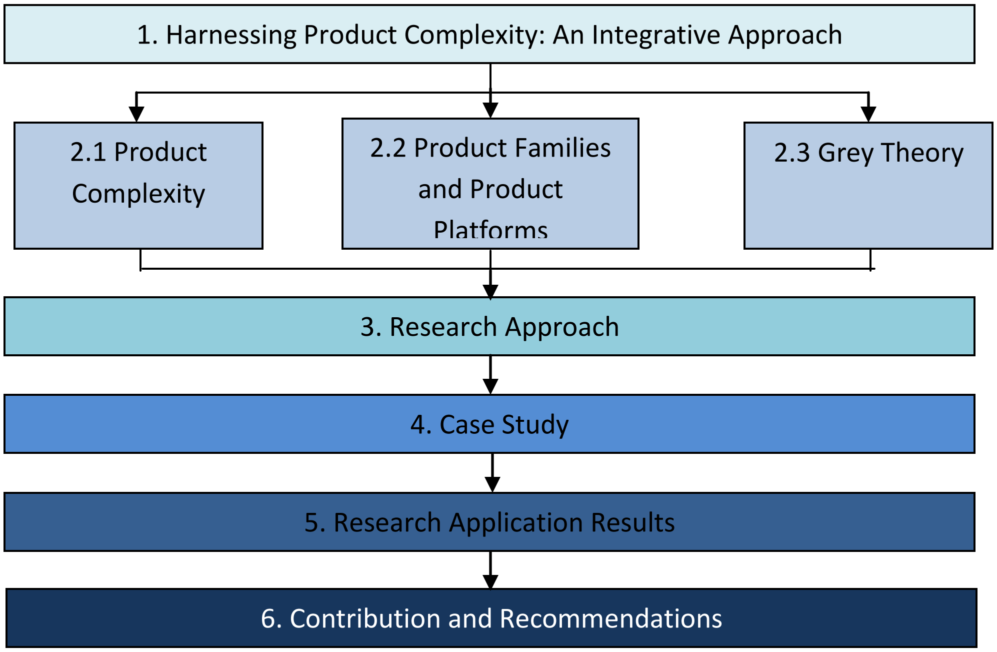


Figure 2: A Pictorial Overview of Dissertation

Chapter 2: Literature Review

2.1 Product Complexity

Complexity is a problem of semantics and interpretations are only relevant within the same context [8]. Complexity has been mentioned in many different research domains and has captured the interest of mathematicians, scientists and engineers. It has been stated, that the many given definitions for complexity found in research, is a reflection of the high interest in this topic. The simplest definition of complexity identifies it as a measure of the difficulty in understanding or working with something, which increases with the increase in the number of related attributes or situations that exist [9].

"Choice of measures of product complexity depends of the objectives of the analysis, the product and production system, and in some case, the accessibility of data." [10]. This citation is a reflection of how different and customized approaches, definitions and measurements for product complexity can be found in the literature. The following provides a discussion of the different approaches to product complexity found in the literature, followed by a brief on existing product complexity measurements, and the costs associated with product complexity.

2.1.1 Product Complexity Approaches

Variety of product offerings or of product components – is the most commonly used definition for product complexity. According to Blackenfelt [11] product complexity in a narrow sense, is more or less synonymous with product variety defined by the quantity of tailored components and the hierarchical manner in which they are integrated. While, MacDuffie et al. [1] referred to Variety as what companies offer to consumers as part of a product market strategy and Complexity as one dimension of the manufacturing tasks that result from this product market strategy. Variety is considered "good" when it provides market place advantages outweighing the negative impact it has on quality, productivity, costs and efficiency.

Some researches identify limitations of focusing solely on variety and go beyond this definition to identify other dimensions of product complexity, such as product geometry, component interconnectivity and uncertainty [1, 12]. In this section, approaches to product complexity in the areas of product design and development, manufacturing, assembly, and supply chain management, relevant to this research are described.

Product Complexity in Product Design and Development

Product complexity is a significant factor in product design and development process, as it is intensively associated with product cost, quality, production cycle time, and customer satisfaction [13]. Literature in this area can broadly be divided into two main approaches; those that consider variety to be the only source of product complexity and those that identify other significant complexity causes. The approach developed by Salminen et al.[9] falls within the fist category. Salminen et al. decomposed complexity into two main types (Figure 3): External Complexity, consisting of all uncertain and uncontrollable elements surrounding the organization; and Internal Complexity, which consists of three main parts, one of which is Product / Service Complexity. In their approach Product / Service Complexity is associated with the need to meet the diverse demand of customers; hence, it is a reflection of the variety in product offerings.

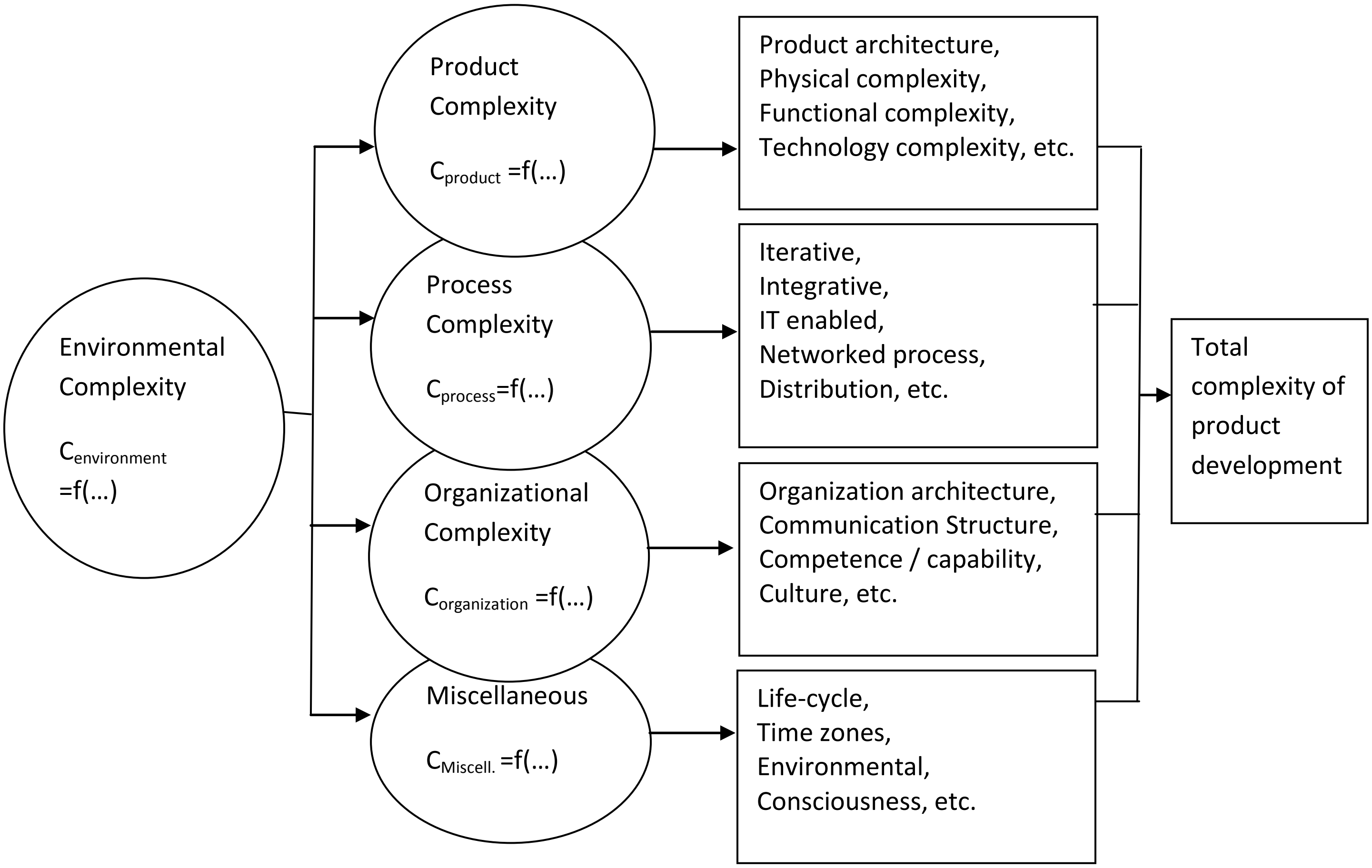


Figure 3: Decomposition of Total Complexity [9]

According to Suzue and Khodate [14] widespread product variety is not always a result of customer requirements, as it can be driven by decisions made during product design and product development; for example a small customer-driven design change may have an impact on parts within the product, where modification was not of importance to the targeted customer. Accordingly, in addition to market demands, internal design decisions can add to the level of product complexity.

Based on the presumption that simple designs are preferred to complex design; Pahl and Beitz [15] provide a Simplicity Rule for product design, which is evaluated based on the number of unique functions, processes and components; hence, reducing complexity is based on standardization. However, similar to many other researches in this area, they failed to provide a quantitative measurement for complexity; instead qualitative interpretations by designers are used.

Although many researches in product complexity have linked the increasing number of parts (component variety) to increasing complexity; some have argued that reducing part counts will also increase product complexity. In their approach, Fagade et al. [16] argued that the functions of eliminating parts, and the usage of product platforms, can often lead to consolidated fewer and more geometrically complex parts; by eliminating parts, components may become more difficult and expensive to manufacture, and complex components can lengthen the product development cycle, become less reliable, replacement costs substantially increases and product flexibility is reduced.

There are other researches in this area that have gone beyond the consideration of product and component variety, to consider other sources. In an attempt to understand the role of complexity analysis in product design, Toro et al. [8] identified two levels of product complexity, as shown in Figure 4. Component Complexity is an aspect of the design that relates directly to each component, it includes: Manufacturing Complexity, which is directly related to the geometry of a component; accordingly, designers need to ensure that reducing material and part count are not outweighed by the cost of more complex in shape and type materials; and Process Complexity where the emphases is on quantifying the difficulty associated with alignment, insertion and handling operations. The levels of both Manufacturing and Process Complexities are to be chosen by the designer, no specific calculations were established. Assembly Complexity on the other hand, encompasses aspects of a design that impact the efficiency of the assembly sequence; these are: Structural Complexity, which relates to the configuration of a product in terms of its product structure and Sequence Complexity reflecting the number of operation, required assembling a product.

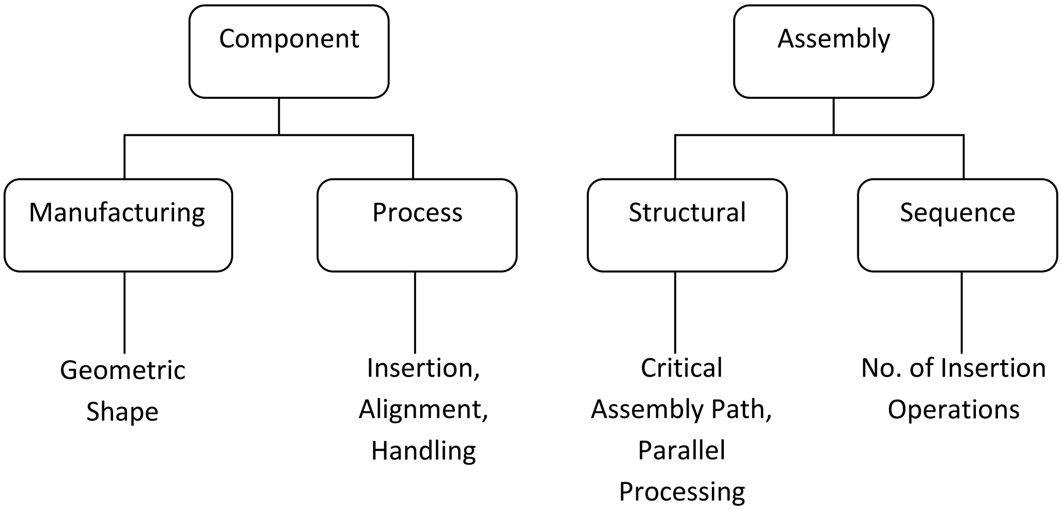


Figure 4: Different complexity factors considered at a particular level [8]

Barclay and Dan [17] developed an assessment tool and methodology (ATM) designed to evaluate past product development projects, external evaluation and pre-development assessment of a product. The developed ATM uses product complexity to evaluate new product development performance, where five main factors were identified to have significant impact: Structural Complexity, Functional Complexity, Product Newness, Project Complexity and Commercial Constraints. Structural Complexity is reflected in the physical make-up of the product. It includes five main categories: number of components, number of process stages, degree of connectivity, number of technologies, and, technological difficulty of design, manufacture, assembly and test. Functional Complexity, on the other hand, was described in terms of the number of functions performed and customers' perceptions of use and aesthetics. Product Newness Complexity, was considered more as a perceived level of complexity, and considered in terms of newness to the company and newness to the customers. Finally, Project Complexity related to the complexity of the project itself, and measured in terms of total timescale and personnel required.

Ameri et al.[18], added Behavioral Complexity to both Structural and Functional Complexity. In their approach, Structural Complexity relates to the physical arrangement and connection of the product's components; while Functional Complexity describing the number and connectivity of the product's basic and supporting functions. Behavioral Complexity covered the complexity related to the predictability and understandability of a product's behavior in the field. Similar to many other new product development complexity based assessment tools, ATM developed by Barclay and Dann [17] and the complexity dimensions by Ameri et al.[18] fail to consider the impact of product family on complexity, and offered no quantitative measurements for complexity

To distinguish between good and bad design, Suh [19] provides two main axioms; axiom 1 is the Independence Axiom which requires the independence of functional requirements; and axiom 2 is the Information Axiom, which requires the minimization of information content. Without these axioms, Suh considers design decisions to be "ad hoc". According to Suh [20], there are two types of complexity in axiomatic design: Time-dependent and Time-independent Complexity. Time-dependent Complexity is caused by uncertainty, and events that cannot be predicted. While Time-independent Complexity includes: Real Complexity, the uncertainty of meeting functional requirements of a design; and Imaginary Complexity, which can be reduced when the design matrix is known. Accordingly, Suh identified complexity as a measure of uncertainty in achieving the specified functional requirements, which is impacted by information availability and content.

Zhang and Luo [13] identified four dimensions for product system complexity, Figure 5: technology, size, organization and environment. They identified technology as the original factor that determines product complexity, with two sub-factors: the number of technologies involved and maturity of each technology. Product size is determined by: (1) the number of product components; (2) product volume, where too little or too large volume can increase product complexity compared to the volume that is adequate to contain components or satisfy operations; and (3) density, meaning something relative to its components and volume. Usually, product complexity increases as the density increases. The third dimension, organization reflects human factors that influence product complexity in manufacturing processes, which is determined by the number of people and departments involved in operations relative, the amount of information transferring among the people and departments in the processes, and the style of allocation of resources. With the increase of people, departments and information transformation, complexity of product system increases. The last dimension, environment, refers to the interrelationships and interactions between product system and outside conditions. This dimension considers the number of suppliers, customers, regulations and standards, and market competition.

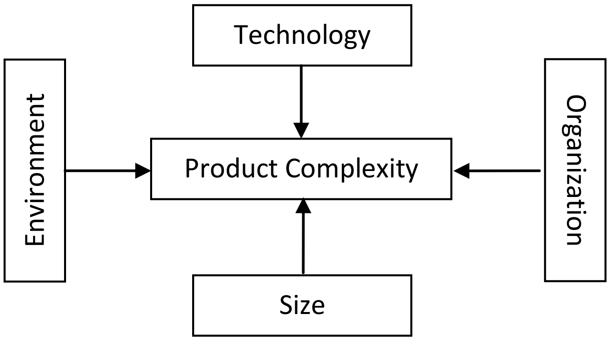


Figure 5: Product System Complexity [13]

As shown above, there have been several different strands of approaches to complexity in product design and development throughout the literature, the above is just a brief of the most common areas of focus. There is a clear overlap, and some have used same classifications for definitions. Failure to provide a validated measurement approach for product complexity is among the top drawbacks of existing research; obviously impacted by the failure to provide a unified definition and product complexity sources.

Product Complexity in Manufacturing and Assembly

Increasing the product variety level has presented difficulties in the operation and management of assembly and manufacturing systems, negatively impacting the performance of assembly systems in terms of both quality and productivity; which has been shown through empirical data and simulations [21]. By using Activity Based Costing (ABC), Banker et al. [22] studied a car component (head and tail lights) manufacturer and observed that product complexity, which was defined as the number of moving parts in a mold, significantly impacted the cost of supervision, quality control, and tool maintenance. Following up on this study, McDuffie et al. [1] explained how product variety can decrease productivity and quality in automotive assembly plants. As the number of platforms and body styles increases within a plant, there will be higher set-up costs; while increasing both parts and options, production workers face a more complicated array of different parts, hence, impacting direct labor productivity and quality. Balancing the assembly line for consistent cycle times at each work station also becomes more difficult due to multiple models and varied option combinations. MacDuffie et al. [1] established an empirical relationship between complexity and manufacturing system performance; by statistical analysis, a significant negative correlation between the complexity measures they developed and manufacturing performance was found.

Unlike in the areas of product design and new product development, research on product complexity in manufacturing systems is limited [23]. In this research area, variety is still considered the most common approach to defining product complexity. Among the limited research that can be found, Cooper et al. [24] developed three main indices to measure product complexity: the Product Index represents the variety in the type of products offering; the Process Index is a reflection of the difficulty of the process itself; and the Product-Process Index captures the product-process interactions in a way that accounts for the unique processes required for differences in product design.

Another approach using variety was developed by MacDuffie et al.[1], as they defined three main types of product mix complexity in manufacturing systems based on different types of variety: Model Mix Complexity caused by the mix of different products and product variants produced in a plant; Part Complexity, measuring parts and components variation; and Option Content, consisting of variations independent of the core design. Accordingly, as the model mix become more diverse, alternative options increase in the manufacturing plant, balancing assembly lines becomes more problematic, and parts planning and production scheduling systems become increasingly complex.

Zhu et al. [23] developed models for evaluating complexity in multistage mixed-model assembly systems by measuring complexity based on the choices the operators need to make at the station level due to variety in customer orders. Complexity was shown to be positive monotonic to the amount of uncertainty; hence, the more options available to the operator, the more errors made and decision time needed. Building on this research, Hu et al. [25] are among the few that attempted to provide a quantitative measure of complexity by integrating both product variety and assembly process information. However, in their approach no consideration is given to the impact of decisions made by upstream stations; as more decisions are made by upstream stations, uncertainty and alternative options are reduced for downstream stations, hence, reducing their level of complexity.

Hu et al. determined complexity in an assembly system as the sum of several types of complexities, including Choice Complexity, Feed Complexity and Transfer Complexity. Operators are required to make correct choices in selecting the right parts to meet customer requirements, in addition to other decisions, such as selecting the right tool and assembly process; accordingly, as product variety increases, operators face more uncertainty about making choices, creating Choice Complexity. During the assembly process, some activities are caused by the distinctive feature of the concerned station; the complexity associated with such assembly activity is defined as Feed Complexity. Similar to Choice Complexity, Feed Complexity is impacted by the level of product variety. Feed Complexity is also impacted by choices performed in previous stations, this particular component of assembly system complexity, is known as Transfer Complexity. Accordingly, similar to the complexity in axiomatic designs identified by Suh [20], Choice Complexity is impacted by the availability of information as well as the level of variety.

Approaches other than variety, although very limited, can also be found in the literature. In an attempt not to constrict the definition of complexity to simply a snapshot of the number of products or process, Frizelle [26] established two types of complexity related to manufacturing; Static and Dynamic Complexity. Static or Structural Complexity relates to how a factory is structured; which products are assigned to which resources. This type of complexity relates directly to both Product and Part Complexity; the more products and parts involved in the production process, the more complex the structure becomes. The second form of complexity is Dynamic Complexity in which uncertainty becomes a feature of complexity. This form of complexity is related to different possible paths for operations to follow, of which production plan is just one option, and may not be the best alternative.

In general, a main drawback of research on product complexity in manufacturing and assembly is the focus on defining complexity in terms of quantity; whether quantity of products, parts and / or processes. Additionally, most research in this area has focused on assembled products, such as the study conducted by MacDuffie et al.[1] on the relationship between complexity and manufacturing systems based on automobile assembly plants. Very little research in this area has considered product complexity in manufacturing of non-assembled products or process industries where the interdependence level among components and the type of process at different production stages can impact the level of complexity. Similar to complexity in product design and development, the focus in this area has been on individual products, the impact of using product families on product complexity in manufacturing and assembly has rarely been addressed. Additionally, few provided quantitative objective measurements.

Product Complexity in the Supply Chain

Product complexity research in this area is even less than that found in manufacturing and assembly and very few have suggested a correlation between supply chain management decisions and the level of product complexity. However, in the research conducted by Perona et al.[27], empirical findings suggested a strong correlation between lower complexity index, which was considered as an element of both variety and uncertainty, and investing in supplier partnerships. It was suggested that complexity reduction improves both efficiency and effectiveness of the supply chain system.

Novak and Eppinger [28] identified three main elements of product complexity in the supply chain system: number of product components, extent of interactions to manage these components; and the degree of product novelty. Using collected and existing data on automobile companies, they were able to demonstrate significant and positive relationships between product complexity and vertical integration, where quality penalties were shown for outsourcing complex systems. According to Hu et al. [29] the complexity of a supply chain is determined by: (1) the number of elements in the supply chain and their relationships; (2) the variety of each element of the chain; and (3) the demand uncertainty of each element in the supply. Sivadasan et al. [30] classified product complexity in the supply chain to two types; Structural Complexity, which is embedded in a static system and is related to the number of elements within the chain, and Operational Complexity, which is associated with the uncertainty in the dynamic system. Uncertainty in information and material flow is defined and measured as the deviation from the planned state in both time and quantity.

Although very limited, complexity literature in supply chain management has mostly focused on variety and uncertainty as main complexity sources; hence, entropy, which is the amount of information required to describe the state of the system, has been used to describe the associated operational complexity; this is because as in any system, with more uncertainty, more information is required to monitor the system [30]. Factors such as type of production processes and performance attributes are rarely addressed, although such dimensions can impact costs and efficiency within the supply chain.

2.1.2 Product Complexity Measurement

Very few researches in the area provide a direct measurement for product complexity. Most approaches depend on qualitative assessment tools for measuring product complexity, such as the ATM developed by Barclay and Dann [17], which is an assessment tool based on a questionnaire, divided into four parts: success criteria, product complexities, integration activities and development process. Among the few that developed quantitative measurements, Bashir and Thomson (2001) offer an empirically derived equation that relates the function of a design product with complexity; where complexity is based on the number of product functions and the level at which they appear in a decomposed function tree.

Toro et al. [8] identified the objective of minimizing the overall complexity by finding the optimum balance between elements of Component and Assembly Complexities. Accordingly, total complexity is measured by:

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

(1)

$C_m = f$ (geometry, material, tooling, process, batch size),
$C_p = f$ (geometry),
$C_{st} = f$ (levels in hierarchy, number of sub-assemblies, max number of components / sub-assemblies),
$C_s = f$ (number of assembly operations),
$w_i =$ numerical constraints, where $i = 1, 2, 3, 4$

Noting that most of the variables in this measurement are identified by design and production ratings. From the above, the optimum number of components can be found by:

$$\frac{dC_T}{dn} = \frac{d}{dn}\left(\frac{w_1 C_m + w_2 C_p + w_3 C_{st} + w_4 C_s}{w_1 + w_2 + w_3 + w_4}\right) = 0$$

(2)

Cooper et al. [24] developed measurements for the three indices: Product, Process and Product-Process Index. The indices developed were to measure complexity for semiconductor wafer manufacturing plant. The measurement for Produce Index is based on the number of chips that can be produced from a specific wafer $\mathrm{CMAX_i}$ and the number of bits memory associated with the chip$\mathrm{M_i}$.

$$\mathrm{PROD_i} = \frac{\mathrm{CMAX_i}.\,\mathrm{M_i}}{\mathrm{CMAX_b}.\,\mathrm{M_b}}$$

(3)

Where,
PRODi= Product index for the i chip type
CMAXb = Maximum number of chips that can be produced from a wafer corresponding to the base chip, b; and
Mb = Number of bits memory associated with the base chip, b.

The Process Index (PROCt) is measured in terms of adjustment difficulty for specific technology:

$$\text{PROCt} = \frac{\text{DA}_\text{t}}{\text{DA}_\text{B}}$$

(4)

Where,
DAt= Total number of difficulty-adjusted activities for technology t, and
DAB = Number of difficulty-adjusted activities for the base process, B

The third index, Product-Process Index, is just the product of both Product Index (PRODi) and Process Index (PROCt).

Focused on car assembly, MacDuffie et al.[1], identified Model Mix Complexity as a measure that includes the number of distinct platforms (i.e. each having a unique underbody and floor pan and serving as the foundation design for multiple models), models (i.e. variants on a common platform), body styles, drive train configurations and export variations (i.e. right-hand vs. left-hand steering). In their calculations, each item was weighted in accordance with interview data. They then adjusted the measure to accommodate for the number of assembly lines and body shops, for example, a plant with two parallel assembly lines producing a single model on each is given the same model mix score as that of another plant that builds one model with one assembly line. After adjustments, scores were added including weights to represent the volume of direct labor required by each functional area.

In an attempt to manage the cost of variety MacDuffie et al.[1], established a measurement for Option Content by identifying the percentage of all vehicles actually built in a plant that have a particular option, from a list of eleven options. The options for each product were weighted by their cost, and the total cost of options as a percentage of selling price was calculated based on the concept that the price of the option reflected the amount of labor required to install the option.

2.1.3 Impact of Complexity

As product complexity increases, the lifecycle cost of the product increases. Several research have demonstrated increased direct costs due to increase in product complexity [1] [31],[21]. Complex products can be a result of and can cause complicated costly product design and development processes; increasing the direct costs associated with engineering time required for longer product development cycle, analysis and qualification tests. Complex components and processes tend to lengthen the product development cycle and delay the product launch as the number of required functions and design iterations increase [12].

Product complexity not only affects the cycle time of product development, but also impacts production cost, quality, serviceability and customer satisfaction [13]. In manufacturing and assembly direct costs of complex products can be reflected in higher set-up costs and the need for more capital equipment and training. Within the supply chain, research has shown that product complexity can increase direct material and labor costs, as well as manufacturing overhead and process investments.

Identifying the indirect costs of product complexity is more difficult. There are several drawbacks to product complexity that can increase indirect costs; drawbacks such as the increasing difficulty of balancing assembly lines and production scheduling, the need for higher quality control [12], and the negative impact on flexibility during product development and manufacturing. Furthermore, complex products can cause various managerial, information and logistic problems in the supply chain [18], all of which can add to the indirect costs of production and the supply chain management system. Inventory holding costs, whether raw material, work in process, finished goods or post-sales service inventory, can also increase with product complexity. Reduction in capacity due to setups, loss of economies of scale and delays in learning are other consequences of product complexity [18, 32].

2.1.4 Product Complexity Summary

Product complexity is still a theoretical concept. The literature provides different approaches, definitions and measurements to product complexity in different research areas. Quantity and variety of product offerings, components, functions and production processes have been the most commonly used approach to product complexity. However, variety has been proven to be a limited approach by many researchers. Table 1 provides a list of different research and approaches to understanding product complexity found in the literature.

Further, there has been little progress in establishing a complexity measurement framework. As shown in the previous section, some methods for measuring product complexity can be found in the literature. However, a comprehensive quantitative methodology is needed for designers to make product development decisions, evaluate complexity levels of different designs, and support product complexity management strategies. This methodology cannot be achieved without a more comprehensive view of product complexity and its impact throughout the product's life cycle. Additionally, literature in the area of complexity management has failed to provide approaches to evaluate the validity of existing measurements in controlling product complexity [27].

Table 1: Product Complexity in Existing Research

	Research Authors		
Product Complexity Approach	**Product Design and Development**	**Manufacturing and Assembly**	**Supply Chain Management**
Variety			
Number of Products	Salminen et al.[9]	MacDuffie et al.[1], Cooper et al.[24], Hu et al.[25], Frizelle[33], Sum et al. [34]	
Number of Parts	Pahl and Beitz[15], Rodriguez-Toro et al. [35]	MacDuffie et al.[1], Frizelle[33],	Sivadasan et al.[30], Hu et al.[25], Novak and Eppinger[28], Perona et al. [27]
Number of Process	Pahl and Beitz[15], Rodriguez-Toro et al. [35]	Cooper et al. [24]	
Number of Functions	Ameri et al.[18], Barclay and Dann[17], Pahl and Beitz [15]	MacDuffie et al. [1]	
Product / Component Geometry	Fagade et al.[12], Rodriguez-Toro et al. [35]		
Relation between components	Ameri et al.[18], Barclay and Dann [17]	Cooper et al. [24]	
Uncertainty	Ameri et al.[18]	Zhu et al.[23], Hu et al.[25], Frizelle [33]	Sivadasan et al.[30], Hu et al.[25], Perona et al. [27]
Product Newness	Barclay and Dann [17]		Novak and Eppinger [28]

2.2 Product Families and Product Platform

Literature provides a variety of definitions for product platform, all of which agree that the existence of a common element is essential in managing costs and variety among and across product families. Simpson et al. [36] define a product family as a group of related products, sharing common features, components and subsystems. Meyer et al. [37] define a product family as a group of related products that are derived from a product platform to satisfy a variety of market niches, where product platform is a set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched. Fellini et al. [3] define product platform as a set of all components, manufacturing processes, and/or assembly steps that are common in a set of products. Ulrich [38] defines product platform as a collection of assets that are shared by a set of products.

A successful and robust product platform design can offer companies multitude of benefits. Product platforms enable efficient derivation of product variants by keeping development costs and time-cycles low [3]; as an example, after adopting platform design, Black and Decker's power tool division were able to launch one new product every week for several years [6]. Cost-saving in product platform design, can be found through many of its advantages, such as: decreased lead-time and risk in the development stage, lower inventory and handling costs, reduction in setup and retooling time, increased standardization, and reduction in number of components to test and qualify within the family [4] [39] .

Despite the many advantages of platform design, there are several drawbacks that have caused companies to shy away from this design strategy. First, there are significant costs associated with product platforms that may not make them appropriate for all product and market conditions. In addition to the high fixed investments in developing platforms, they can also result in the overdesign of low-end variants in a product family to enable subsystem sharing with high-end products new markets is essential for long term growth.[40]. Second, defining a product platform is one of the most challenging aspects of product family design [41]. A platform-based approach can be risky, as too much commonality can cause internal competition among similar products within the family [42]. The objective of the product platform is to share elements for common functions and to differentiate each product in the family. In many cases, the individual product requirements are conflicting when designing a product family and designers must balance the tradeoff between maximizing commonality and minimizing individual product performance deviations [3]. The design challenge is to select the product platform that will generate family designs with minimum deviation from individual requirements, making product platform and family design, a much more complex process than individual product development. This section describes existing approaches and evaluation techniques for product family and platform design.

2.2.1 Product Family Design

The objective of a product family is to provide a group of related products that share common features, components, and subsystems, in order to satisfy a variety of market niches. Hence, once targeted market segments and needs are identified, companies can identify the best platform leveraging strategy to increase their market share.

As shown in Figure 6, Meyer [37, 43] identified three product platform leveraging approaches. In horizontal leveraging, product family subsystems of components are leveraged from one market segment to the next given tier of price/performance, such as Gillette Sensor-Excel razor that use exact same razor cartridge in both male and female market segments by changing shape, color and general design. In vertical leveraging a platform is leveraged to address a range of price/performance tiers within one specific market segment; this is done by either removing functionality from high-end platform to achieve lower price products or by adding functionality to achieve higher price products. In the beachhead leveraging approach, both horizontal and vertical leveraging are combined by developing a low-cost effective platform for a particular market segment to scale up the performance characteristics of the platform (vertical leveraging) and add other features to target new market segments (horizontal leveraging). This approach was used by Compaq computers in the 1980s, where after the company established a foothold in the portable computer market, it slowly introduced a stream of other products for other market segments with different price/performance tiers, including desktop PCs [37].

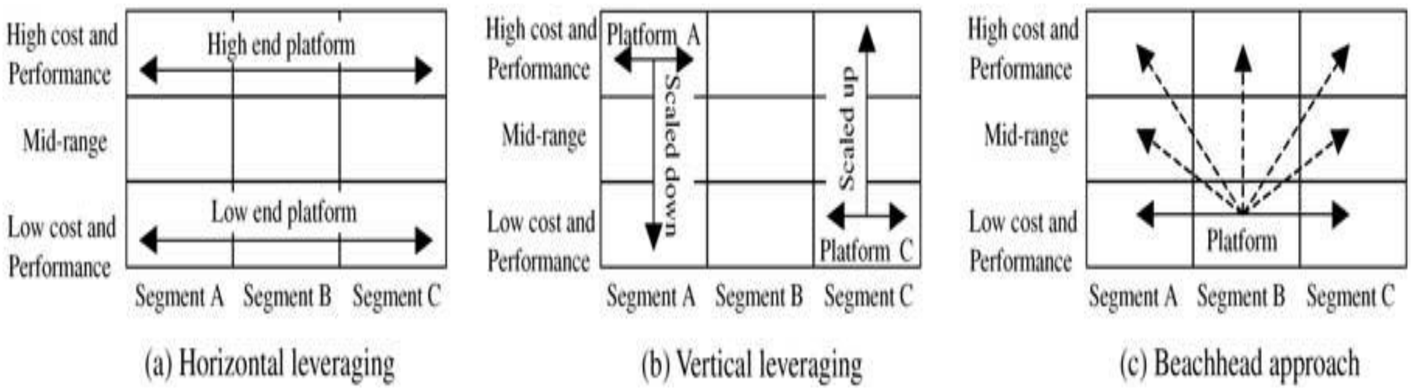


Figure 6: Market segmentation grid and corresponding platform leveraging strategies [37]

In their examination of existing product family examples found in the literature, Simposn et al.[36] identified two main approaches to product family design: (1) Top-down (a priori) approach, where a company develops and manages a product family based on a product platform and its derivatives; and (2) Bottom-up (a posteriori) approach, in which case the company consolidates an existing group of distinct products by standardizing components to improve economies of scale.

According to the above, based on marketing strategy and design requirements, companies need to decide on both their platform leveraging strategy and product family design approach. Using Meyer’s market grid, Simpson et al.[44] introduced the Product Platform Concept Exploration Method (PPCEM) as a top-down approach for product platform and product family design. PPCEM consists of five main steps describing how to formulate and solve the product family problem.

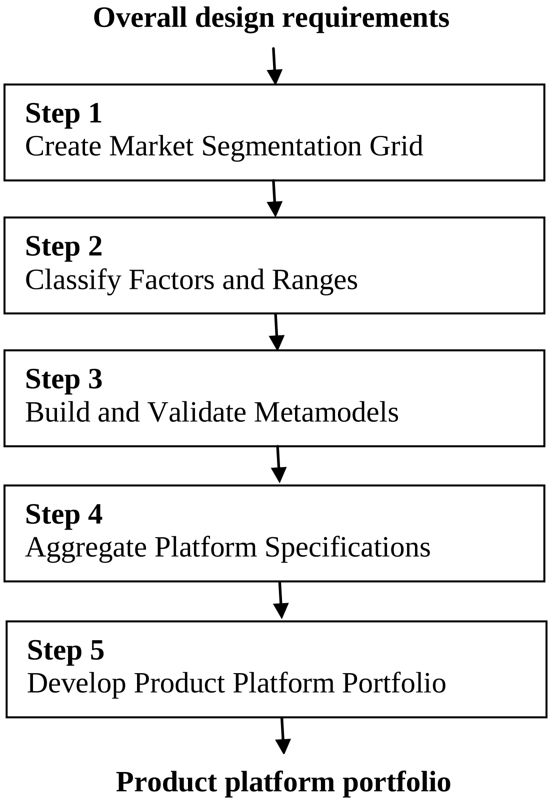


Figure 7: PPCEM Steps

2.2.2 Product Platform Architecture

A successful product family development requires balancing the tradeoff between commonality and distinctiveness, which can be achieved through product platform planning. Meyer et al. [37] describe platform planning in management context Figure 8, where the objective of product families are to meet the requirements of the company's targeted and potential markets. Each product family is based on common architecture built on a combination of shared subsystems and interfaces that provide the essential functionality of the products. The underlying building blocks for the platforms are the core technologies and processes. According to this framework, Meyer et al [37] define product platform management as the integration of building blocks (core technologies and processes) with common architectures (shared subsystems and interfaces), with end user requirements to produce product families that serve a spectrum of price and performance for one or more market segment.

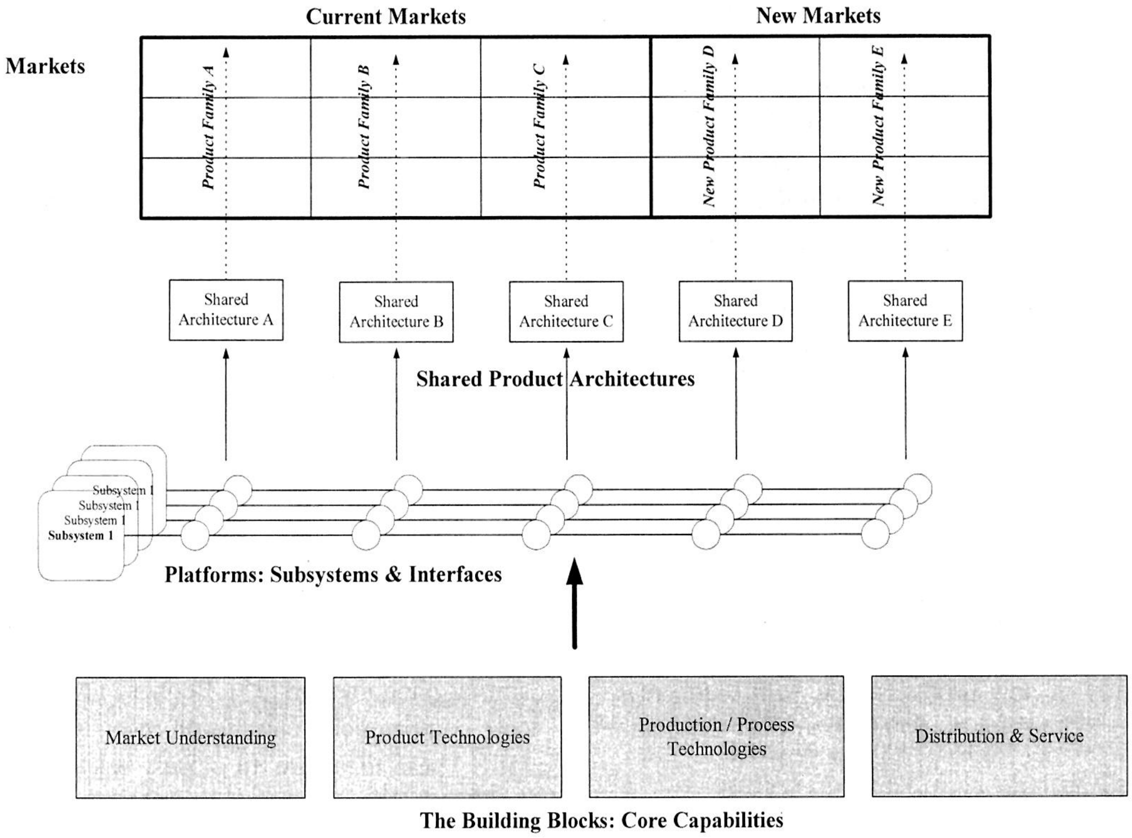


Figure 8: Product Platform Management [37]

Ulrich [45] defines product architecture as the structure that integrates components and subsystems of a product into a coherent mechanism to perform intended functions; to realize a product the overall functionality of the product needs to be decomposed into a set of defined function and component parts that will provide those function, and then the interfaces between the components are specified. The product architecture encompasses the information on how many components the product consist of, how these components work together, how they are built and assembled, used, and disassembled [46].

Developing the common architecture of a product family, is obviously more difficult than that of a single product; in a single product designers need only consider its functions and components, while in a product family functions and components of various products must be considered. Additionally, in a product family designers need to identify the optimum balance between commonality and distinctiveness. There are two main architectures for product family found in the literature, modular and integral architectures, which will be discussed next.

Modular Architecture

A modular architecture maps the functional requirements to the product components [38]. Modularization is an approach to organizing complex design and operations more efficiently by decomposing complex systems into simpler portions, allowing designers to use a combination of groups of components to develop larger quantity of products [47]. Similar to this definition to modularization, Mikkola and Gassman [48] define modularity as an approach for organizing complex products and processes efficiently by decomposing complex tasks into simpler activities that can be managed independently.

The most common purpose behind product modularization is to generate product variety in a rational way, and the concept of modularization is strongly related to concepts such as design for variety, product family design and platform development [49]. Modular system architectures facilitate product variety by adding, removing or substituting one or more modules to the platform. In a platform design, the use of different modules allows the realization of greater number of combinations resulting in more diversity of products but also increasing the costs, while the use of more commons modules than different modules reduce the number of combinations and related costs [47]. This tradeoff is reflected in the matrix in Figure 9. According to Jiao et al. [50] the selection of a module as standard or unique depends on both its utility to product distinctiveness and costs.

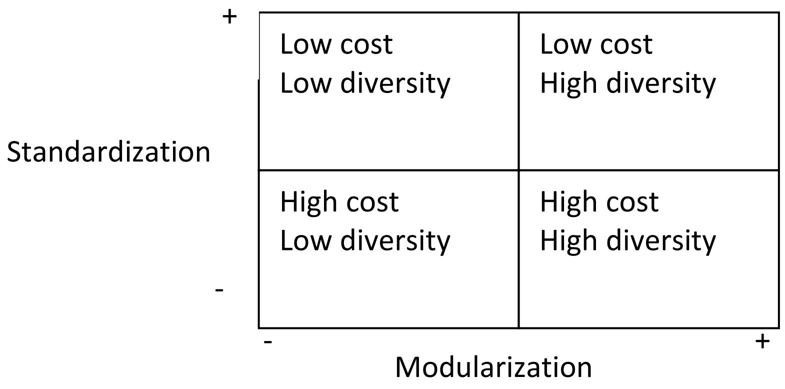


Figure 9: Impact of cost having different level of modularization and standardization [47]

Degree of modularity is dependent on the level of: 1. economies of components substitution; 2. disaggregating and recombining the system into new configurations; and 3. a system achieving greater functionality through components being specific to one another [48]. Accordingly, Mikkola and Gassman uses a mathematical model for analyzing the degree of architecture modularity by taking into consideration the number of components, degree of coupling and the substitutability of new-to-firm components.

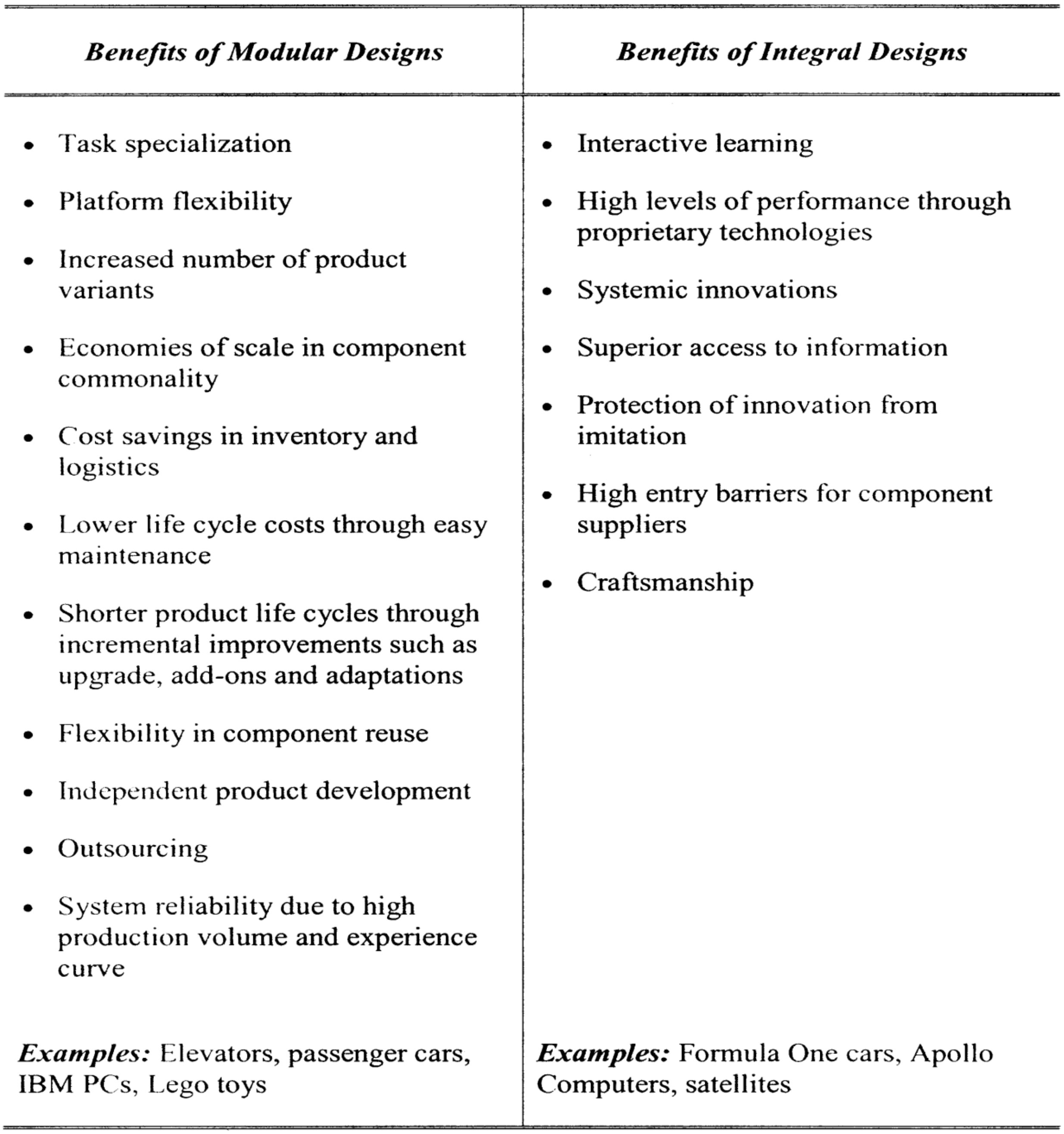
Many other methods for combining components and subsystems to develop modules can be found in literature. Hata et al [51] use a method to develop modules based on product life cycle, while Otto [52] uses heuristics to group product functions translated from market requirements into modules to manage variety. Thomas [53] establishes an algorithm to standardize group of components and form standard modules.

Integral Architecture

Unlike modular design, integral product architecture includes complex relationships - not a one-to-one mapping - between components and functional elements, as well as complex interfaces connecting components [45, 47]; changes to one component are impossible without changes in another. Hence, integral architecture provides a less flexible platform than modular architecture. Examples of integral platform found in the literature include the telecommunication network for spacecrafts [54] and automobile bodies [45].

Despite its complexity, there are several advantages to an integral architecture. Integral architecture designs enhance knowledge sharing and interactive learning. Additionally, integral architecture is designed to achieve maximum performance, where the implementation of functional elements is distributed across multiple components. For example, in the 1980s Apollo Computer was more integral in architecture than IBM PCs; in which case high performance was emphasized and the workstation was designed with a proprietary architecture based on Apollo’s own operating and network management systems, this is because Apollo’s designers believed that it was necessary for various parts of the design to be highly interdependent for achieving high levels of final product performance[48]. Other advantages of an integral architecture include systematic innovation, protection from imitation and high entry barriers for component and module suppliers[47]. Mikkola et al. [48] identifies the advantages of both modular and integral architecture, as can be seen in the following table:

Table 2: Tradewoffs between modular and integral product architecture design [48]



Benefits of Modular Designs	***Benefits of Integral Designs***
• Task specialization • Platform flexibility • Increased number of product variants • Economies of scale in component commonality • Cost savings in inventory and logistics • Lower life cycle costs through easy maintenance • Shorter product life cycles through incremental improvements such as upgrade, add-ons and adaptations • Flexibility in component reuse • Independent product development • Outsourcing • System reliability due to high production volume and experience curve	• Interactive learning • High levels of performance through proprietary technologies • Systemic innovations • Superior access to information • Protection of innovation from imitation • High entry barriers for component suppliers • Craftsmanship
Examples: Elevators, passenger cars, IBM PCs, Lego toys	***Examples:*** Formula One cars, Apollo Computers, satellites

2.2.3 Evaluating Product Platform Design

Evaluating the design of a product platform is a much more challenging task than evaluating a single product concept; since a platform must effectively support multiple product variants over a prolonged period of time [55]. These added requirements make single product evaluation methods not directly applicable for a platform. Literature provides vast techniques and tools to evaluate platform design. As the main objective of a platform design is to reduce costs of product variety to meet the requirements of different market niches, many existing tools have focused on evaluating platforms based on cost savings; ability to manage and provide variety; and meeting customer demands. This section discusses several platform evaluating tools found in the literature.

Cost Savings

As previously mentioned, the objective of platform strategies is to reduce costs and time required to develop a new product. Not only do common components reduce production costs by improving economies of scale, but also the number and components in inventory and other production support activities. Accordingly, an important measure of a successful product platform is the overall costs of the product family and how cheap and fast a new product can be generated from the existing platform.

Meyer et al. [43] developed several metrics to evaluate the derivative product generation from an existing platform. Among the measurements developed by Meyer et al. is Platform Efficiency, which measures the average research and development costs in developing a derivative product, to that of developing the platform from which the product is derived. The closer the Platform Efficiency measurement is to zero, the better; while the closer it is to one, the less efficient the base platform is in deriving new product variants. If a platform is well developed, then Platform Efficiency should improve with every new product derived from the platform, due to the learning that takes place. Meyer and Dalal [56] further expanded the platform efficiency measurement to measure platform phenomena for non-assembled products by considering non-variable manufacturing-related expenses, which in non-assembled products can exceed expenses for product design and engineering. The following is the equation used to calculate Platform Efficiency for a single non-assembled product (p):

$$E_p = \frac{(C + M + R)_p}{\sum_{g=\text{first generation}}^{\text{latest generation}} (C + M + R)_g}$$

(5)

Where

C = Product engineering costs attributable to platform development, or derivative product development based on these platforms

M = Manufacturing engineering costs

R = Retooling and related capital costs for manufacturing equipment

g = Generation of the product line

Meyer et al. [43] also developed a Platform Effectiveness measurement, which compares the product sales to product development costs, and can be measured at the individual product variant level or at the product family level. Platform Effectiveness may decline if the platform has outlived its utility to create new product variants that are valuable in the market.

The Setup Index (SI) developed by Martin and Ishii [57] is an indirect measure of how switchover costs contribute to the overall costs of the product; hence, SI will be reduced with more commonality. SI is meant to act as a general indicator of how substantial setups are for a specific product:

$$SI = \frac{\sum_{i=1}^{n} v_i c_i}{\sum_{j=1}^{v_n} C_j}$$

(6)

Where,

v_i = Number of different products existing process i

c_i = Cost of set-up at process i

C_j = Total cost (material, labor and overhead) of j product

Activity Based Costing (ABC) has also been used to evaluate the cost savings of a platform design. One of the objectives of using ABC for cost estimation is to identify opportunities to reduce production costs through: 1. activity elimination; 2. activity reduction; 3. activity selection; and 4. activity sharing. Using a case study, Thyssena et al.[58] investigate the merits of ABC as a tool for assessing the cost consequences of modular product architecture design. Park and Simpson [59] established a cost estimation framework to evaluate product platform design using ABC as an analysis tool. The framework consists of three main stages: 1) allocation, where the production activities and corresponding resources are identified and modeled; 2) estimation stage, in which production costs are estimated by estimation methods selected based on available information; and 3) analysis, which is the final stage of the framework and components potential to be used in a product family design are investigated.

Managing Variety

Many of today's companies are faced with the challenge of providing as much variety as possible for the market (product variety) with as little variety between products as possible (components variety); which has caused many companies to use product families and platform based product development strategies [2]. Commonality ratios are among the most common methods to manage part variety across and within product families and different techniques to measure such ratios can be found in the literature. A commonality index is a metric to assess the degree of commonality within a product family based on different parameters such as number of common components and component costs [60]. According to Fellini et al. [3] two types of sharing is possible while selecting a product platform: component and scaled sharing. In component sharing, one or more components are exactly common across a product family; while in "scaled" sharing, some attributes of the shared component, such as height or weight, may differ within the product family. Very few commonality ratios found in the literature consider "scaled" sharing.

Martin and Ishii [61] developed a Commonality Index (CI) to identify the ratio of the number of unique components in a product family to the total number of components in the family; measuring how well the design utilizes standardized components and parts. The CI ranges from 0 to 1; where 1 represents the highest level of commonality possible.

$$CI = 1 - \frac{u - \max p_j}{\sum_{j=1}^{V_n} p_j - \max p_j}$$

(7)

Where,

u = # unique part numbers

p_j = # parts in model j

V_n = final # of variety offered

However, according to this measurement, an optimal product family is one with all common parts. This is obviously a drawback for the index, as the higher the commonality, the lower level of product variant distinctiveness; the optimal solution should be a balance between commonality and distinctiveness. This drawback can be found in many commonality ratios.

To resolve the limitation in the CI, Commonality Diversity Index (CDI) was developed by Thevenot et al. [62] which scores the difference between existing and ideal tradeoff within and across product families. In this case an ideal tradeoff is defined as: (1) common functions should use common components, (2) unique functions should use unique components and (3) variant functions should use variant components, in the same proportion, where functions are defined by function attributes.

Simpson et al [36] developed Product Variety Tradeoff Evaluation Method (PVTEM) to assess the varying levels of commonality and variety of alternative product platform concepts. The PVTEM helps designers resolve the tradeoff between product platform commonality and the individual performance of the product variant, achieved through two developed indices Non Commonality Index (NCI) and the Performance Deviation Index (PDI). This combination overcomes the limitation of other commonality related measurements by reflecting the tradeoff that occurs between performance and commonality. The NCI is a measure of the variability of design variable settings across members of the product family [36]. NCI is measured by the weighted sum of average relative variations in design variables within a family of products; hence, a smaller NCI reflects more commonality within a product family. PDI provides a measure of how well products within the family meet their individual performance targets. This is an important index, as identifying the level of commonality on its own, can cause a high level of commonality without considering the impact on the distinctive performance goals and constraints for each product variant.

Based on the understanding that both commonality and diversity are the key to product family development, Thevenot et al. [4] developed the Design for Commonality and Diversity Method (DCDM) based on two commonality indices: the Commonality Diversity Index (CDI) and the Comprehensive Metric for Commonality (CMC). The DCDM helps designers manage the tradeoff between commonality and diversity during all the stages of the product family development, as it works on two main stage of product realization. The first stage during preliminary project, where customer needs and requirements are identified, DCDM uses CDI to help designer focus on which functions to make common, variant or unique in the product family. In stage two of the realization process, where detailed product and process design are studied, DCDM use CDI and CMC to: (1) ensure that the functions and the corresponding components maintain the appropriate diversity and commonality and (2) help designers improve the commonality between components without sacrificing diversity.

From the above, most commonality ratios in the literature favor standardization and reduction in part counts. However, this can often lead to more geometrically complex parts [12]. Furthermore, too much standardization can be a drawback; as the level of distinctiveness between products is reduced the possibility of internal competition between products in the family is increased.

Approaches other than commonality ratios can be found in the literature. Otto and Holtta [55] present three metrics to measure how a platforms ability to provide product variety: carryover, common unit and different specification. If a specific function can be incorporated, i.e. carried over, into different products without change and technology upgrades, then the function should be isolated into a module. Ideally a module has either 100% carryover of its functions or none at all. To capture this concept, Otto and Holtta developed a metric to measure the carry over level of a platform:

$$\text{Ycarry} = 10\ (\#\ \text{functions to carryover}/\#\ \text{functions}) \cdot 100 \qquad \textbf{\textit{(8)}}$$

According to this metric, if a function is shared by more than one product, it is called a common unit. To identify the different specification, which are the functions that distinguish each product variant, a scale from 0 to 10 (0 requiring unique interface for each variant, 10 can be swapped into any variant) was established.

Another approach is identifying where differentiation occurs. Martin and Ishii [32] developed the Differentiation Index (DI) to evaluate product platforms and families: DI relates to where differentiation occurs within the process flow. Accordingly, the lower the DI the better as it reflects that differentiation occurs later in the process flow, hence more commonality exists. In general DI is an important index to identify cost savings of differentiating later in the process; differentiating the product later in the process can help reduce costs related to inventory, set-ups and other related production costs.

$$\mathrm{DI} = \frac{\sum_{i=1}^{n} d_i v_i\, a_i}{n d_1 v_n \sum_{i=1}^{n} a_i}$$

(9)

Where,

v_i = Number of different products existing at process i
n = Number of processes
v_n = Final number of variety offered
d_i = Average throughput time for process i
d_1 = Average throughput time from beginning of production to sale
a_i = Value added at processes i

Another way to consider the ability of a product platform design in providing variety efficiently is by considering the platform's reuse level. A robust product platform architecture, facilitate reuse of common subsystems for new products; greater reuse of subsystems lead to lower engineering and manufacturing costs. Meyer and Dalal expressed the reuse measure (U) for a single product (p) as the percentage of the products subsystems and interfaces shared with other products in the product family:

$$U_p = \frac{\sum(S', I')_p}{\sum(S, I)_p}$$

(10)

Where,
S = A major subsystem within the current product architecture
I = A major interface within the current product architecture
S' = A major subsystem that is common to one or more products in the product family
I' = A major interface that is common to one or more products in the product family

Meeting Customer Demand

Another important objective to consider when evaluating developed platforms is how well the platform(s) meet the demands of the targeted market segment. This is especially important for multi platform strategy where the objective is to identify the number of platforms to be used in meeting market segment requirements. A Quality Function Deployment (QFD) matrix is commonly used to evaluate whether customer needs and wishes were met against existing products, modules, performance and components. QFD translates customer requirements into appropriate technical requirement for each stage of product development and production[63]. Literature on QFD is extensive and can be found in many research areas, such as transportation, communication and team work. Over the years researchers have extended the QFD: for example Modular Function Deployment was developed to translate customer requirements to modules [64] and [65] developed a Function-Behavior matrix to express the relationship between production function and behaviors (technologies).

In product family development, QFD has been used to identify common customer requirements, which is then used to identify the optimum platform for the family[66], [67],[68]. Kreng and Lee [69] have used QFD for the design of modular products in two phases; phase 1 explores design requirements, including customer needs, company's strategies and designers' preference, and phase 2 uses modular product analysis and liner programming to establish module configuration.

Martin and Ishii [70] also proposed a two phased QFD to develop product platforms; the first phase identifies customer requirements including the expected range of change over platform life, while in the second phase the identified engineering metrics from the first phase is matched with components. Generation Variety Index, which is a measure of the amount of redesign effort required for future generations of a product family, is used in the second phase to evaluate the estimated cost of change in each component to meet the most stringent future metric target values identified in the first phase.

Techniques other than using QFD for evaluating the platforms ability to meet customer demands can be found in the literature. Otto et al. [55]developed a customer need metric to measure how well the customer needs are met by the platform. The metric is organized as a hierarchy of the product variants’ requirements. Product variants are compared to ideal target on each critical requirement to what the platform can actually provide. They use the following calculations to evaluate the platforms ability to meet customer demands:

$$Y_{CR} = \frac{1}{M} \sum_{\text{variants } i} \frac{1}{K} w_{ij} R_{ij}$$

(11)

Where,

w_{ij} = The revenue weighted importance requirement j for product i
R_{ij} = The customer score for a customer requirement j for product i in scale 0–10
K = The number of requirements
M = The number of variants

Other Evaluation Criteria

In addition to cost savings, managing variety and meeting customer demands, other criteria for evaluating product family design can be found in the literature, such as market life measurement, which is a reflection of the longest time a product from a specific product family generation is marketed [71]. Longer product family market life can enhance variety to meet different customer demands.

In any design project (for a single or family of products), designers consider multiple objectives and constraints - such as fulfilling customer requirements, budget and capacity constraints, stakeholder expectations...etc. - making it impossible to evaluate any design form just one single perspective. There are few multi-criteria approaches to evaluate product platform design in the literature, for example Otto and Holta [55] developed 19 criteria for platform evaluation, grouped into six main categories: customer satisfaction, variety, after sale, organization, flexibility, and complexity. The tool is focused on the early platform architecture phase, before proof-of-concept prototyping. In their framework, the last group, complexity, aimed to reduce the apparent complexity of the product platform architecture. This group includes 5 metrics:

function and form alignment, interface flexibility, anti-synergy avoidance, 1 DOF adjustment and limited extremes.

The function and form alignment metric penalized a platform architecture that has functions in more than one module and / or a module whose parts are in more than one separate location. The interface flexibility metric evaluates the redesign effort when a platform and modules have to change to adapt to new, often unexpected, requirements. The anti-synergy level evaluates the interactions between input and output flows of a module as the product family system grow. The fourth metric, 1 DOF adjustments, rates the architecture based on the number of adjustments needed to the module to apply in new product variants. The last metric, limited extremes, compares the new requirements of the architecture under development to the requirement of model in the market; architectures that have requirements that are difficult to meet cam cause development problems.

There is very limited research using product complexity measurements to evaluate product platform designs. Salminent et al. [9] qualitatively describe how modular design and product platforms can be used to handle the increasing product complexity and go as far as mentioning that complexity can be measured through the degree of modularity. However, they fail to provide any quantitative reasoning behind this assumption. Martin and Ishii [32] consider variety as a synonym for product complexity and in their Design for Variety model they attempted to capture the indirect costs of variety through three main indices: commonality, differentiation point and set-up cost[57]. Building on their original DFV model, Martin and Ishii [72] identified two new indices to help manage variety during the design stage: the Generational Variety Index (GVI) as a measure of the amount of redesign effort required for future generations of a product family and the Coupling Index (CI), which measure the coupling among components of a product. Although their DFV model can be used to measure the impact of variety and help manage variety at the design phase, they fail to consider how non-unique parts are shared across models and how factors such as geometry and function may impact the percentage of shared parts.

2.3 Grey Theory

Many systems, such as those that are social, economic or industrial, are named based on the fields and ranges to which the research subjects belong. In contrast, the name grey systems, is chosen based on the colors of the subjects under investigation. The information system whose internal characteristic is completely known is a “white” system; unknown information systems are considered “black”; a system that contains known and unknown information is a “grey” system [73]. Deng developed grey theory in 1982 [74], and can be found used in many different research areas and applications in the literature.

The grey system theory is a method, which makes full use of known information to decrease unknown information [75]. Grey system is described by grey number, grey equation, grey matrix …etc. Fields covered by Grey theory include systems analysis, data processing, prediction, as well as decision making and control [76]

Although there are similarities, several researchers have applied Fuzzy and Grey theories together in their analysis [77], [78]. Slight differences between both theories have been highlighted in the literature: fuzzy theory aims to help make decisions characterized by imprecise information; while Grey theory, deals with making decisions characterized by incomplete information [77]. Additionally, grey systems emphasize on objects with definite external extensions and vague internal meanings, while fuzzy mathematics mainly studies objects with definite internal meanings and vague external extensions [78]. Additionally, the steps used in an evaluation procedure for grey clustering are markedly less than those for fuzzy logic [76].

Often an observational object or system can possess many characteristic features, making it difficult to provide an overall classification for the object. Grey cluster is a method based on whitenization weight functions of grey numbers, that classifies observations into definable classes [79]. The following describe the general steps taken to whitenize grey numbers and determining overall classifications [73]:

Step 1: Calculate values for each of the indices for all decision units being analyzed. x_{ij} denote the calculated value of indices j for decision units i

Step 2: Formulate the whitening functions, f_j^k, which serves as a criterion for judging the category level among all values of x_{ij}.

There are different types of whitening functions. A typical whitening grey function is reflected in Figure 10; assume that the whitenization weight function f_j^k, of a j-criterion k^th subclass, then the points $x_j^k(1)$, $x_j^k(2)$, $x_j^k(3)$ and $x_j^k(4)$, are called turning points of f_j^k.

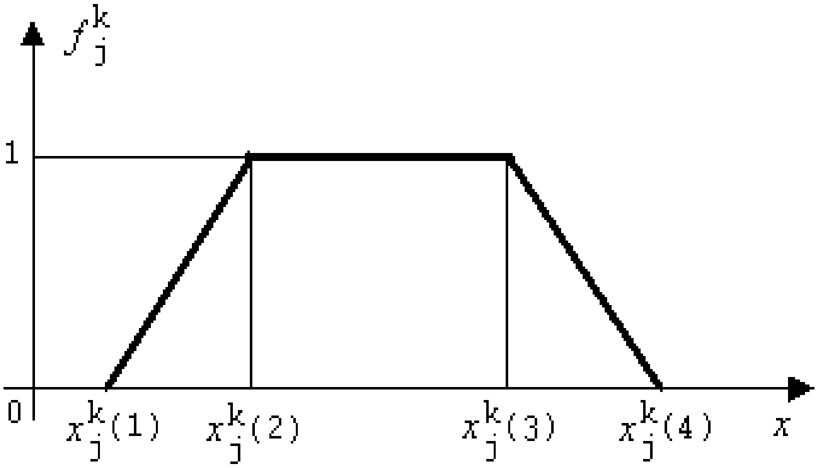


Figure 10: Typical Whitening Function [79]

The triangular whitenization function is used in this research, which requires two main steps [79]:

Step 2a: Divide the individual ranges of the criteria into s grey classes: let (a_1, a_{s+1}) be the range of the values of criterion j, then divide (a_1, a_{s+1}) into s grey classes:(a_1, a_2) , ..., (a_k, a_{k+1}) , ..., (a_s, a_{s+1}) .

Step 2b: Let the whitenization weight function value for (a_k, a_{k+1}) /2 to belong to the kth grey class be 1, if $(\frac{a_k+a_{k+1}}{2}, 1)$ is connected to the starting point a_{k-1} and ending point a_{k+2} to obtain a triangular whitenization weight function as shown in Figure 2. To compute the degree of membership of $f_j^k(x)$ to the kth class, the following function is used:

$$f_j^k(x) = \begin{cases} 0, & x \notin [a_{k-1}, a_{k+2}] \\ \dfrac{x - a_{k-1}}{\lambda_k - a_{k-1}}, & x \in [a_{k-1}, \lambda_k] \\ \dfrac{a_{k+2} - x}{a_{k+2} - \lambda_k}, & x \in [\lambda_k, a_{k+2}] \end{cases}$$

Where, $\lambda_k = \frac{a_k + a_{k+1}}{2}$

(12)

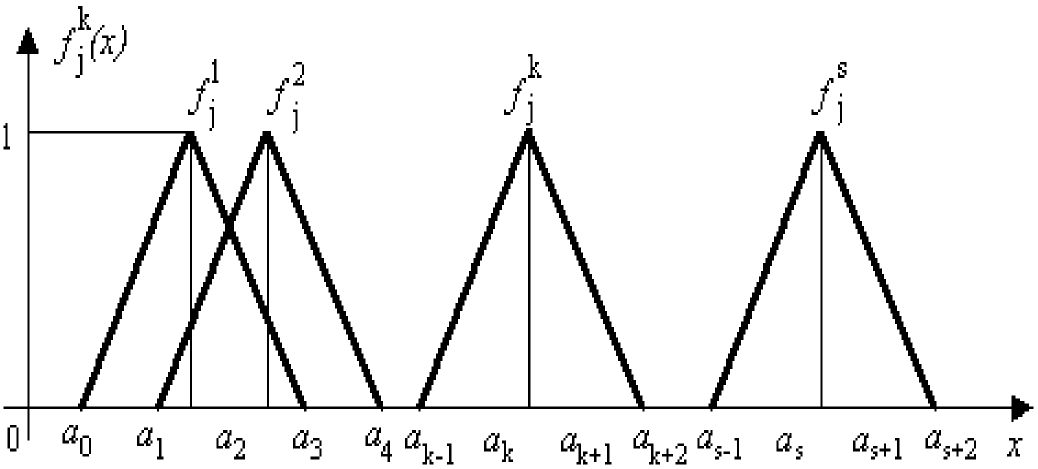


Figure 11: Construction of a triangular whitenizing weight function [79]

Step 3: Compute the decision weight parameters, by establishing the relative importance of the decision indices, w_j, where$\sum_{j=1}^{m} w_j = 1$. The decision weight parameter is calculated by:

$$\sigma_j^k = \sum f_j^k(x_{ij}).\, w_j$$

(13)

Step 4: Grey clustering classifies the decision unit i into a certain category, by ranking the weight parameters of unit i and selecting the highest among all categories j.

2.4 Summary of Chapter 2

In this chapter, different approaches to defining and measuring product complexity found in the literature were discussed. Although there are some methods for measuring product complexity, a comprehensive quantitative methodology is needed for designers to make product development decisions and manage product complexity levels..

This chapter also discusses existing concepts, approaches and techniques in product family and platform architecture, with specific focus on product platform evaluation methods. As shown, there is limited research that considers product complexity, as an approach to evaluate the cost savings and efficiency of platform architecture.

Related product complexity research has generally failed to give consideration to how the unique make-up of non-assembled products can impact complexity levels. This is also true in the study of platform architecture, while there exist descriptions of platform methods applied to assembled products, it is hard to find similar work for non-assembled ones [80].

Based on the previous work discussed in this chapter, and applying several of the tools, techniques and grey clustering methodology, Chapter 3 introduces a new approach to evaluate product complexity levels within a product family design. This approach is based on a comprehensive product complexity definition, from which indicators and measurements are drove.

Chapter 3: Approach and Methodology

The main objective of this research is to develop a new approach in evaluating and managing product complexity levels in product family designs. The proposed approach will provide a comprehensive understanding of product complexity, by considering sources and impacts of product complexity during different product lifecycle stages. Additionally, a new approach to identify possible components for standardization within product families to support complexity management is put forward.

The complexity evaluation approach in this chapter is applicable to product families that are based on modular architecture; where the platform is established based on a collection of common product components. Utilizing earlier research in product complexity, product family evaluation techniques, grey clustering and other decision support tools, this chapter addresses the problems and questions raised in Chapter 1 to achieve the research objectives set in Section 1.4.

3.1 Product Complexity Measurement Framework

In order to establish a complexity measurement framework, it is important to first understand what product complexity is; i.e. to identify the sources and indicators to be measured. By understanding complexity definitions in different research areas, this section puts forward a definition for product complexity, which is then used to derive product complexity indicators.

3.1.1 Defining Product Complexity

In general, complexity has been a topic of interest in many different research domains; such as psychology, mathematics, biology, software engineering, manufacturing…etc. Not surprisingly, complexity definitions can be found in the literature that differs by the area of research, scope, objective and available data. Broadly, complexity definitions can be classified into two general approaches: the first approach considers the impact of complexity on the system being analyzed, and the second approach considers the features or elements of the system that cause complexity. The complexity definition provided by Salminen et al. [9] falls within the first approach, as they provide a simple explanation of complexity by defining it as a measure of the difficulty in understanding or working with something. Another example for the first approach is the definition for computer program complexity, which is represented by the execution time and storage required to perform the computation [81]. In economics, complex systems naturally arise in the economy and hinder the reaching of some asymptotic state or equilibrium [82]. According to MacDuffie et al.[1] complexity is a dimension of the manufacturing tasks that result from variety strategies; where variety is considered “good” when it provides market place advantages outweighing the negative impact complexity has on costs and efficiency. From these different perspectives, it is clear that complexity causes operational inefficiencies due to lack of flexibility within the system.

The Oxford Dictionary definition for something complex, which is "made of (usually several) closely connected parts" would fall in the second type of definition approaches. In organization studies, a complex organization is determined by the number of sub-systems and activities within this organization [83]. While in biology, a complex system, such as cells, consists of very large numbers of functionally diverse, and frequently multifunctional, sets of elements interact selectively and nonlinearly to produce coherent behaviors [84]; this definition of complexity looks at the number, functionality and relationship between elements within the system. According to Blackenfelt [11] product complexity is defined by the number of variant products provided. While according to Hobday [85] product complexity is defined by: the quantity of tailored components and the hierarchical manner in which they are integrated. Hence, definitions in the second approach consider the number of system elements and relationship between these elements as the main source of complexity.

From the above two approaches, when trying to define Product Complexity, there are three factors to consider. The first of these factors is the system being analyzed. Zhang and Luo [13] define product system from the perspective of the product life cycle to functionally include physical and extensive characteristics and timely to include different phases of the product’s life cycle. A product family, which is broadly defined as a group of related products sharing common elements, can be described as a larger system with several product variants as subsystems.

The second factor to consider is the domain and scope of the analysis. In this research, consideration is given to the impacts of product complexity on product design, development and manufacturing, which represent the timely elements in the above product system definition by Zhang and Luo. The actual impact complexity has on these phases, is the third factor considered when defining product complexity. Combing all these elements together (as shown in Figure 12), a definition for product complexity is set forth as:

All physical and extensive characteristics of the product family and generated product variants that reduce flexibility and cause inefficiencies throughout the different stages of the product's life cycle

1. System being analyzed	**2. Analysis domain**	**3. Impact of Complexity**
All physical and extensive characteristics of ***the product family and generated product variants*** *that reduce flexibility and cause inefficiencies throughout the different stages of the product's life cycle*	*All physical and extensive characteristics of the product family and generated product variants that reduce flexibility and cause inefficiencies throughout* ***the different stages of the product's life cycle***	*All physical and extensive characteristics of the product family and generated product variants that* ***reduce flexibility and cause inefficiencies*** *throughout the different stages of the product's life cycle*

Figure 12: Breakdown of Complexity Definition

3.1.2 Product Complexity Indicators

From the above definition, sources and indicators are identified by understanding the impact of the physical and extensive characteristics of the product family and product system on complexity in product design, development and manufacturing. According to Zhang and Luo [13] , the physical characteristics of product system include: number of components and the structure and relationship between these components. Given that a product family is a group of related products that are derived from a product platforms [37], generated product variants and platforms are additional physical characteristics in product family system. Hence, from the identified set of physical characteristics, the following are among complexity sources and indicators:

- **Number of components:**

Total number of components represents the complexity caused by the size of the product. However, as discussed in section 2.2, research has shown that commonality among components within a product family improves efficiency in both design and production. Hence, the ratio of unique components to total number of components must also be considered as an indicator of product complexity. Accordingly, two indicators can be derived from this source:

  - Total number of components
  - Ratio of unique components

- **Relationship between components:**

Different approaches are used to describe the relationship between components. Given the domain of the analysis, to identify the relationship between components, two different perspectives need to be considered:

  - Design relationship
  - Production relationship

- **Number of unique platforms and number of generated product variants**

These two indicators represent the additional physical characteristics associated with the product family larger system.

On the other hand, extensive characteristics of a product system include the functionality and production of the product [13]. To determine indicators related to the extensive characteristics, an understanding of how features of the product functions and production process can reduce flexibility and cause inefficiency is necessary. Accordingly, indicators considered include:

- **Functional requirements:**

The more functions the product has to perform the higher the level of perceived complexity [17]. According to Salminen and Yassine [9] product complexity is increasing due to the need to continuously develop new generations of products with multiple functions. Two main indicators are derived from this source:

- Priority / importance of functional attributes

The importance of a specific functional attribute is derived by market demand. Additionally, changes in the design of a component in a product will impact product performance. Accordingly, how sensitive end users are to changes in components to meet important functional requirements can impact flexibility levels in design, development and manufacturing.

- Performance standards tolerance level

Performance standards may not cause complexity. However, ranges are set for most performance standards; the tighter the tolerance levels of performance requirements (the smaller the range), the higher the level of perceived complexity and the less flexibility in both development and manufacturing.

- **Number of production paths and usability:**

In production, the level of uncertainty in production scheduling and logistical management is increased, when the number of production paths increase. However, increasing the number of production paths has been considered as an approach in increasing production flexibility. Accordingly, in order to identify the impact of adding production paths to complexity, it is essential to understand the feasibility of each path in producing different types of components within the product family.

By deriving sources and indicators from the established product complexity definition, Question 1.1 in section 1.3 is addressed. The above indicators are categorized into four main dimensions: Structural, Functional, Production and Design. Figure 13 reflects the established product complexity dimensions and indicators.

The indicators are represented through qualitative and quantitative measurements. All measurements are set to be successively increasing variables; meaning that product complexity increases, with the increase in the indicator. The following discusses the established measurements within each dimension, and hence, address Question 1.2 raised in section 1.3.

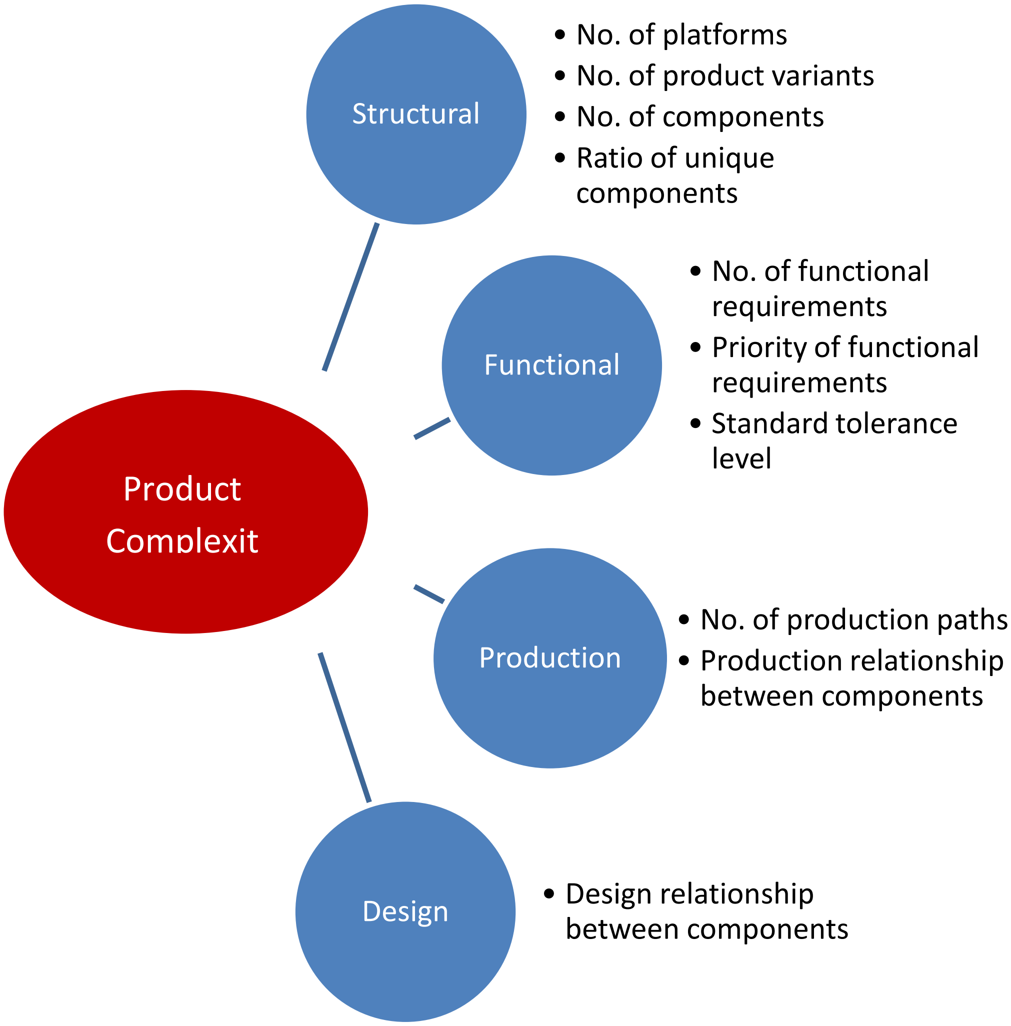


Figure 13: Product Complexity Dimensions and Indicators

Dimension 1: Structural

This dimension is a reflection of the complexity associated with the physical make up of the product family and generated product variants. Four indicators are grouped in this dimension: number of platforms, number of product variants, number of components and ratio of unique components. To represent these indicators two measurements are developed: Product Variety Index and Component Variety Ratio.

1. Product Variety Index

In this approach, product variety is defined as an index that measures fundamental variety within the product family. It includes the number of important design aspects, which would differ from one product to another; such as geometry and size for car tires, memory size for chips and drive train configurations (i.e. right-hand vs. left hand steering) for automobiles. Product Variety Index (PVI) is also defined based on the number of distinct platforms, used components and generated product variants.

Similar to the Model Mix Index established by MacDuffie et al. [1], discussed in section 2.1.2, points / weights for each item is derived by design and production expert ratings about the item's contribution to overall complexity levels. Accordingly, PVI is impacted by the type of product and industry. Given weighted scores are summed, and the resulted PVI is then scaled from 0 to 1.

2. Component Variety Ratio

As mentioned in section 2.2.3, commonality indices are among the most common methods to manage component variety across and within product families and different techniques to measure such ratios can be found in the literature. A commonality index is a metric to assess the degree of commonality within a product family based on different parameters such as number of common components and component costs [60].

When selecting a product platform, two types of sharing is possible: component sharing, where one or more components are exactly common across a product family; and “scaled” sharing, where some attributes of the shared component, such as height or weight, may differ within the product family [3]. Most existing commonality ratios found in the literature are based on exact component sharing, which may be difficult for non-assembled products.

In this research, component variety is measured through the inverse of a Weighted Component Commonality Ratio (WCCR). WCRR is the ratio of common parts to total parts in a product family weighted by unique design aspects (such as geometry and memory size) that may impact the decision of using a specific component. Further, a product is an artifact made of components; each main component can be broken down into several elements and compounds that can be either integrated or assembled [3]. Hence, increasing the commonality among the component elements within a product family can reduce complexity levels. Accordingly, this approach weights each component commonality ratio by the average commonality ratio of its elements. Hence, WCCR allows for “scaled” sharing of components; which is essential, especially for non-assembled products, where commonality may be in the decomposed component, yet design aspects (such as size) can prevent 100% commonality. Accordingly, this measurement partially answers Questions 2.1 and 2.2 raised in section 1.3. For each component i, WCCR can be calculated as:

$$\mathrm{WCCR} = \frac{\mathrm{p_i}}{\mathrm{p}} * \overline{\mathrm{CR}_{\mathrm{p_{ix}}}} * \overline{\mathrm{CR}_{\mathrm{i_e}}} \quad ,$$

$$\text{Where,} \qquad \mathrm{CR}_{\mathrm{p_{ix}}} = {}^{\mathrm{p_{ix}}}\!/_{\mathrm{x}} \, ,$$

$$\mathrm{CR}_{\mathrm{i_e}} = {}^{\mathrm{i_e}}\!/_{\mathrm{i}}$$

(14)

p_i = number of products in the product family using component i

p = total number of products in the product family being analyzed

$\mathrm{CR}_{\mathrm{p}_{\mathrm{ix}}}$ = ratio of number of product variants in the product family using component i with identical design specification x, such as size, height…etc. to total number of unique design specification x within the product family

$\mathrm{CR}_{\mathrm{i}_{\mathrm{e}}}$ = total number of components i in the product family sharing element e to total number of components i used in the product family

The above calculation is averaged for all product components to evaluate the level of commonality within a product family. When WCCR is closer to 1 this reflects higher standardization and less component variety related complexity; accordingly, 1-WCCR will be used to reflect the component variety related complexity.

Dimension 2: Functional

This dimension reflects the complexity associated with the functional and performance attributes of the generated product variants. To address the two related indicators, shown in Figure 13, two measurements are developed:

1. Customer Sensitivity Level

The need to meet a large number of functional requirements can increase the product design and development cycle time, reduce design flexibility and add to the quality control requirements in both the product realization and production stages [86]. The priority of each performance attribute will differ across product families. As mentioned earlier, the importance of a specific functional attribute is derived by market demand and how sensitive end users are to changes in components to meet important functional requirements impacts the level of flexibility in design, development and production. Accordingly, this measurement captures these three elements: number of functional requirements, priority of each requirement and sensitivity of end users.

The first step is to rate the priority (p) of product family performance requirements (i), in which case design engineers along with marketing can identify such rates (p_i). The level of end users sensitivity to changes in a specific component design on a specific performance requirement (c_{ei}), can also be rated by designers; in this approach, a rate from 1 to 5 is used, where 5 reflects high sensitivity to change in design and 1 reflects low sensitivity to change. Accordingly, a Customer Sensitivity Level (CSL) can be identified for each component across all (m) functional requirements by averaging:

$$CSL_e = p_i c_{ei}, \text{ where } \sum_{i=1}^{m} p_i = 1$$

(15)

p_i = Relative importance of performance attribute *i*
c_{ei} = Sensitivity of end user to the impact of changes in component *e* in meeting performance attribute *i*

A component with high CSL is critical in meeting important functional requirements. An average CSL for a product family can be obtained, by averaging the CSL for all components.

2. Specificity Level

Similarly, another important indicator of functional complexity is the degree of function specificity; the tighter the tolerance levels of performance requirements the higher the level of perceived complexity and the less flexibility in both design and manufacturing [86]. Specificity Level (SL) can be obtained for each functional requirement by identifying the upper (U) and lower (L) limit of set standard for each function. SL is a value from 0 to 1; the higher SL, the higher the associated complexity level. To calculate on a product family level, the SL for all functions are averaged.

$$SL = 1 - \frac{U - L}{U}$$

(16)

Dimension 3: Production

Indicators in this dimension are specifically related to the production stage. Three main measurements are applied: Process Variety Ratio is used to represent the number of production paths and usability indicator; while Part Level Index and Interconnectivity Level are used to reflect the production relationship between components.

1. Process Variety Ratio

Among the important production complexity indicators is the number of trajectories – production paths – available per product and its associated components. Although increasing the number of production paths has been used as a strategy to increase flexibility, research has shown that the larger the number possible paths, the higher the level of uncertainty and complexity in production scheduling and logistical management [86]. Accordingly, in order to identify the impact of adding production paths to complexity, it is essential to understand the feasibility of each path in producing different types of components. Such measurement is reflected in the Process Variety Ratio.

If the usage ratios of different processes and production paths across the products manufactured are low, then the complexity of production scheduling and planning is increased. The process commonality ratio considers the ratio of total number of components (i) following a specific production path or work center (w), to total number of work centers (M) that can be used by component (i). Component design specification - such as tire geometry – is a factor in determining the usage ratio of different production paths, accordingly average Commonality Ratio for all unique design specifications can impact the work center commonality ratio calculation.

$$Process\ Commonality\ Ratio\ (PCR) = \frac{i_w}{\sum_{w=1}^{M} i_w} * \overline{CR}_{p_{ix}} \tag{17}$$

$\mathrm{CR}_{\mathrm{p}_{\mathrm{ix}}}$ = ratio of number of product variants in the product family using component i with identical design specification x, such as size, height…etc. to total number of unique design specification x within the product family.

1 – PCR is used to reflect the level of process variety. Accordingly, a lower PCR will reflect higher variety and associated complexity. The average PCR for all components is used to reflect the PCR of a product family.

2. Part Level Index

A large number of components can add to the product development cycle time, inventory and quality control requirements in production, and logistical management requirements in the supply chain. A Bill of Material (BOM) describes the relationship between the end item (final product) and its constituent components, lower level items [87]; components or parts produced first will be at the lowest level of the BOM. As we go upward in the BOM lower level components are assembled or integrated to produce other higher level parts. Accordingly, it is more flexible and less costly, i.e. less complex, to rework a lower level component than a higher level one. Hence, the component level within the BOM can add to its structural complexity.

Based on the number of components and elements per component and the component level in the BOM, a part level index can be established as an indicator of a component's and product's complexity level. Assuming in a BOM the final product has a part level of 1, and part level increases by one as we go lower in the BOM, a Part Level Index (PLI) can be calculated as:

$$\mathrm{PLI} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{e}_{\mathrm{i}}\, \mathrm{BOM}_{\mathrm{i}}}{\left(\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{e}_{\mathrm{i}}\right) \mathrm{BOM}^{\mathrm{Max}}}$$

(18)

Where,

e_{i} = the number of elements or components in level i

$\mathrm{BOM}_{\mathrm{i}}$ = the BOM level of component i

$\mathrm{BOM}^{\mathrm{Max}}$ = is the highest level in the BOM

The Part Level Index is a number from 0 to 1, where the larger the resulted index, the higher the level of product complexity.

3. Interconnectivity Level

Another essential indicator of production complexity is the degree of interrelationship among components. This connectivity relationship between components can help in differentiating between the complexity of assembled and non-assembled products [86]; the complexity of an assembly interconnectivity is less than that of an integrative one (for example chemical bonding), especially in terms of quality control - where an assembled sub-system can be disassembled to meet quality requirements, while the same cannot be applied for an integrative product or sub-product. Accordingly, this measurement also addresses Questions 2.1 and 2.2 in Section 1.3.

The first step in establishing the interconnectivity level is developing the basic physical layout of the product; which includes the basic technology to be used and production process linking components. Once this information is obtained, an interconnectivity matrix can be established to reflect expert ratings on the degree of interconnectivity (integration vs. assembly) of the relationship between each two components. The average of ratings between all components, reflect the overall interconnectivity level within a product family.

Dimension 4: Design

This dimension of product complexity reflects the design relationship between components. Among the most significant design relationship between components, is the coupling level.

1. Coupling Level

Two components are considered coupled if a change made to one of the components will require change to the other component [72]. In order to understand the coupling level between components, it is important to start with developing the physical layout of the product. This would be followed by considering the specification flows among components; specification flows are design information that must be passed between designers to design their respective components, which help teams explicitly describe relationships that couple components. After identifying the specification flows, designers can easily rate the coupling level between components. In this research, the ratings established by Martin and Ishii [72] in Table 3 are followed. The average coupling level for all components is used to reflect the coupling level within a product family.

Table 3: Coupling Level Ratings

Rate	Description
9	High Sensitivity: small change in specification impacts the receiving component
6	Medium-high Sensitivity
3	Medium-low Sensitivity
1	Low Sensitivity: large change in specification is required to impact the receiving component
0	No relationship

Using the specification flow and the above ratings, a coupling matrix can be established between components; where the columns reflect impacting components, the rows reflect impacted components, and each cell in the matrix reflect the rating of the most important specification flow between two components. The average of columns (C) reflects the strength of the component in impacting other components and the average of rows (R) represents the vulnerability of component in being impacted by change in other components.

3.2 Product Complexity Evaluation and Management Approach

This section addresses Questions 1.3 and 1.4 raised in Section 1.3, by establishing an approach to evaluate and manage product complexity within product families. Figure 14 reflects the steps and tools required to achieve this objective.

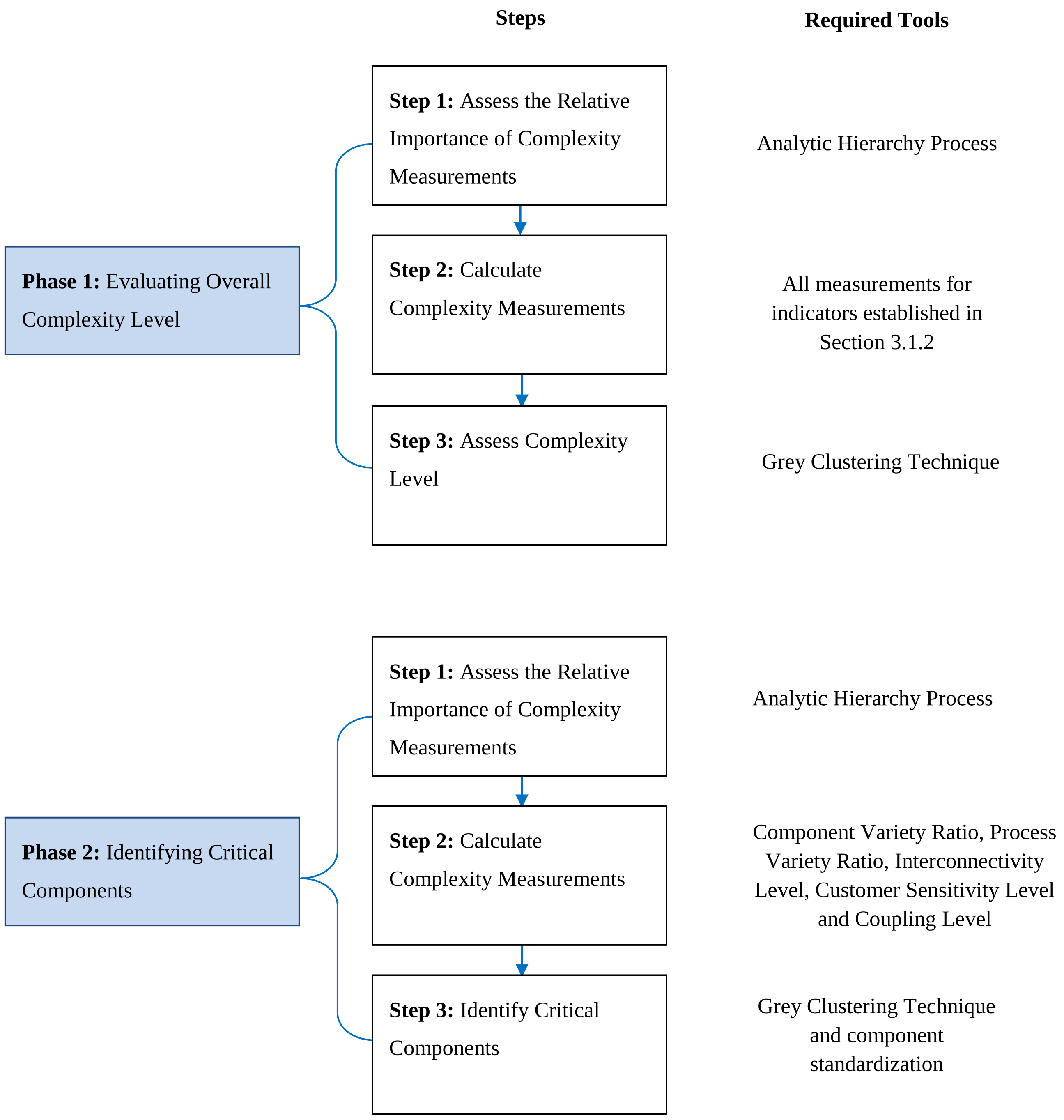


Figure 14: Product Complexity Evaluation Approach

3.2.1 Phase 1: Evaluating Overall Complexity Levels

In this phase of the approach the developed complexity measurements, along with grey clustering, are used to evaluate overall complexity level of a product family design.

Step 1: Assess the Relative Importance of Complexity Measurements

As shown in the previous section, overall complexity level is impacted by different indicators. The importance or relative contribution to complexity levels of each indicator, represented by its established measurement, will differ by the type of product, industry and stage of product's life cycle. In this research relative weights are identified using the same evaluation technique used in Analytic Hierarchy Process (AHP).

AHP is a decision making support method for prioritizing alternatives when multiple criteria need to be considered [88]. AHP has been applied in many different research areas, including product design, supply chain management and data mining. Expert judgments on absolute importance are used to drive the AHP approach, which are used to establish a Pair wise Comparison Matrix (PCM). Pair wise comparison expresses the relative importance of an item versus another; in the PCM each value represents an estimate of the ratio of the weight of the two criteria being compared. Overall relative importance for each item is obtained through the principal eigenvector of the PCM [89].

Step 2: Calculate Complexity Measurements

In this step, the indicators measurements developed in Section 3.1.2 are calculated for the product families being analyzed.

Step 3: Assess Complexity Level

In order to evaluate if a product family is high or low in complexity, relationships between indicators are established using grey clustering and triangular whitening function discussed in Section 2.3. Grey cluster is a method that uses weight functions to classify observations into definable classes. Grey clustering is used when there are different characteristics for a system and an overall classification is difficult to obtain; which coincides with evaluating the complexity levels of a product family given that there are eight different measurements considered. To apply grey clustering, it is important to determine the number of possible complexity level categories, which will be used to classify product families. To compute the degree of membership of $f_j^k(x)$ to the kth class, the following function is used:

$$f_j^k(x) = \begin{cases} 0, & x \notin [a_{k-1}, a_{k+2}] \\ \dfrac{x - a_{k-1}}{\lambda_k - a_{k-1}}, & x \in [a_{k-1}, \lambda_k] \\ \dfrac{a_{k+2} - x}{a_{k+2} - \lambda_k}, & x \in [\lambda_k, a_{k+2}] \end{cases}$$

$$\text{Where, } \lambda_k = \frac{a_k + a_{k+1}}{2}$$

(19)

By applying the relative weights, w_j, determined in Step 1, where$\sum_{j=1}^{m} w_j = 1$; the decision weight parameter for each class can be calculated as:

$$\sigma_k = \sum f_j^k(x_{ij}).\, w_j$$

(20)

Grey clustering classifies the product family, i, into a certain category, by ranking the weight parameters of unit i and selecting the highest among all categories. In other words, the category with the highest σ_k, represents the overall complexity level for the analyzed product family.

3.2.2 Phase 2: Identifying Critical Components

After identifying the complexity level on a product family basis, Critical Components, which are considered as main contributors to complexity, are identified. Steps in Phase 2 are similar to that in Phase 1; however, not all measurements are applicable on a component level. Only five measurements will be considered in this phase of the evaluation approach: Component Variety

Ratio, Process Variety Ratio, Interconnectivity Level, Customer Sensitivity Level and Coupling Level.

Step 1: Assess the Relative Importance of Complexity Measurements

Similar to Step 1, in Phase 1, AHP is used to identify the relative importance of each measurement. It should be noted that not all established measurements are used; hence, a PCM different from that of Phase 1, will be established, resulting in a different principal eigenvector and relative weights.

Step 2: Calculate Complexity Measurements

In this step, the selected developed measurements for indicators in Section 3.1.2 are calculated for each main component identified. The Coupling Level for components will be divided into two measurements: C, which reflects the average strength of the component in impacting other components; and R, reflecting the average vulnerability of the component in being impacted by change in other components.

Step 3: Identify Critical Components

Similar to Step 3 in Phase 1, grey clustering and decision weight parameters are used to evaluate and categorize the complexity level of different components. Components classified in the highest complexity category, are considered as Critical Components.

As shown in Chapter 2, previous research has proven that complex components can lengthen product development cycle, reduce product flexibility and cause production difficulties [16] [1]. Accordingly, identifying Critical Components is an essential first step in managing product complexity levels.

Several of the indicators impacted by component may be difficult to control, such as changing the design and production relationships between components. However, managing complexity levels for a product family can be obtained by standardizing Critical Components as part of the product family platform. The direct impact of standardizing such components will be reflected in several complexity measurements, including: Product Variety Index, Component Variety Ratio and Process Variety Ratio. Additionally, several cost saving opportunities are achieved through standardization, such as reduction in setup costs and inventory, as well as higher economies of scale.

Chapter 4: Case Study

The research approach described in Chapter 3 is applied to evaluate the complexity level of three different product families produced by a tire manufacturing company. Results of this evaluation will be reflected in the following chapter. Due to confidentiality, actual data will not be disclosed. Accordingly, where appropriate, letters and scaled data will be used for illustrative purposes.

All three product families generate vehicle tires produced by the same manufacturing plant, which handles close to 2,000 product sizes. The three product families chosen capture different challenges for product development and manufacturing. Tires in Product Family 1 (PF1) have high commonality in component material but low commonality in geometry; while, Product Family 2 (PF2) has low commonality in both materials and geometry. Product Family 3 (PF3) generates highly customized products that are low in production. It was perceived by both design and production engineers that complexity within PF3 would be the highest.

4.1 Pneumatic Tires

In general, a tire is a flexible, strong rubber casing attached to the rim of a wheel, providing a gripping surface for traction and a cushion for moving vehicles [1, 90]. Most vehicles use pneumatic tires; where air is held under pressure inside the tire. Pneumatic tires contain a variety of rubber compositions, each contribute to the overall performance of the tire; since a tire is a mechanical structure, any rubber component is to be evaluated on how it functions in the system rather than on individual properties [91].

The tire is the only component of the vehicle which makes contact with the road surface with a main function to transmit the forces which drive, brake and guide the vehicle [91]. Absorbing road surface irregularities over a wide range of road material types is also another important function of a tire.

4.2 Pneumatic Tire Structure

A tire consists of several main components and compounds, all with important functions. The Carcass is the most important framework of a tire, which is the entire inner layer of cord fabric. The carcass acts to support air pressure, vertical load and absorb shocks. The Tread must provide wear resistance and be tough and resilient to minimize cuts and cracks and to protect the tire body from bruising impacts [91]. The Belt is a strong reinforcement found between the Tread and the Carcass; it reduces shocks, prevents rips or injury of the tread from reaching the carcass directly, while increasing tread rigidity.

The flexible sidewall protects the carcass and enhances the ride. A tire’s type, size, structure, pattern, manufacturing company, product name and various characters are indicated here. The sidewall may also include a decorative compound as surface layer [91]. Overlay components supports and enhances shape stability, specifically at high speeds.

The bead attaches the tire to the rim and wraps the end of the cord fabric; it is designed to be slightly tight around the rim so that in the case of a sudden drop in inflation pressure, the tire will not fall off the rim. Plies wrap around the bead wire bundles, pass across the tire to wrap around the bead wire bundles on the other side, while, Apex is established on the top of the bead bundles to fill void between plies and turned up ply ends on the outside [92].

The inner liner is made of a layer of rubber that resists air diffusion and replaces the inner tube within a tire. Toe guards protects against chafing by providing a rubber layer between Plies and the wheel rim.

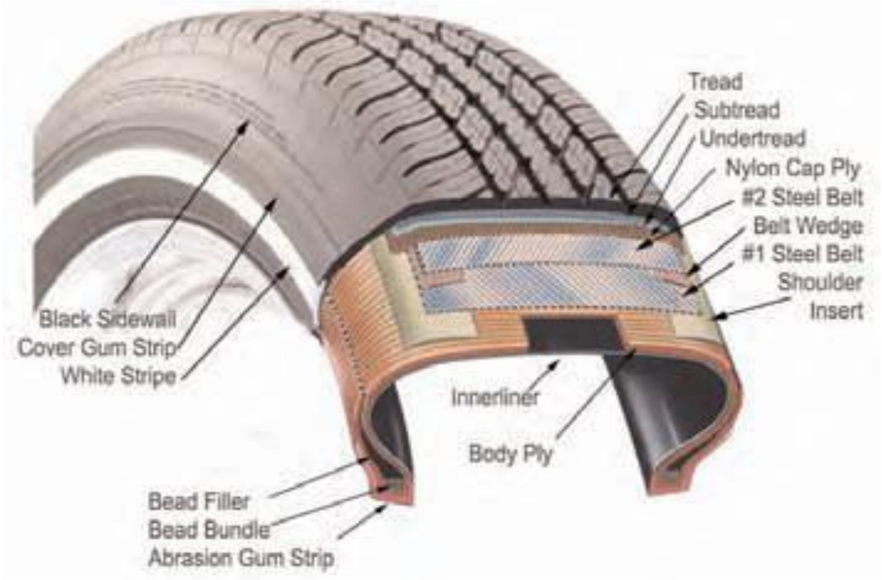


Figure 15: Component of a Tire [93]

4.3 Performance Criteria

Tires must meet necessary performance criteria, each having particular quality standards – which may differ by product line - and testing procedures. The following is the list of performance criteria considered in the case study [93]:

Wear rate (Tread Wear)

Traditionally tested using sets of tires that are driven at prescribed speeds to evaluate wear rate, usually measured in miles of travel per thousandth of an inch of tread depth loss (i.e., miles per mil) or as tread loss per mileage increment (i.e., mils/1000 mi).

Endurance

Endurance testing usually involves loading a vehicle to the maximum specified load and inflation, or more, and driving on a closed road course at a specified schedule of speeds.

Handling: dry, wet and snow

In handling tests, tires are evaluated for response, stability, recovery linearity, on-center-feel, brake in turning, and other characteristics. Tests range from lane change maneuvers to maximum cornering capability.

Ride comfort

A vehicle's perceived ride comfort can be significantly influenced by tires. Tires are evaluated for impact harshness over highway joints and railroad tracks, for damping and bounce memory after road disturbances, plushness (road isolation), nibble (steering wheel oscillations), shake, vibration and other vehicle-specific features.

Rolling resistance

The force necessary to overcome hysteretic losses in a rolling tire is known as rolling resistance. Rolling Resistance is tested by placing load cells in the wheel spindle and measuring the rolling resistance force in the horizontal direction.

Noise

Significant effort goes into designing tire tread patterns and constructions to minimize noise. Using prepared test areas, tire evaluators are able to sense not only airborne pattern noise but also structure-borne noise, which is transmitted through the tire carcass, the wheel and suspension.

4.4 Case Study

The case study focuses on three product families produced by the same plant. Tires within each product family are evaluated using the performance criteria in Section 4.3. However, quality standards and importance of each criterion differs for each product family.

The following are the ten main tire components considered in the analysis: Carcass, Liner, Toe guard, Ply, Bead, Apex, Sidewall, Belt, Overlay and Tread. Each component consists of several elements, such as compounds, wires, fabrics…etc.

Tire size is defined in terms of a combination of rim diameter, aspect ratio and section width. According to experts, tire size is the main aspect of the tire that impacts design and production decisions. For measurements that require subjective ratings, feedback from engineers in design, development and production were sought in order to provide different perspectives. The following table provides some additional information on each product family, noting that numbers are scaled for confidentiality.

Table 4: Case Study Information

	PF1	**PF2**	**PF3**
Number of Tire Sizes	17	8	4
Number of Components	90	49	102
Number of Product Variants	43	8	17
General Description	High component commonality, low size commonality	Low commonality in component and size	Low produced, highly customized
Relative Perceived Complexity Level	Low	Moderate	High

Chapter 5: Research Results

In Chapter 3, phases and steps for evaluating and managing product complexity in a product family were developed. In this chapter, the developed approach is applied on the three product family case studies presented in Chapter 4.

5.1 Phase 1: Evaluating Overall Product Complexity Level

In Phase 1 of the approach, three main steps are applied to identify and evaluate the overall complexity levels of each product family design.

Step 1: Assess the Relative Importance of Complexity Measurements

Overall complexity level is impacted by different indicators, and hence, different measurements are used to quantitatively represent these indicators. As mentioned in Chapter 3, the importance or relative contribution to complexity levels of each indicator, represented by its established measurement, will differ by the type of product, industry and stage of the product life cycle.

To identify the relative value of each measurement for the case study, expert ratings from design and production engineers were sought. Experts were requested to rate each measurement from 1 to 5, where 5 reflects highest impact on product complexity level. The average received ratings and standard deviation are reflected in Table 5.

Table 5: Absolute Expert Ratings of Complexity Measurements

Measurement	Average Rating	Std Dev.
Product Variety Index	1.8	1.03
Component Variety Ratio	2.5	1.27
Process Variety Ratio	4.6	0.55
Product Level Index	4.1	0.99
Interconnectivity Level	3.4	0.89
Customer Sensitivity Level	2.4	0.99
Specificity Level	2.2	0.92
Coupling Level	2.8	1.30

A pair-wise Comparison Matrix (PCM) was established using identified expert ratings. Each value in PCM represents the ratio of the ratings of the two criteria being compared. For example in Figure 16, the PCM value for Component Variety Ratio to Process Variety Ratio is *(highlighted in Figure 16):*

$$^{2.5}/_{4.6} = 0.543$$

	Product Variety Index	**Component Variety Ratio**	**Process Variety Ratio**	**Product Level Index**	**Interconnectivity Level**	**Customer Sensitivity Level**	**Specificity Level**	**Coupling Level**
Product Variety Index	1.000	0.720	0.391	0.439	0.529	0.750	0.818	0.643
Component Variety Ratio	1.389	1.000	0.543	0.610	0.735	1.042	1.136	0.893
Process Variety Ratio	2.556	1.840	1.000	1.122	1.353	1.917	2.091	1.643
Product Level Index	2.278	1.640	0.891	1.000	1.206	1.708	1.864	1.464
Interconnectivity Level	1.889	1.360	0.739	0.829	1.000	1.417	1.545	1.214
Customer Sensitivity Level	1.333	0.960	0.522	0.585	0.706	1.000	1.091	0.857
Specificity Level	1.222	0.880	0.478	0.537	0.647	0.917	1.000	0.786
Coupling Level	1.556	1.120	0.609	0.683	0.824	1.167	1.273	1.000

Figure 16: Complexity Measurements PCM – Phase I

The relative weight (w_j) for each complexity measurement (j) is obtained by calculating the principal eigenvector of PCM. Table 6 reflects the calculated results for w_j.

Table 6: Complexity Measurements Relative Weights – Phase I

Measurement (j)	w_j
Product Variety Index	0.076
Component Variety Ratio	0.105
Process Variety Ratio	0.193
Product Level Index	0.172
Interconnectivity Level	0.143
Customer Sensitivity Level	0.101
Specificity Level	0.092
Coupling Level	0.118
Total	1.000

Step 2: Calculate Complexity Measurements

The results of applying the complexity related measurements introduced in Chapter 3 on the three product families in the case study are reflected in Table 7, and discussed in more details below.

Table 7: Case Study Measurement Results

	PF1	**PF2**	**PF3**
Measurement (j)	x_{1j}	x_{2j}	x_{3j}
Product Variety Index	0.42	0.19	0.36
Component Variety Ratio	88.57	84.63	97.01
Process Variety Ratio	42.5	21.8	70.1
Part Level Index	61	62	58
Interconnectivity Level	5.89	5.89	5.89
Customer Sensitivity	28	29	27
Specificity Level	4	3	3.25
Coupling Level	6.10	6.10	6.10

Product Variety Index

As mentioned in Chapter 3, Product Variety Index (PVI) is a reflection of fundamental variety, based on the mix of different product variants within the product family and associated variety in product platforms, design aspects and components. In the case study, tire size was the design aspect considered as essential in impacting design, development and production decisions. Weights used to calculate PVI were identified by requesting expert ratings on each item in terms of its contribution to overall complexity levels; ratings were requested from 1 (low contribution) to 5 (high contribution). Feedback was received from both design and production perspectives, and average ratings were rounded to identify the points to use for each item:

- 4 points for each tire size
- 3 points for each component
- 2 points for each product variant

Component Variety Ratio

In order to calculate the Component Variety Ratio, the Weighted Component Commonality Ratio (WCCR) is needed for each of the 10 main components. The results of calculating WCCR for each component in each product family is reflected in Appendix A. Results show that PF3 has the highest component variety ratio, followed by PF2 and PF1, which coincides with the perceived type of product families highlighted in Table 4 in Chapter 4.

Process Variety Ratio

Weighted Process Commonality Ratio is calculated using the developed Equation (14) in Chapter 3. This ratio is needed to calculate the Process Variety Ratio; the breakdown of calculations is reflected in Appendix B.

Part Level Index

To measure Part Level Index, the Bill of Material (BOM) for the possible largest size product in each product family is identified (found in Appendix C). The largest possible product is identified by the largest number of components used in each BOM level.

To develop the BOM, the identified 10 main components are broken down to their main elements, which include compounds (Cmpd), wire, fabric…etc. The final product is the cured tire, which is in level 1 of the BOM. Part Level Index is then calculated using Equation (18) in Chapter 3.

Interconnectivity Level

To calculate the Interconnectivity Level, expert feedback from production engineers was provided to illustrate the build sequence, layout and relationship between components. Based on this feedback, production experts were required to rate the interconnectivity level between components. As both Coupling Level and Interconnectivity Level reflect relationship between components, in these case studies both levels used the same ratings introduced in Chapter 3.

Appendix D reflects the feedback provided by production experts, noting that due to confidentiality, not all build sequence and layout information is included. In this case, given that all three product families are of similar product types, Interconnectivity Levels are similar.

Customer Sensitivity Level

In order to calculate Customer Sensitivity Levels using Equation (18), two different ratings were required from design experts. The first required feedback provided relative ratings on the importance of each of the selected eight performance attributes for the different product families. Design engineers were also required to rate from 1 to 5 how sensitive end users are to the impact of change in a component on meeting expected performance attributes. Both ratings, along with calculated Customer Sensitivity Level are provided in Appendix E.

Performance Specificity Level

In order to calculate the Specificity Level for each performance attribute across the product families, ratings from 1 to 5 are provided by design and production experts; where 1 is the lowest specificity level, and 5 is the highest. Ratings received are then used to calculate the average Specificity Level for each product family, which are shown in Table 8.

Table 8: Specificity Level

Performance Attribute	**PF1**	**PF2**	**PF2**
Durability	5	5	5
Tread wear	4	2	3
Dry Performance	3	5	3
Wet Performance	4	4	3
Ride	4	2	4
Rolling Resistance	5	2	1
Winter Performance	3	1	3
Noise	4	3	4
Average	**4**	**3**	**3.25**

Coupling Level

The Coupling Level is the last measurement. In order to understand the coupling level between components, it is important to start with developing the physical layout of the product, followed by considering the specification flows among components. After identifying the specification flows, design engineers can rate the coupling level between components. The specification flow and ratings provided for the case studies are reflected in Appendix F. The average Coupling Level between components, reflect the Coupling Level within the product family.

Step 3: Assess Complexity Level

In this step, the whitening weight function and decision weight parameter discussed in Chapter 3 are applied to identify the overall complexity level for each product family. In order to do so, the possible result range for each measurement must be classified into the appropriate *s* number of classes. In most approaches found in the literature, the number of classes and turning points for each class are identified either arbitrarily or through expert feedback. However, in this case study the measurement and evaluation approach are new concepts for the tire manufacturing company, making it difficult to use expert ratings. To resolve this issue, *k*-means clustering is used to identify the required number of classes and turning points. Appendix G, reflects the usage of Validity measure to assess the resultant *k*-means clusters.

From Appendix G, three classes are used to evaluate overall product complexity levels; low, medium and high. The identified classes and turning points for each class are reflected in Table 9.

Table 9: Grey Classes

Measurement (*j*)	***Low ($a_1 - a_2$)***	***Medium ($a_2 - a_3$)***	***High ($a_3 - a_4$)***
Product Variety Index	(.15-.35)	(.35-.60)	(.60-.85)
Component Variety Ratio	(12-45)	(45-78)	(78-99)
Process Variety Ratio	(5-25)	(25-51)	(51-85)
Part Level Index	(25-45)	(45-65)	(65-85)
Interconnectivity Level	(1.2-3)	(3-6)	(6-8.5)
Customer Sensitivity	(5-15)	(15-34)	(34-64.5)
Specificity Level	(1-1.5)	(1.5-3)	(3-4.5)
Coupling Level	(1.2-3)	(3-6)	(6-8.5)

By applying the triangular whitening weight function and the decision weight parameter from Chapter 3, overall complexity classification for each product family can be obtained; the class with the highest decision weight parameter (σ_k) represents the complexity classification for the product family. From Table 10, PF1 and PF2 can be classified as having medium complexity levels, while PF3 is high in complexity level; which coincides with the perceived complexity level discussed in Chapter 4.

Table 10: Whitening Weight Functions and Decision Weight Parameters – Phase 1

	PF1			PF2			PF3		
Measurement (j)	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3
Product Variety Index	0.51	0.83	0.19	0.60	0.12	0.00	0.69	0.63	0.06
Component Variety Ratio	0.00	0.27	0.96	0.00	0.38	0.91	0.00	0.02	0.18
Process Variety Ratio	0.24	0.90	0.41	0.81	0.51	0.00	0.00	0.31	0.95
Part Level Index	0.13	0.80	0.53	0.10	0.77	0.57	0.23	0.89	0.44
Interconnectivity Level	0.03	0.65	0.68	0.03	0.65	0.68	0.03	0.65	0.68
Customer Sensitivity	0.25	0.91	0.38	0.21	0.89	0.41	0.29	0.94	0.36
Specificity Level	0.00	0.22	0.80	0.00	0.67	0.67	0.00	0.44	0.79
Coupling Level	0.00	0.60	0.73	0.00	0.60	0.73	0.00	0.60	0.74
σk	0.14	**0.68**	0.58	0.24	**0.59**	0.48	0.13	0.53	**0.58**

5.2 Phase 2: Identifying Critical Components

In Phase 2 the Complexity Measurement Framework is applied on a component level to identify Critical Components with highest levels of complexity contribution. Only five of the eight measurements are directly linked to components: Component Variety Ratio, Process Variety Ratio, Interconnectivity Level, Customer Sensitivity Level and Coupling Level. Hence, product complexity levels for components will be evaluated using these five measurements only.

Step 1: Assess the Relative Importance of Complexity Measurements

Similar to Step 1 in Phase 1, the first step is to identify the relative importance of each measurement. The absolute ratings provided by design and production experts in Table 5, are applied for the five selected measurements. Using these ratings, the following PCM is established:

	Component Variety	Process Variety	Interconnectivity Level	Customer Sensitivity	Coupling Level

	Ratio	**Ratio**		**Level**	
Component Variety Ratio	1.000	0.543	0.735	1.042	0.893
Process Variety Ratio	1.840	1.000	1.353	1.917	1.643
Interconnectivity Level	1.360	0.739	1.000	1.417	1.214
Customer Sensitivity Level	0.960	0.522	0.706	1.000	0.857
Coupling Level	1.120	0.609	0.824	1.167	1.000

Figure 17: Complexity Measurement PCM – Phase 2

Using the principal eigenvector, the relative weight (w_j) for each complexity measurement (j) is obtained and reflected in Table 11.

Table 11: Complexity Measurements Relative Weights – Phase 2

Measurement (j)	w_j
Component Variety Ratio	0.159
Process Variety Ratio	0.293
Interconnectivity Level	0.217
Customer Sensitivity Level	0.153
Coupling Level	0.178
Total	1.000

Step 2: Calculate Complexity Measurements

Component Variety Ratio

In order to calculate this ratio, average WCCR for each main component must be calculated, which is reflected in Appendix A. From Tables 12, 13, and 14, Tread and Sidewall are the worst two components for all three product families. However, consideration is needed when evaluating these components, which are highly impacted and customized by tire size. Components following these two components’ ratios are shown as follows: Liner for PF1 and PF3; Belt for PF2 and PF3; and Ply for PF1 and PF2.

Process Variety Ratio

From Tables 12, 13 and 14, Tread is among the top two components with the highest Process Variety Ratios, which also includes Bead for PF1, Apex for PF2 and Belt for PF3. The breakdown of Process Variety Ratio calculations is reflected in Appendix B.

Interconnectivity Level

By understanding the build sequence and interrelationship between components, as shown in Appendix D, an Interconnectivity Level for each component is obtained to reflect the average impact each component has on other components.

Customer Sensitivity Level

As stated in Phase 1, the breakdown of ratings and calculations for Customer Sensitivity Levels is shown in Appendix E. Tables 12, 13 and 14 reflect the average sensitivity level for each related component.

Coupling Level

The Coupling Level between components is reflected in Table 31 in Appendix F. For each component, the averages of columns (C) and of rows (R) are calculated in the table; C reflects the strength of the component in impacting others, while R reflects the vulnerability of the component to the change in others. Both C and R reduce flexibility during the design stage; accordingly, both are used to evaluate the Coupling Level of each component as shown in Tables 12, 13 and 14.

Table 12: Complexity Measurements for PF1 Components

	Liner	Toe guard	Ply	Bead	Apex	Sidewall	Belt	Overlay	Tread
Component Variety Ratio	98.39%	92.78%	97.73%	97.48%	92.56%	98.67%	93.89%	15.27%	99.03%
Process Variety Ratio	0.00%	0.00%	62.97%	84.14%	46.49%	34.22%	9.87%	25.83%	81.97%
Interconnectivity Level	6	5	6	7.5	5	6	5	5	7.5
Customer Sensitivity Level	18.93%	18.30%	28.77%	30.85%	16.06%	23.58%	36.96%	35.32%	44.01%
Coupling Level (C)	6	5	5.4	6.75	7.5	7	5.25	8	4.5
Coupling Level (R)	0	4.5	5.57	7	7.5	7	6	3	7.2

Table 13: Complexity Measurements for PF2 Components

	Liner	Toe guard	Ply	Bead	Apex	Sidewall	Belt	Overlay	Tread
Component Variety Ratio	95.35%	82.38%	95.87%	80.98%	87.78%	99.42%	96.98%	10.95%	97.10%
Process Variety Ratio	0.00%	0.00%	25.56%	0.00%	45.99%	2.00%	31.49%	0.00%	51.52%
Interconnectivity Level	6	5	6	7.5	5	6	5	5	7.5
Customer Sensitivity Level	19.27%	18.96%	30.54%	33.33%	17.10%	24.14%	38.54%	37.07%	43.42%
Coupling Level (C)	6	5	5.4	6.75	7.5	7	5.25	8	4.5
Coupling Level (R)	0	4.5	5.57	7	7.5	7	6	3	7.2

Table 14: Complexity Measurements for PF3 Components

	Liner	Toe guard	Ply	Bead	Apex	Sidewall	Belt	Overlay	Tread
Component Variety Ratio	97.18%	92.71%	96.87%	96.86%	97.14%	97.88%	97.18%	96.03%	98.93%
Process Variety Ratio	36.83%	79.07%	62.51%	75.73%	67.76%	54.61%	80.91%	78.96%	80.72%
Interconnectivity Level	6	5	6	7.5	5	6	5	5	7.5
Customer Sensitivity Level	18.93%	18.52%	29.35%	30.89%	16.47%	23.81%	37.07%	35.45%	42.49%
Coupling Level (C)	6	5	5.4	6.75	7.5	7	5.25	8	4.5
Coupling Level (R)	0	4.5	5.57	7	7.5	7	6	3	7.2

Step 3: Identify Critical Components

Similar to Step 3 in Phase 1, the whitening weight function and decision weight parameter are applied on a component level to identify complexity levels. For consistency in evaluation, three classes are used: low, medium and high. Results of the whitening function for each main component in the three product families are reflected in Table 15, Table 16 and Table 17. As highlighted in the results tables, Bead, Sidewall and Tread are among the components with high Complexity Levels for each of the three product families. For PF2, Apex is also shown to have high complexity levels. PF3, which is the product family with the highest complexity level, also has Apex, Belt and Overlay as components with high complexity levels.

Table 15: Results of Weight Functions for PF1

	Liner			**Toe guard**			**Ply**			**Bead**			**Apex**		
	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3
Component Variety Ratio	0.00	0.02	0.14	0.00	0.17	0.63	0.00	0.03	0.20	0.00	0.04	0.22	0.00	0.27	0.55
Process Variety Ratio	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.48	0.87	0.00	0.02	0.50	0.13	0.82	0.40
Interconnectivity Level	0.00	0.63	0.71	0.26	0.88	0.47	0.00	0.63	0.71	0.00	0.25	0.86	0.26	0.88	0.47
Customer Sensitivity Level	0.63	0.71	0.11	0.65	0.68	0.10	0.22	0.89	0.40	0.13	0.84	0.46	0.75	0.57	0.03
Coupling Level (C)	0.00	0.63	0.71	0.26	0.88	0.47	0.15	0.78	0.56	0.00	0.44	0.88	0.00	0.25	0.86
Coupling Level (R)	0.00	0.00	0.00	0.38	1.00	0.47	0.11	0.76	0.50	0.00	0.38	0.94	0.00	0.25	0.86
σ_k	0.10	**0.36**	0.32	0.27	**0.65**	0.38	0.08	**0.69**	0.67	0.02	0.34	**0.76**	0.21	**0.65**	0.62

	Sidewall			**Belt**			**Overlay**			**Tread**		
	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3
Component Variety Ratio	0.00	0.01	0.12	0.00	0.14	0.53	0.50	0.07	0.00	0.00	0.00	0.08
Process Variety Ratio	0.47	0.89	0.21	0.64	0.15	0.00	0.70	0.63	0.02	0.00	0.06	0.56
Interconnectivity Level	0.00	0.63	0.71	0.26	0.88	0.47	0.26	0.88	0.47	0.00	0.25	0.86
Customer Sensitivity Level	0.43	0.95	0.75	0.00	0.70	0.63	0.00	0.73	0.59	0.00	0.51	0.85
Coupling Level (C)	0.00	0.38	0.94	0.19	0.81	0.53	0.00	0.13	0.57	0.38	1.00	0.35
Coupling Level (R)	0.00	0.38	0.94	0.00	0.63	0.71	0.77	0.55	0.00	0.00	0.33	0.99
σ_k	0.20	0.68	**0.69**	0.28	**0.62**	0.50	0.48	**0.62**	0.30	0.07	0.39	**0.73**

Table 16: Results of Weight Functions for PF2

	Liner			**Toe guard**			**Ply**			**Bead**			**Apex**		
	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3
Component Variety Ratio	0.00	0.10	0.40	0.00	0.44	0.86	0.00	0.08	0.36	0.00	0.48	0.83	0.00	0.30	0.98
Process Variety Ratio	0.00	0.00	0.00	0.00	0.00	0.00	0.71	0.62	0.01	0.00	0.00	0.00	0.14	0.83	0.49
Interconnectivity Level	0.00	0.63	0.71	0.26	0.88	0.47	0.00	0.63	0.71	0.00	0.25	0.86	0.26	0.88	0.47
Customer Sensitivity Level	0.61	0.73	0.12	0.63	0.72	0.12	0.14	0.85	0.45	0.03	0.78	0.54	0.70	0.62	0.06
Coupling Level (C)	0.00	0.63	0.71	0.26	0.88	0.47	0.15	0.78	0.56	0.00	0.44	0.88	0.00	0.25	0.86
Coupling Level (R)	0.00	0.00	0.00	0.38	1.00	0.47	0.11	0.76	0.50	0.00	0.38	0.94	0.00	0.25	0.86
σ_k	0.09	**0.37**	0.36	0.27	**0.70**	0.42	0.28	**0.73**	0.47	0.00	0.39	**0.72**	0.20	0.66	**0.72**

	Sidewall			**Belt**			**Overlay**			**Tread**		
	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3
Component Variety Ratio	0.00	0.00	0.05	0.00	0.05	0.26	0.34	0.00	0.00	0.00	0.05	0.25
Process Variety Ratio	0.07	0.00	0.00	0.54	0.80	0.15	0.00	0.00	0.00	0.00	0.71	0.62
Interconnectivity Level	0.00	0.63	0.71	0.26	0.88	0.47	0.26	0.88	0.47	0.00	0.25	0.86
Customer Sensitivity Level	0.41	0.98	0.73	0.00	0.65	0.69	0.00	0.69	0.64	0.00	0.53	0.83
Coupling Level (C)	0.00	0.38	0.94	0.19	0.81	0.53	0.00	0.13	0.57	0.38	1.00	0.35
Coupling Level (R)	0.00	0.38	0.94	0.00	0.63	0.71	0.77	0.55	0.00	0.00	0.33	0.99
σ_k	0.08	0.42	**0.61**	0.25	**0.79**	0.51	0.25	**0.41**	0.30	0.07	0.59	**0.77**

Table 17: Results of Weight Functions for PF3

	Liner			**Toe guard**			**Ply**			**Bead**			**Apex**		
	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3
Component Variety Ratio	0.00	0.05	0.25	0.00	0.17	0.63	0.00	0.06	0.27	0.00	0.06	0.27	0.00	0.05	0.25
Process Variety Ratio	0.39	0.96	0.28	0.00	0.13	0.65	0.00	0.48	0.87	0.00	0.20	0.76	0.00	0.37	0.99
Interconnectivity Level	0.00	0.63	0.71	0.26	0.88	0.47	0.00	0.63	0.71	0.00	0.25	0.86	0.26	0.88	0.47
Customer Sensitivity Level	0.63	0.71	0.11	0.65	0.69	0.10	0.19	0.88	0.42	0.13	0.84	0.46	0.73	0.59	0.04
Coupling Level (C)	0.00	0.63	0.71	0.26	0.88	0.47	0.15	0.78	0.56	0.00	0.44	0.88	0.00	0.25	0.86
Coupling Level (R)	0.00	0.00	0.00	0.38	1.00	0.47	0.11	0.76	0.50	0.00	0.38	0.94	0.00	0.25	0.86
σ_k	0.21	**0.65**	0.42	0.27	**0.69**	0.58	0.08	**0.69**	0.71	0.02	0.39	**0.85**	0.17	0.48	**0.75**

	Sidewall			**Belt**			**Overlay**			**Tread**		
	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3	f_j^1	f_j^2	f_j^3
Component Variety Ratio	0.00	0.03	0.18	0.00	0.05	0.25	0.00	0.08	0.35	0.00	0.00	0.09
Process Variety Ratio	0.00	0.65	0.69	0.00	0.09	0.60	0.00	0.13	0.66	0.00	0.09	0.60
Interconnectivity Level	0.00	0.63	0.71	0.26	0.88	0.47	0.26	0.88	0.47	0.00	0.25	0.86
Customer Sensitivity Level	0.42	0.96	0.74	0.00	0.69	0.64	0.00	0.73	0.60	0.00	0.55	0.80
Coupling Level (C)	0.00	0.38	0.94	0.19	0.81	0.53	0.00	0.13	0.57	0.38	1.00	0.35
Coupling Level (R)	0.00	0.38	0.94	0.00	0.63	0.71	0.77	0.55	0.00	0.00	0.33	0.99
σ_k	0.06	0.61	**0.83**	0.09	0.58	**0.63**	0.19	0.47	**0.54**	0.07	0.40	**0.74**

Identifying critical components is a main and essential first step in managing complexity levels. Not all sources of product complexity can be easily controlled. For example it is difficult to adjust the Coupling and Interconnectivity Levels between two components. However, standardizing critical components as part of the product platform can significantly help manage overall product complexity levels and related cost impact.

Sidewall and Tread were identified among the critical components for PF1, however, given the nature of these two components, standardization will not be possible as they are customized based on tire size. Bead is another critical component identified for PF1. Within the 43 product variants in PF1 there are 5 Beads (BE1,…,BE5), with different Component Variety Ratios as shown in Figure 18. Table 18 reflects the allocation of the 5 Beads across the 43 product variants and 17 tire sizes, noting that tire size is the main design aspect that impacts the usage of component types. The table also reflects the unit tire cost for each of the 5 Beads.

According to feedback from design experts, BE1 and BE2 are interchangeable. In addition, given that Product Variants (PV) 6 and 7 are similar in size with PV8, PV9 and PV10, BE4 can be replaced with BE1. Both changes not only save costs through reducing setups and unit costs, but will also improve complexity levels of PF1, by improving the overall Component Variety Ratio for Bead from 97.48% to 93.91% and improve the product's family Product Variety Index from 0.42 to 0.40.

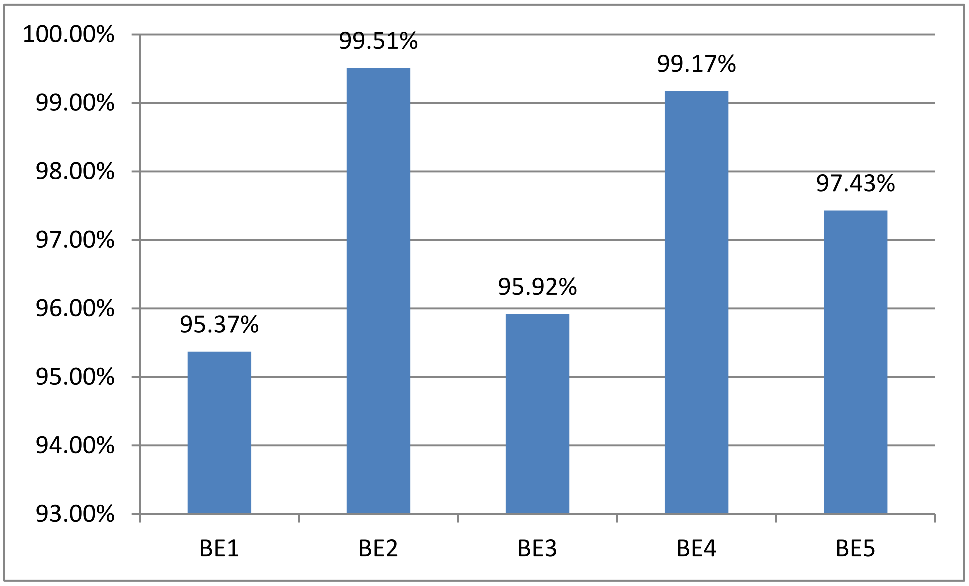


Figure 18: PF1 Bead Component Variety Ratios

Table 18: Bead Usage in PF1

Product Variant	Tire Size	BE1	BE2	BE3	BE4	BE5
PV1	**TS1**			**x**		
PV2	**TS1**			**x**		
PV3	**TS2**			**x**		
PV4	**TS2**			**x**		
PV5	**TS2**			**x**		
PV6	**TS3**				**x**	
PV7	**TS3**				**x**	
PV8	**TS3**	**x**				
PV9	**TS3**	**x**				
PV10	**TS3**	**x**				
PV11	**TS4**	**x**				
PV12	**TS5**	**x**				
PV13	**TS5**	**x**				
PV14	**TS5**	**x**				
PV15	**TS6**		**x**			
PV16	**TS6**		**x**			
PV17	**TS6**		**x**			
PV18	**TS7**		**x**			
PV19	**TS7**		**x**			
PV20	**TS7**		**x**			
PV21	**TS8**	**x**				
PV22	**TS8**	**x**				
PV23	**TS9**		**x**			
PV24	**TS9**		**x**			
PV25	**TS9**		**x**			
PV26	**TS10**	**x**				
PV27	**TS10**	**x**				
PV28	**TS11**	**x**				
PV29	**TS12**	**x**				
PV30	**TS13**			**x**		
PV31	**TS13**			**x**		
PV32	**TS13**			**x**		
PV33	**TS13**			**x**		
PV34	**TS14**			**x**		
PV35	**TS14**			**x**		
PV36	**TS14**			**x**		
PV37	**TS15**			**x**		
PV38	**TS15**			**x**		
PV39	**TS15**			**x**		
PV40	**TS15**			**x**		
PV41	**TS16**					**x**
PV42	**TS17**					**x**
PV43	**TS17**					**x**
Unit Tire Cost		**1.12**	**1.12**	**0.51**	**1.09**	**1.13**
Set-up Cost		0.17	0.17	0.05	0.17	0.17
Machine Cost		0.29	0.29	0.08	0.29	0.29
Labor Cost		0.16	0.16	0.04	0.16	0.16
Material Cost		0.50	0.50	0.32	0.47	0.50

5.3 Summary

A complexity measurement framework is developed and used along with grey clustering techniques to evaluate the product complexity levels of different product family designs and identify Critical Components that are main contributors to complexity levels. A case study of three product families produced by a tire manufacturing company was used to demonstrate the applicability of the proposed evaluation approach.

Overall complexity levels for the product families were evaluated during Phase 1 of the approach. In Phase 2, evaluation within the product families were conducted to identify Critical Components. A Critical Component identified for PF1 was further analyzed to identify possible standardization opportunities to manage complexity.

The results of the analysis coincided with the perceived complexity level of both design and production experts. Additionally, the approach and research helped highlight new sources of product complexity, previously not considered by the company, and introduced a new method to identify cost saving opportunities.

Chapter 6: Contributions and Recommendations

In this dissertation, a method to evaluate product complexity levels of product family designs is developed and tested. Additionally, a new method to determine possible platform components, by identifying Critical Components, that are most likely contributors to complexity, is recommended as an approach to managing complexity levels.

In this chapter, a review of the research objectives and proposed approach is presented, along with answers to the research questions introduced in Chapter 1. The resulting contributions and limitations of the research are then summarized in section 6.2, followed by opportunities for future research in section 6.3.

6.1 Research Summary

As discussed in Chapter 1, the main objective of this research is to develop a measurement framework and evaluation approach to assess the product complexity levels of product family designs. To achieve this objective, a definition of product complexity is established by understanding the impact of complexity on the product and product family systems throughout product design, development and production. Indicators of product complexity were derived from the established definition, by identifying physical and extensive characteristics of the product and product family systems that can cause complexity.

Product complexity indicators are grouped into four main dimensions: Structural, Functional, Production and Design. Leveraging the work of earlier research in different areas and analyzing the data for three product families provided quantitative representation and measurements for the identified indicators. Eight main measurements are used in the framework: (1) Product Variety Index reflects the variety within the product family structure by weighting the impact of variety in products, platforms, design aspects and components; (2) Component Variety Ratio is a measurement to reflect the ratio of unique components, by considering scaled sharing of components within the product family; (3) Process Variety Ratio indicates the feasibility of using different production paths given different design aspects; (4) Interconnectivity Levels represents the production interrelationship between components; (5) Product Level Index reflects the relationship between components and final product through BOM levels; (6) Customer Sensitivity Level measures the level of end user sensitivity to the impact of change in components on performance attributes impacted by the attributes relative importance; (7) Specificity Level indicates the rigidity caused by the specified performance standard range; and (8) Coupling Level is an indicator of the sensitivity of one component to the change in the design of another.

Using grey clustering, the developed measurements are applied across product families to evaluate product complexity levels. The evaluation methodology is also applied within product families, on a component level, to identify Critical Components as main contributors to complexity levels. Identifying Critical Components is the first step in managing product complexity through standardization.

A case study of three product families, with a total of 68 product variants (tires) was used to test and validate the approach. Producing tires requires several integrative and assembly processes; choosing such a product helps generalize the measurement and evaluation approach by considering the nature of both assembled and non-assembled products. Results coincided with perceived levels of complexity within the tire manufacturing company. Additionally, the research helped highlight new sources of complexity that were not previously considered by the company.

One of the main lessons learned from the case study application, is that levels of complexity, sources of complexity and importance of each source are perceived differently from both design and production. Hence, integrating these perspectives is necessary to provide a comprehensive overview of product complexity and its impact. Additionally, the applicable indicators and related measurements may differ if the analysis is focused solely on a specific stage of the product life cycle; if the analysis is limited to design and development, then indicators related to Production Dimension will not be applicable.

The case study application also showed the need for consistent, reliable and complete information from different aspects of design, development and production. The proposed framework facilitates the integration of such information to accommodate the required inputs to different measurements.

Another essential lesson learned from the case study relates to the sensitivity of the final complexity level to changes to the weights given to complexity measurements and the pre-specified cluster turning points. Analysis showed that changes in both these elements results in slight changes in the values of the decision parameters, but rarely changes the actual classification; while, changes in weights has a larger impact on classification change. Additionally, the classification for PF3 seems to be the most impacted by the change, unlike the classifications for PF2 and PF1.

Different types and combinations of change were conducted to test the sensitivity levels, Figure 19, Figure 20 and Figure 21 illustrate some of the analysis conducted. Figure 19 reflect the impact of change to weight assigned to a specific measurement, while Figure 20 and Figure 21 reflect the impact of change to the cluster turning points – in Figure 20 the analysis is conducted by changing the center of each cluster and impacting the thresholds accordingly and in Figure 21 changes in the value of a3 (which is the turning point between medium and high classification) is tested. All three figures show that change in classification only occurred to PF3.

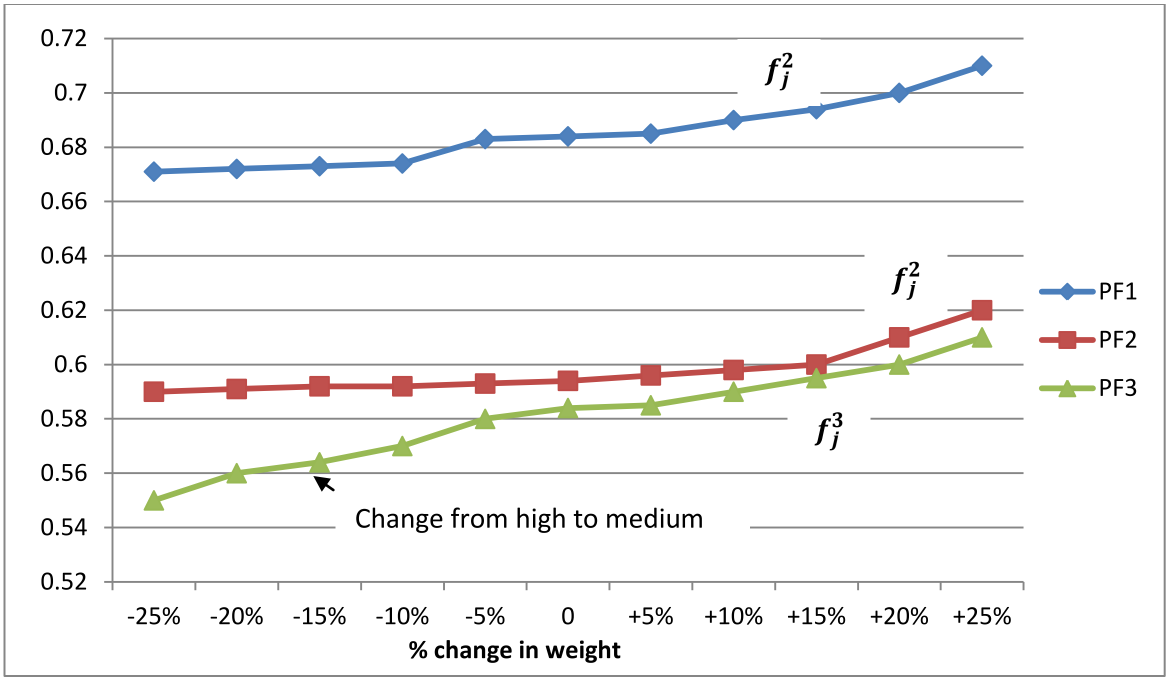


Figure 19: Impact of Change in Measurement Weight

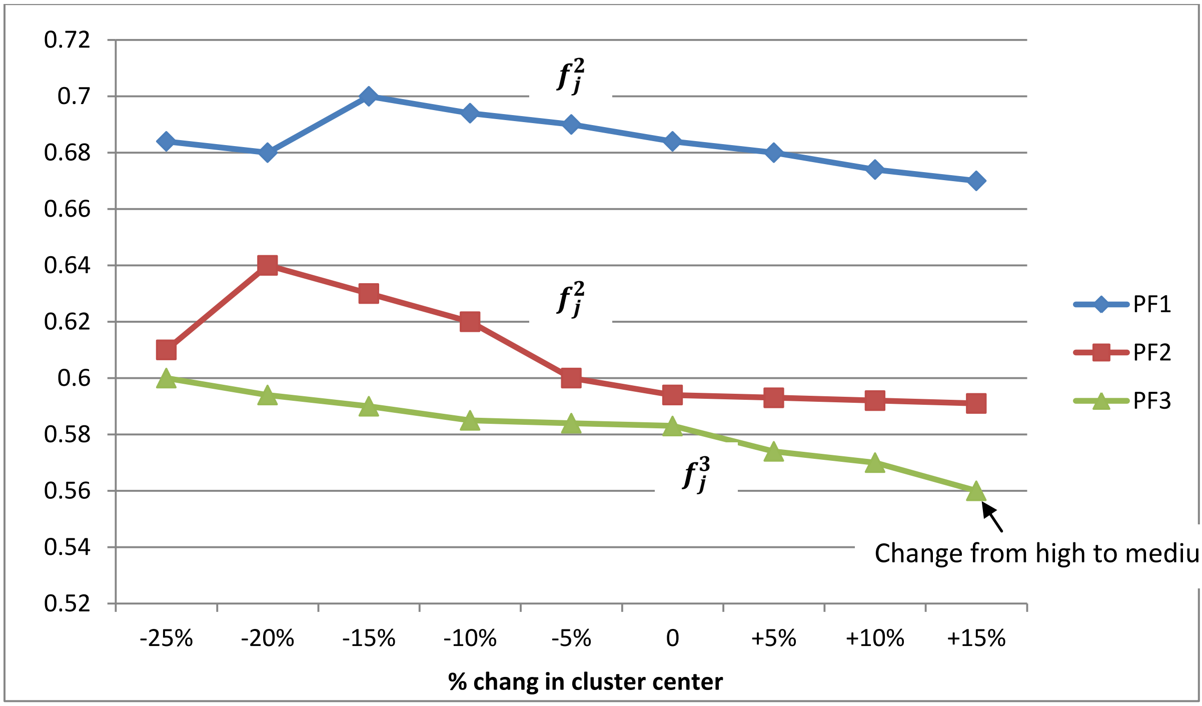


Figure 20: Impact of Change in Cluster Turning Points (1)

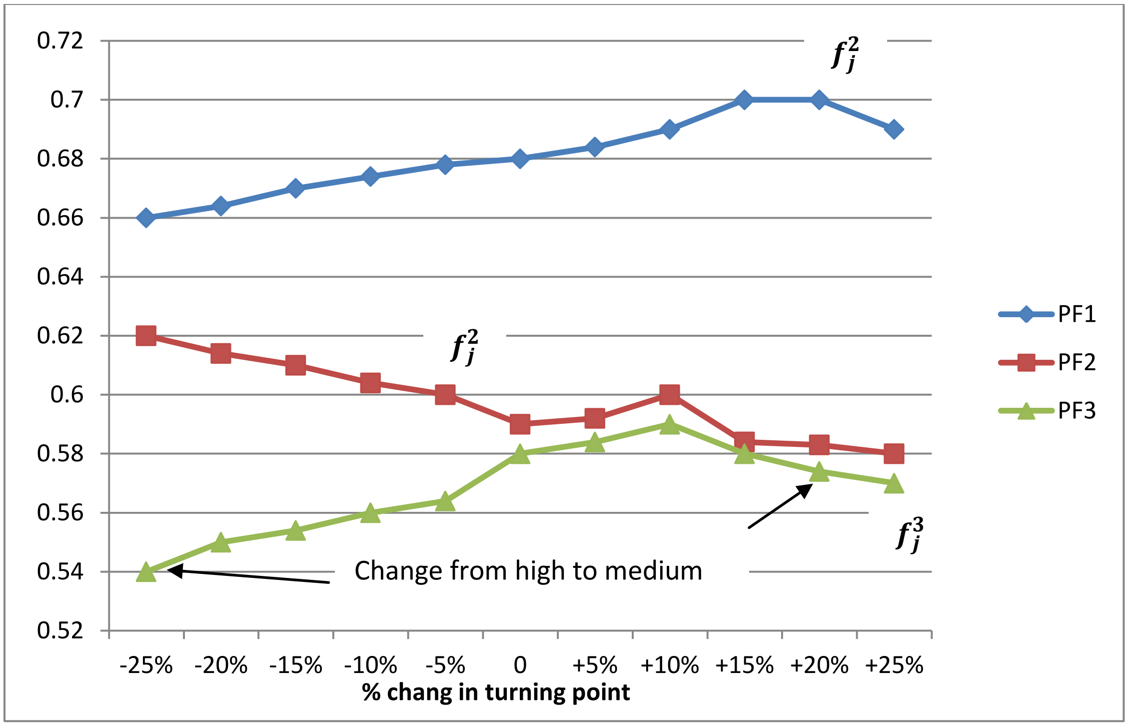


Figure 21: Impact of Change in Cluster Turning Points (2)

Two main research problems, along with several sub-questions, were raised in Chapter 1:

Problem 1: *How can design and development engineers be supported in evaluating product family design and managing the associated impact of product complexity?*

Problem 2: *How does the nature of non-assembled products impact product complexity?*

To address the first problem, sources of product complexity had to be identified and measured. The established measurement framework was then evolved to allow for evaluating different product family designs and identifying Critical Component. Hence, addressing this problem was achieved by answering the four related questions raised in Chapter 1.

Question 1.1: *What sources and indicators of product complexity should be considered when evaluating a product family design?*

Question 1.2: *How can the identified indicators (from Q1.1) be quantitatively represented in a complexity measurement framework?*

Question 1.3: *How can a product complexity measurement framework be used to evaluate product family design?*

Question 1.4: *How can measurement and evaluation results be used to manage the impact of product complexity?*

To answer the first question, a product complexity definition was put forward in Chapter 3, by identifying three main elements: (1) The system being analyzed (product family and generated product variants); (2) Domain of the analysis; and (3) The impact of complexity on the system. Indicators are derived by understanding the physical and extensive characteristics of the system that can lead to product complexity. Measurements and quantitative representations are established for each indicator in Chapter 3, leading to the complexity measurement framework and an answer to the second question of Problem 1.

A total of eight measurements were identified for the indicators. The analysis of a single product family would lead to different complexity levels for each measurement. Hence, an approach to provide an overall product complexity level for the product family is needed, which is achieved through Step 3 in Phase 1 of the evaluation approach developed in Chapter 3. In Section 5.1, AHP is applied in Step 1 in Phase 1 of the evaluation approach, to identify relative priority weights for each measurement. While Step 3 uses grey clustering techniques to calculate the decision weight parameter for each cluster, and identify the overall complexity level classification for the analyzed product family designs. Hence, answering the third question of Problem 1.

Earlier research, highlighted in Section 3.2.2, has shown that components with high complexity levels (Critical Components) can lengthen product development cycle, reduce product flexibility and cause production difficulties. Accordingly, focusing on indicators applicable on a component level, and using the same evaluation approach as that in Phase 1, Critical Components within the product family are identified. To identify such Critical Components for the case studies, steps in Phase 2 in section 5.2 are followed. Similar to Phase 1, AHP is used to identify the relative importance of each measurement, while grey clustering is used to provide an overall complexity level for each analyzed component. Standardizing such critical components, support managing associated product complexity within the product family, and hence, providing an answer the forth question in Problem 1.

To address the second problem, it is essential to understand the nature of non-assembled products, where the final product is a result of an integrative relationship between its components and large capital investments for retooling production is essential. By understanding the relationship between components, an added measurement is established: Interconnectivity Level. In this measurement, the layout, sequence and relationship rating between components are identified, as shown in Section 5.1, Step 2. Additionally, the nature of non-assembled products highlighted the need to consider scaled commonality ratios in both Component and Process Variety Ratios. This accordingly led to answering the two questions shown below related to Problem 2.

Question 2.1: *What are the product complexity sources for non-assembled products?*

Question 2.2: *How can product complexity for non-assembled products be incorporated in the complexity measurement framework?*

6.2 Research Contributions and Limitation

The main contribution of this research is the development of an approach that enables the evaluation of product families' complexity levels and supports the management of product complexity and related impact. Moreover, the results of this research have provided a general comprehensive definition of product complexity along with the identification of different complexity sources and indicators throughout different stages of the product's life cycle.

Through complexity definition, and derived indicators and measurement framework, a gap in existing research is filled, subsequently supporting companies in managing product complexity levels. A Complexity Management Tool (CMT) is also developed to support design engineers in evaluating and managing product complexity. CMT calculates indicators' measurements and evaluates complexity levels of different product families and components, resulting in identifying Critical Components and highlighting cost saving opportunities through standardization. The steps to follow are shown in Figure 26 in Appendix H.

The research also contributes in the area of re-designing product families and platforms by developing a new method to identify possible component platforms. Additionally, by using the case study in Chapter 4 to support the research, the nature of both assembled and non-assembled products are captured in the approach.

To successfully evaluate product complexity levels, the proposed method requires complete and accurate design and production related information. It also requires information that reflects design and production team perception and ratings. Unfortunately, all product data and knowledge is not always available, accurate and complete; while certain biases can impact results. Accordingly, there is always some uncertainty associated with the data and information used as inputs. Additionally, given the required type of information needed, the method cannot be applied during early product design and development stages.

Relying on clustering techniques for evaluation is another limitation; the proposed research method is sensitive to the number of classes and turning points for each class. Selecting such variables requires some degree of subjectivity; it may require trial and error, along with the analyst's intuition and experience with the approach, measurements and products.

A main assumption in the complexity management approach is that identified Critical Component can be standardized. Although component commonality, which is an important objective for platform architecture, is part of the complexity measurement framework, other factors must also be considered when identifying platform components. Standardizing components must be balanced with the objective of optimizing the individuality of generated product variants to avoid internal competition and meet market demands.

6.3 Future Research Opportunities

A large proportion of all product costs are determined at early design stages and much of this cost is incurred during assembly [8]. Accordingly, significant cost saving and operational efficiency enhancement opportunities can be obtained if product complexity levels are managed from the early product design and realization stage. However, the type of information required for the proposed approach can only be applied on fully developed product families. For future study, the complexity measurement and evaluation approach will be adapted to allow the use of limited design and production information, along with historical data to support design decisions to systematically mange complexity levels from early design stage.

Furthermore, contributions of this research can be expanded to designing new product families and platform architectures. Chapter 1 highlighted the need to identify optimum level of variety in product offerings given the associated costs of complexity and of complexity from other sources – as shown in Figure 1. This research supports the evaluation of existing product family designs and identifying possible platform components. By adapting the approach to allow early application, and incorporating other platform development techniques and optimization tools to overcome previously mentioned limitation of the proposed method, the approach can support designing product families with optimum balance between generated product variants and complexity levels.

Chapters 1, 2 and 3 indicated the impact of product complexity on efficiency and costs. Accordingly, in addition to the above mentioned extension of research in product design, the contribution of the proposed approach can be extended to different stages of a product's life cycle, by incorporating different efficiency measurements as well as cost estimation and allocation techniques to reflect the impact of complexity management.

Clustering must be performed such that it is valid and rigorous. Hence, selecting the appropriate number of clusters and threshold for each cluster is not a trivial process. As mentioned in

Chapter 2, there are different clustering techniques in the literature. For future study, a fuzzy clustering technique will be investigated. In an attempt to give a clearer understanding of the underlying structure and relationship between complexity indicators, results and impacts of using fuzzy techniques will be evaluated against that of grey clustering.

Glossary

Analytic Hierarchy Process (AHP): A decision making support method for prioritizing alternatives when multiple criteria need to be considered.

Bill of Material (BOM): Describes the relationship between the end item (final product) and its constituent components, lower level items.

Commonality Index: A metric to assess the degree of commonality within a product family based on different parameters.

Component Variety Ratio: A measurement to reflect the ratio of unique components in a product family, by considering scaled sharing of components.

Coupling Level: An indicator of the sensitivity of one component to the change in the design of another.

Critical Components: Components with high product complexity levels; considered main contributors to complexity in a product family design.

Customer Sensitivity Level: A measurement of the level of end user sensitivity to the impact of change in components on performance attributes impacted by the attributes relative importance.

Grey Cluster: A method that uses weight functions to classify observations into definable classes.

Grey Theory: A method that makes full use of known information in a system to decrease unknown information.

Interconnectivity Level: A measurement that uses expert ratings to represents the production interrelationship between components.

k-mean Clustering: A method of clustering data points into a predefined K number of clusters; it aims to minimize the sum of squared distance between points and the cluster center of interest.

Modular Architecture: Type of product family architecture, where the platform is established based on a collection of common product components.

Non-assembled Products: A final product that is a result of an integrative relationship between its components – e.g. glass and petroleum products.

Pair wise Comparison Matrix (PCM): A matrix in which each value expresses the relative importance of an item versus another.

Process Variety Ratio: A measurement that indicates the feasibility of using different production paths given different design aspects.

Product: An artifact made of components; each main component can be broken down into several elements.

Product Complexity: All physical and extensive characteristics of the product family and generated product variants that reduce flexibility and cause inefficiencies throughout the different stages of the product's life cycle.

Product Family: Group of related product variants that share common product platform.

Product Level Index: A measurement that reflects the relationship between components and final product through BOM levels.

Product Platform: A set of elements – components, manufacturing process, assembly steps and / or technology – that are common in a set of products.

Product System: A system that functionally include physical and extensive characteristics and timely to include different phases of the product's life cycle.

Product Variants: Different products derived from same platform architecture to meet demand of different market niches.

Product Variety Index: A measurement that reflects the fundamental variety within a product family, based on the mix of different product variants and associated variety in product platforms, design aspects and components.

Specificity Level: A measurement indicating the rigidity caused by specified standard range for different performance attributes.

Validity Measure (for k-mean clustering): A measure to identify the ideal value of k, by considering both the sum squared distance from point to the cluster centers (intra-cluster distance) and the distance between the cluster centers themselves (inter-cluster distance).

Weighted Component Commonality Ratio: A ratio of shared / common components in a product family to overall components, scaled by both design aspects and the usage ratio of component elements.

Appendix A: Calculation of Component Variety Ratio

This appendix shows the calculation of the Component Variety Ratio, by presenting the breakdown calculation for the Weighted Component Commonality Ratio (WCCR), as calculated in the below equation, for all three product families in the case study, using the below equation. It should be noted, that the tables reflect averages for each of the elements for the entire product family. Hence, the column “Average WCCR” is not merely the multiplication of the other three columns.

$$Component\ Variety\ Ratio = 1 - WCCR$$

$$\mathrm{WCCR} = \frac{\mathrm{p_i}}{\mathrm{p}} * \overline{\mathrm{CR}_{\mathrm{p}_{\imath x}}} * \overline{\mathrm{CR}_{\imath_\mathrm{e}}} \quad ,$$

$$\text{Where, } \mathrm{CR}_{\mathrm{p_{ix}}} = {}^{\mathrm{p_{ix}}}/_{\mathrm{x}}\,,$$

$$\mathrm{CR}_{\mathrm{i_e}} = {}^{\mathrm{i_e}}/_{\mathrm{i}}$$

Where,

$\mathrm{p_i}$ = number of products in the product family using component i

p = total number of products in the product family being analyzed

$\mathrm{CR}_{\mathrm{p_{ix}}}$ = ratio of number of product variants in the product family using component i with identical design specification x, such as size, height…etc. to total number of unique design specification x within the product family

$\overline{\mathrm{CR}_{\mathrm{p}_{\imath x}}}$ = average of the Commonality Ratio for all unique design specifications considered for the product family

$\mathrm{CR}_{\mathrm{i_e}}$ = total number of components i in the product family sharing element e to total number of components i used in the product family

$\overline{\mathrm{CR}_\mathrm{e}}$ = average Commonality Ratio for all elements e used by component i.

Table 19: Component Variety Ratio for PF1

	Average WCCR	**Average** $\frac{\overline{p_1}}{p}$	**Average** $\overline{CR_{p_{1x}}}$	**Average** $\overline{CR_{1_e}}$
Carcass	0.08%	2.24%	3.57%	N/A
Liner	1.61%	3.23%	8.01%	89.87%
Toe Guard	7.22%	11.11%	42.53%	50.84%
Ply	2.27%	5.03%	8.87%	69.89%
Bead	2.52%	10.00%	10.00%	37.42%
Apex	7.44%	9.09%	29.47%	81.65%
Sidewall	1.33%	2.47%	4.94%	100.00%
Belt	6.11%	9.20%	22.13%	77.40%
Overlay	84.73%	92.41%	100.00%	83.39%
Tread	0.97%	2.00%	3.59%	92.68%
PF Average WCCR	**11.43%**			
Comp Variety Ratio	**88.57%**			

Table 20: Component Variety Ratio for PF2

	Average WCCR	**Average** $\frac{\overline{p_1}}{p}$	**Average** $\overline{CR_{p_{1x}}}$	**Average** $\overline{CR_{1_e}}$
Carcass	0.48%	6.25%	7.69%	N/A
Liner	4.65%	10.00%	12.31%	86.54%
Toe Guard	17.62%	33.33%	41.03%	46.79%
Ply	4.13%	10.63%	10.38%	87.60%
Bead	19.02%	33.33%	33.33%	83.87%
Apex	12.22%	20.00%	24.62%	93.75%
Sidewall	0.58%	9.50%	10.15%	90.00%
Belt	3.02%	9.17%	10.26%	72.30%
Overlay	89.05%	100.00%	100.00%	80.00%
Tread	2.90%	6.25%	7.69%	85.21%
PF Average WCCR	**15.37%**			
Comp Variety Ratio	**84.63%**			

Table 21: Component Variety Ratio for PF3

	Average WCCR	**Average** $\frac{\overline{p_1}}{p}$	**Average** $\overline{CR_{p_{1x}}}$	**Average** $\overline{CR_{1_e}}$
Carcass	0.74%	3.59%	17.31%	N/A
Liner	2.02%	4.76%	19.84%	32.78%
Toe Guard	7.29%	20.00%	29.17%	19.06%
Ply	3.13%	7.73%	18.00%	58.14%
Bead	3.14%	9.09%	21.21%	44.55%
Apex	2.86%	7.14%	17.86%	24.52%
Sidewall	2.82%	10.95%	16.67%	33.57%
Belt	2.82%	10.95%	16.67%	33.57%
Overlay	3.97%	18.33%	20.83%	9.90%
Tread	1.07%	3.33%	16.67%	47.31%
PF Average WCCR	**2.99%**			
Comp Variety Ratio	**97.01%**			

Appendix B: Calculation of Process Variety Ratio

This appendix shows the calculation of the Process Variety Ratio, by presenting the breakdown calculation for the Process Commonality Ratio (PCR) for all three product families in the case study, using equation presented in Chapter 3. It should be noted, that tables below reflect averages for each of the elements in the equation for the entire product family. Hence, the column "Average PCR" is not the multiplication of the other two columns.

$$Process\ Variety\ Ratio = 1 - PCR,$$

$$\text{Process Commonality Ratio (PCR)} = \frac{\mathrm{i_w}}{\sum_{\mathrm{w}=1}^{\mathrm{M}} \mathrm{i_w}} * \overline{\mathrm{CR}}_{\mathrm{p_{ix}}}$$

Table 22: Process Variety Ratio for PF1

PF1	**Average PCR**	$\frac{\mathrm{i_w}}{\sum_{\mathrm{w}=1}^{\mathrm{M}} \mathrm{i_w}}$	**Average** $\overline{\mathrm{CR}_{\mathrm{p_{ix}}}}$
Carcass	20.73%	30.34%	50.24%
Liner	100.00%	100.00%	100.00%
Toe Guard	100.00%	100.00%	100.00%
Ply	37.03%	42.58%	43.57%
Bead	15.86%	41.35%	21.28%
Apex	53.51%	59.67%	83.80%
Sidewall	65.78%	85.83%	71.16%
Belt	90.13%	93.00%	91.85%
Overlay	74.17%	85.41%	82.66%
Tread	18.03%	27.02%	28.34%
PF Average PCR	**57.52%**		
Process Variety Ratio	**42.48%**		

Table 23: Process Variety Ratio for PF2

PF2	**Average PCR**	$\frac{\mathrm{i}_\mathrm{w}}{\sum_{\mathrm{w}=1}^{\mathrm{M}} \mathrm{i}_\mathrm{w}}$	**Average** $\overline{\mathrm{CR}_{\mathrm{p}_{\mathrm{ix}}}}$
Carcass	38.90%	48.00%	59.54%
Liner	100.00%	100.00%	100.00%
Toe Guard	100.00%	100.00%	100.00%
Ply	74.44%	79.25%	78.77%
Bead	100.00%	100.00%	100.00%
Apex	54.01%	60.50%	74.92%
Sidewall	98.00%	98.00%	98.00%
Belt	68.51%	89.67%	72.36%
Overlay	100.00%	100.00%	100.00%
Tread	48.48%	54.25%	51.85%
PF Average PCR	**78.23%**		
Process Variety Ratio	**21.77%**		

Table 24: Process Variety Ratio for PF3

PF3	**Average PCR**	$\frac{\mathrm{i}_\mathrm{w}}{\sum_{\mathrm{w}=1}^{\mathrm{M}} \mathrm{i}_\mathrm{w}}$	**Average** $\overline{\mathrm{CR}_{\mathrm{p}_{\mathrm{ix}}}}$
Carcass	16.13%	35.49%	38.27%
Liner	63.17%	98.06%	63.27%
Toe Guard	20.93%	44.60%	39.93%
Ply	37.49%	61.93%	43.27%
Bead	24.27%	51.93%	46.60%
Apex	32.24%	57.71%	41.04%
Sidewall	45.39%	73.27%	54.93%
Belt	19.09%	58.27%	29.93%
Overlay	21.04%	69.93%	29.93%
Tread	19.28%	39.93%	29.93%
PF Average PCR	**29.90%**		
Process Variety Ratio	**70.10%**		

Appendix C: Part Level Index Calculation

The following three figures represent the BOM level for each product family in the case studies, by considering the largest possible product variant within the product family; larger in terms of number of components and related elements. The BOM is necessary to calculate the Part Level Index (PLI) for each product family.

$$\mathrm{PLI} = \frac{\sum_{i=1}^{N} e_i \, \mathrm{BOM}_i}{\left(\sum_{i=1}^{N} e_i\right)\mathrm{BOM}^{\mathrm{Max}}}$$

Where,

e_i = the number of elements or components in level i

BOM_i = the BOM level of component i

$\mathrm{BOM}^{\mathrm{Max}}$ = is the highest level in the BOM

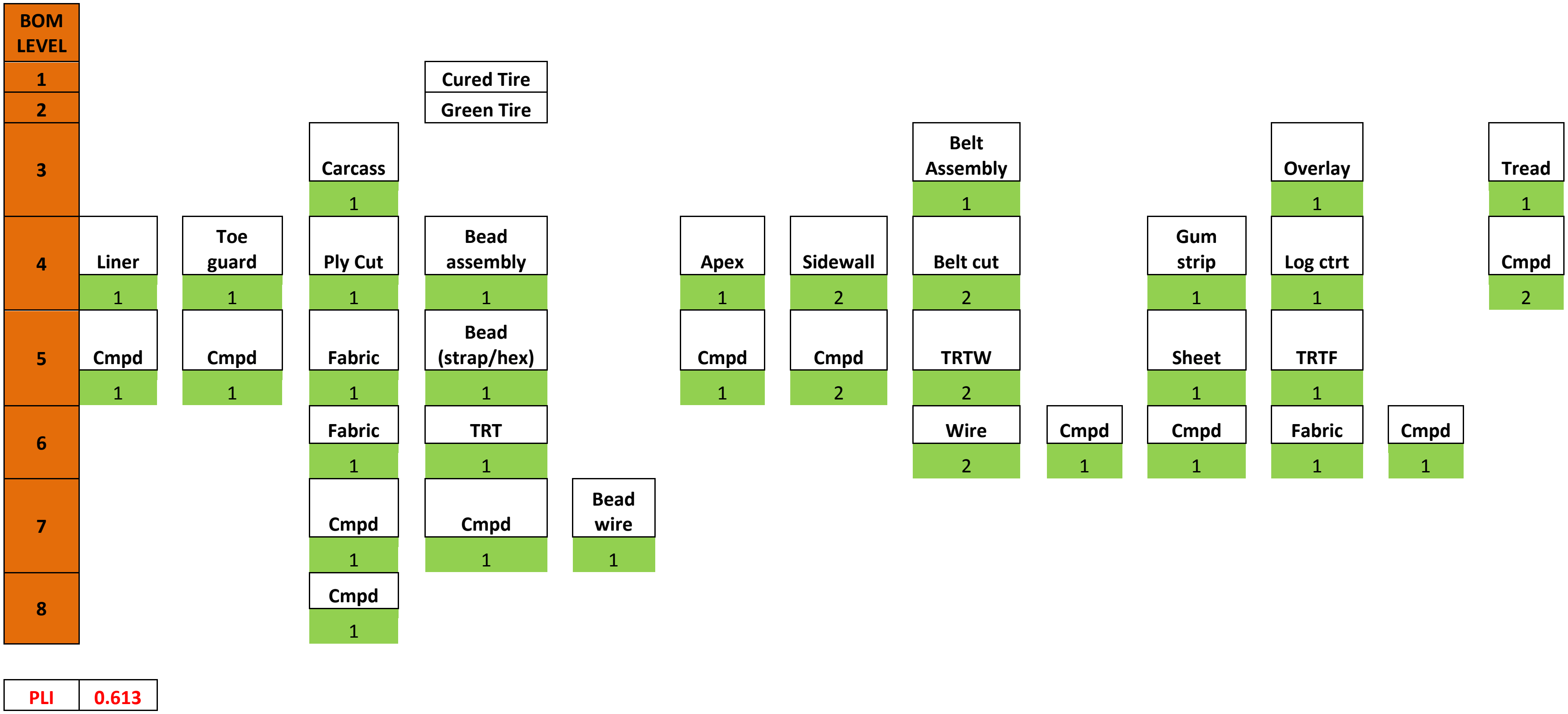


Figure 22: BOM for PF1

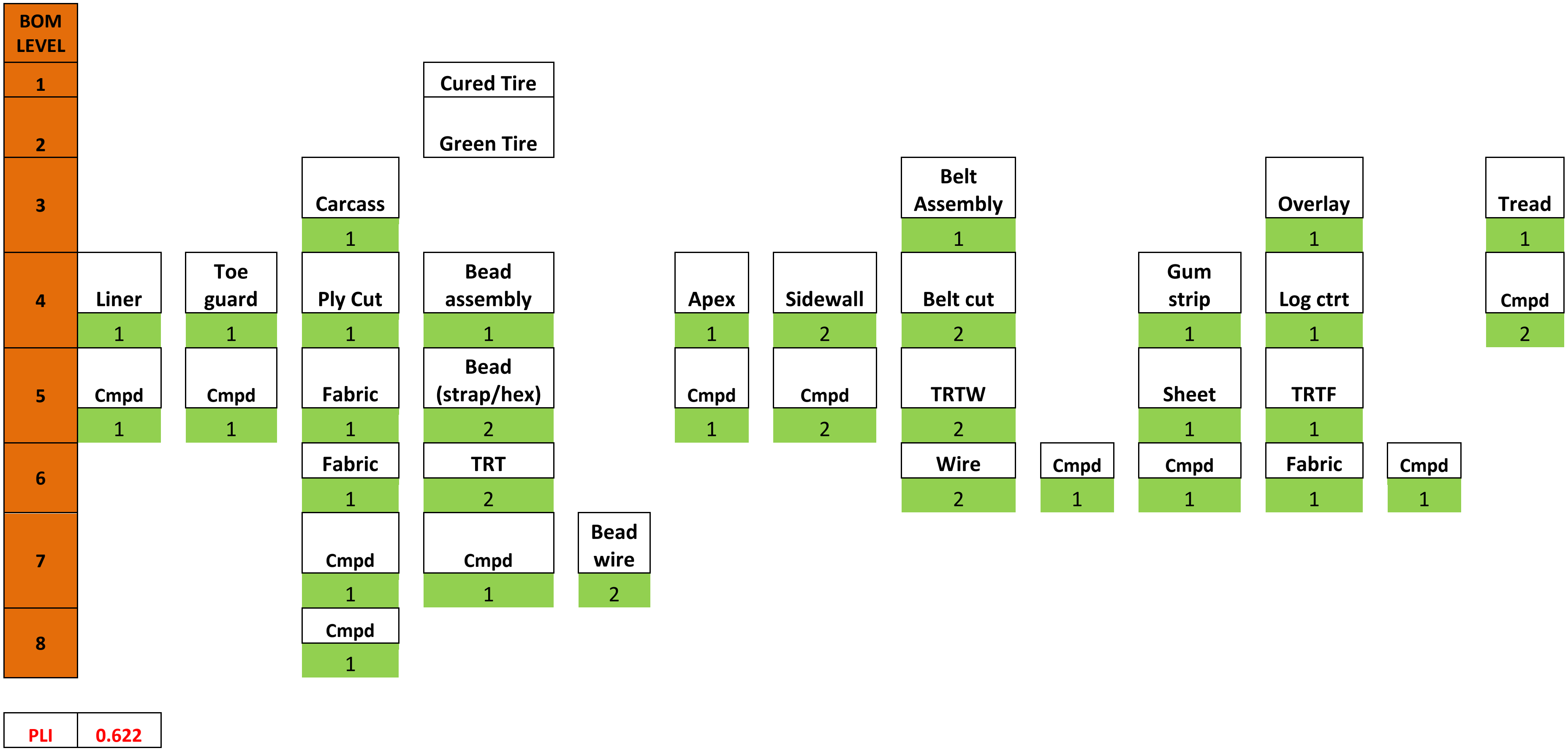


Figure 23: BOM for PF2

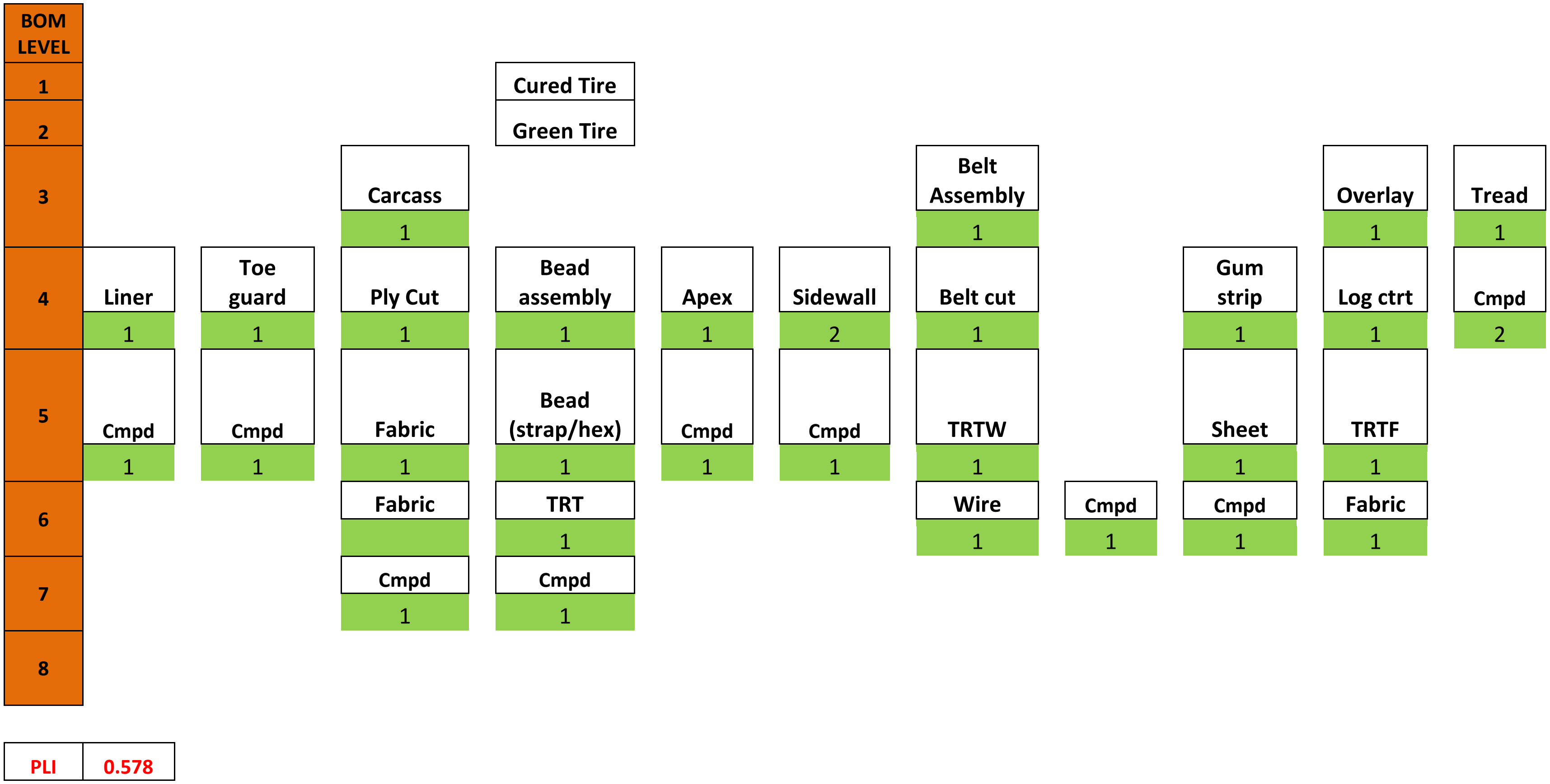


Figure 24: BOM for PF3

Appendix D: Interconnectivity Level Calculation

To establish the Interconnectivity Level between components, build sequence, layout and expert ratings on interrelationship is needed. The following matrix reflects this required information for the three case studies, noting that limited information is provided on build sequence and layout due to confidentiality.

For each component, an average Interconnectivity Level is calculated and used for analysis in Phase 2. The average Interconnectivity Level for all components is used to reflect the level within the product families. Given that all three product families are of similar product type, they have similar Interconnectivity Levels

	Info	Level	Info	Level	Info	Level	Info	Level	Info	Level	Info	Level	Info	Level	Info	Level	Info	Level	Info	Level
	Carcass		**Liner**		**Toe guard**		**Ply**		**Bead**		**Apex**		**Sidewall**		**Belt**		**Overlay**		**Tread**	
Carcass			applied to drum green process	3 9	green process	9	green process	9	green process	9	green process	9	green process	9	green process	9	green process	9	green process	9
Liner					applied to drum	1														
Toe guard							applied to drum	3												
Ply									stapled	6										
Bead											applied to drum	1								
Apex													simul. Appl.	3						
Sidewall															applied to drum	1				
Belt																	applied to B&T	1		
Overlay																			simul. Appl.	6
Tread																				
Average				**6**		**5**		**6**		**7.5**		**5**		**6**		**5**		**5**		**7.5**

PF Interconnectivity Level 5.89

Figure 25: Interconnectivity Level Matrix

Appendix E: Customer Sensitivity Level

The required two marketing and design ratings to calculate Customer Sensitivity Levels are reflected in Table 25 and Table 26. Both ratings are based on average received feedback. The end user sensitivity rating is based on a scale from 1 (low sensitivity) to 5 (high sensitivity).

Remaining tables in this appendix calculate the Customer Sensitivity Levels across components for each product family. The average across all components, reflect the Customer Sensitivity Level within the product family.

$$CSL_e = p_i c_{ei}, \text{ where } \sum_{i=1}^{m} p_i = 1$$

p_i = Relative importance of performance attribute *i*

c_{ei} = Sensitivity of end user to the impact of changes in component *e* in meeting performance attribute *i*

Table 25: Relative Importance of Performance Attributes

Performance Attribute	**PF1**	**PF2**	**PF3**
Durability	0.150	0.227	0.172
Tread wear	0.160	0.091	0.138
Dry Performance	0.100	0.227	0.103
Wet Performance	0.150	0.136	0.103
Winter Performance	0.080	0.045	0.103
Ride	0.100	0.091	0.138
Rolling Resistance	0.160	0.091	0.103
Noise	0.100	0.091	0.138
TOTAL	1	1	1

Table 26: End User Sensitivity to Change

	Durability	Tread wear	Dry Performance	Wet Performance	Winter Performance	Ride	Rolling Resistance	Noise
Liner	2.167	1.250	1.250	1.250	1.250	1.583	1.833	1.250
Toe guard	1.833	1.250	1.500	1.300	1.300	1.500	1.500	1.500
Ply	2.833	2.000	2.667	2.167	1.917	2.833	2.000	2.083
Beads	3.000	1.667	3.167	2.500	1.667	3.167	2.667	1.833
Apex	2.200	1.100	1.100	1.100	1.100	1.300	1.100	1.100
Sidewall	2.300	1.630	1.810	1.710	1.560	2.090	1.990	1.910
Belts	3.500	2.833	3.333	2.833	2.500	3.167	2.833	2.500
Overlay	3.417	2.583	3.167	2.833	2.167	2.917	2.667	2.667
Tread	3.500	4.083	3.500	4.083	3.667	2.333	3.667	2.667

Table 27: Customer Sensitivity Level for PF1

	Durability	Tread wear	Dry Performance	Wet Performance	Winter Performance	Ride	Rolling Resistance	Noise	CSL_e
Liner	0.325	0.200	0.125	0.188	0.100	0.158	0.293	0.125	0.189
Toe guard	0.275	0.200	0.150	0.195	0.104	0.150	0.240	0.150	0.183
Ply	0.425	0.320	0.267	0.325	0.153	0.283	0.320	0.208	0.288
Beads	0.450	0.267	0.317	0.375	0.133	0.317	0.427	0.183	0.309
Apex	0.330	0.176	0.110	0.165	0.088	0.130	0.176	0.110	0.161
Sidewall	0.345	0.261	0.181	0.257	0.125	0.209	0.318	0.191	0.236
Belts	0.525	0.453	0.333	0.425	0.200	0.317	0.453	0.250	0.370
Overlay	0.513	0.413	0.317	0.425	0.173	0.292	0.427	0.267	0.353
Tread	0.525	0.653	0.350	0.613	0.293	0.233	0.587	0.267	0.440
								Average	0.281

Table 28: Customer Sensitivity for PF2

	Durability	Tread wear	Dry Performance	Wet Performance	Winter Performance	Ride	Rolling Resistance	Noise	CSL_e
Liner	0.492	0.114	0.284	0.170	0.057	0.144	0.167	0.114	0.193
Toe guard	0.417	0.114	0.341	0.177	0.059	0.136	0.136	0.136	0.190
Ply	0.644	0.182	0.606	0.295	0.087	0.258	0.182	0.189	0.305
Beads	0.682	0.152	0.720	0.341	0.076	0.288	0.242	0.167	0.333
Apex	0.500	0.100	0.250	0.150	0.050	0.118	0.100	0.100	0.171
Sidewall	0.523	0.148	0.411	0.233	0.071	0.190	0.181	0.174	0.241
Belts	0.795	0.258	0.758	0.386	0.114	0.288	0.258	0.227	0.385
Overlay	0.777	0.235	0.720	0.386	0.098	0.265	0.242	0.242	0.371
Tread	0.795	0.371	0.795	0.557	0.167	0.212	0.333	0.242	0.434
								Average	0.292

Table 29: Customer Sensitivity for PF3

	Durability	Tread wear	Dry Performance	Wet Performance	Winter Performance	Ride	Rolling Resistance	Noise	CSL_e
Liner	0.374	0.172	0.129	0.129	0.129	0.218	0.190	0.172	0.189
Toe guard	0.316	0.172	0.155	0.134	0.134	0.207	0.155	0.207	0.185
Ply	0.489	0.276	0.276	0.224	0.198	0.391	0.207	0.287	0.293
Beads	0.517	0.230	0.328	0.259	0.172	0.437	0.276	0.253	0.309
Apex	0.379	0.152	0.114	0.114	0.114	0.179	0.114	0.152	0.165
Sidewall	0.397	0.225	0.187	0.177	0.161	0.288	0.206	0.263	0.238
Belts	0.603	0.391	0.345	0.293	0.259	0.437	0.293	0.345	0.371
Overlay	0.589	0.356	0.328	0.293	0.224	0.402	0.276	0.368	0.355
Tread	0.603	0.563	0.362	0.422	0.379	0.322	0.379	0.368	0.425
								Average	0.271

Appendix F: Coupling Level

In order to calculate the Coupling Level between components, design engineers identified the specification flow between components. After this, design engineers rated the coupling level between components for the identified specification flow using the ratings found in Table 30. The specification flow and average ratings are reflected in Table 31. It should be noted that due to confidentiality limited information is provided on the specification flow.

Table 30: Coupling Level Rating System

Rate	Description
9	**High Sensitivity**: new compound, die, treatment (at least **two** things change)
6	**Medium-high Sensitivity**: new compound, die, treatment (only **one** thing change)
3	**Medium-low Sensitivity**: same part number, different geometry
1	**Low Sensitivity**: tire building machine adjustment (same component just a different set)

Table 31: Coupling Level Matrix

		Impacted Components																		
		Info	Level	Info	Level	Info	Level	Info	Level	Info	Level	Info	Level	Info	Level	Info	Level	Info	Level	
		Liner		Toe guard		Ply		Bead		Apex		Sidewall		Belt		Overlay		Tread		C
The Impacting Components	Liner																	Gauge	6	6.0
	Toe guard					Ending	3	Geometry	6			Geometry	6							5.0
	Ply			Ending	3			Gauge	6	Ending	6	Ending	6					Ending	6	5.4
	Bead			Geometry	3	Geometry	6			Type	9	Type	9							6.8
	Apex			Geometry	6	Ending	6	Type	9			Type	9							7.5
	Sidewall			Ending	6	Gauge	6											Cmpd	9	7.0
	Belt					Geometry	6					Geometry	6			Geometry	3	Geometry	6	5.3
	Overlay					Geometry	6							Treat	9			Geometry	9	8.0
	Tread					Gauge	6					Gauge	6	Gauge	3	Gauge	3			4.5
	R		0		4.5		5.571		7		7.5		7		6		3		7.2	

Appendix G: Identifying Grey Classifications

Most approaches found in the literature use expert ratings to identify the appropriate number of classifications and their turning points for grey clustering application. However, the measurements established in this research are new for the company used in the case studies. Accordingly, expert ratings cannot be used, and more quantitative approach is needed to identify the clusters; which lead to the usage of k-means clustering.

k-means is a method of clustering data points into a predefined K number of clusters; it aims to minimize the sum of squared distance between points and the cluster center of interest. The main disadvantage of this method is that the number of clusters (*k*) must be a supplied parameter. There are many criteria and methods to evaluate and determine cluster validity found in the literature. All of these have a common goal to find clustering that result in a well separated compact cluster.

In this research, k-means is applied on the complexity measurement results of a sample of product families and related components. The results of the k-means clustering helps identify the appropriate number of grey classes, which will coincide with the best number of k clusters. Additionally, the center for each cluster is used to identify the turning points for the grey classes, where the cluster center will be set to equal λ_k, in the whitening weight function (discussed in Chapter 3).

The Validity measure developed by Ray et. al [94], is used to identify the ideal value of k, by considering both the sum squared distance from point to the cluster centers (intra-cluster distance) and the distance between the cluster centers themselves (inter-cluster distance). The general objective is to minimize the intra-cluster distance, while maximizing the inter-cluster distance. In other words, the objective is to minimize the overall Validity Measure:

$$Validity = \frac{intra}{inter},$$

$$intra = \frac{1}{N}\sum_{i=1}^{k}\sum_{x \epsilon C_i}\|x - z_i\|^2$$

$$inter = \min\left(\|z_i - z_j\|^2\right), i = 1,2, \dots, K - 1$$

$$j = i + 1, \dots, K$$

(21)

Where N is the number of pixels in the cluster, K is the number of clusters, and z_i is the cluster centre of cluster C_i.

Given how each complexity measurement has a different domain, clustering is done for each measurement separately; the lowest possible k for all measurements will be used to identify the number of classes. For all sample results, the analysis starts with K = 2. $K_{Max} = 6$, reflects the final number of clusters to consider in the validity test.

The lowest possible value of k differs for each measurement. In the 206 data points used to cluster Component Variety Ratio, k = 3 resulted in the lowest Validity value of 0.106 (k =2 has a validity value of 0.113, while k = 4 had a validity value of 0.111). Similarly, k = 3 resulted in the lowest validity value for Product Variety Index. The remaining measurements had higher k values. Accordingly, only 3 classes will be used in the grey cluster analysis.

Appendix H: Product Complexity Management Tool

The Excel based CMT requires users to input design, production and cost data for the product family(s) being analyzed; to include the components breakdown of each product, design specifications, alternative possible production paths, and breakdown of manufacturing costs. Users are also required to input several ratings and weights, where necessary.

The user can choose to evaluate and compare the complexity of different product families, in which case the tool will identify critical product family categorized as high in complexity. The critical product family is further analyzed to identify Critical Components. Once a critical component is identified, the tool establishes a construction matrix to help identify possible standardization across the product variants within the family, while reflecting cost saving opportunities

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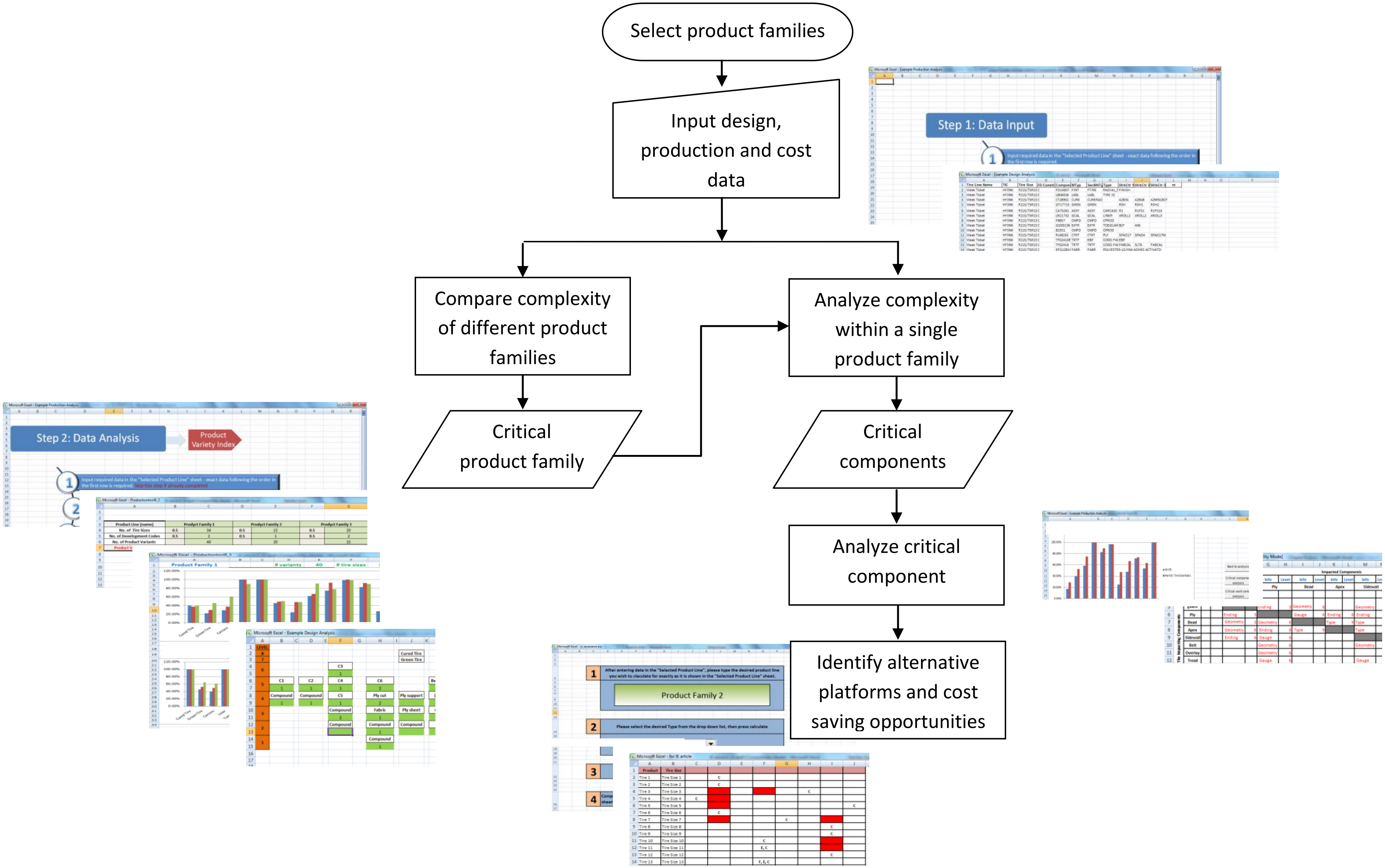

Figure 26: Complexity Management Tool

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