Concurrent Design Modeling and Analysis of Microelectromechanical Systems Products

THESIS

Submitted in partial fulfillment
of the requirements for the degree of
DOCTOR OF PHILOSOPHY

by

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Under the Supervision of
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BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE
PILANI (RAJASTHAN) INDIA
2010

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CERTIFICATE

This is to certify that the thesis entitled "**Concurrent Design Modeling and Analysis of Microelectromechanical Systems Products**" and submitted by **Mr. AMALIN PRINCE A** ID No. **2006PHXF409P** for award of Ph.D. degree of the Institute, embodies original work done by him under my supervision.

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Dedicated

To God

for blessing me with the best
Parents, Teachers & Friends
one can have...

ACKNOWLEDGEMENTS

This thesis arose in part out of years of research that would have been impossible without the help, contribution, advice and goodwill of several persons whom I met and interacted with during the period. It is my privilege to take this opportunity to humbly acknowledge and express my gratitude to them.

First of all I would like to thank Almighty God for granting me the resources – physical, mental, emotional and spiritual – to carry out the work leading to this thesis which I offer up to Him in thanksgiving. May this humble offering be worthy and acceptable to God who made my dream a reality.

Prof. V.P. Agrawal who initiated me on this project and guided me through the entire way deserves special thanks for his unstinting support, constructive discussions, encouragement, valuable advice, suggestions, inspiration and guidance of this research. I thank him from the bottom of my heart.

This dream project might have been left unfulfilled if it had not been for the remarkable patience, concern, vision and enthusiasm of Dr. Iven Jose who stepped in as my research supervisor and helped me continue the work that Prof. Agrawal had helped initiate. He has been my friend, philosopher and guide and besides my research supervisor. I thank Dr. Iven Jose for affording me the freedom to experiment with my work. Thanks to him, the process of working on this thesis has not only enhanced my knowledge and nourished my intellect, but has also given me confidence in my abilities and courage to strive towards greater heights.

I acknowledge with deep gratitude and respect Late Prof. T.C. Goel, Former Director, BITS-Pilani K.K. Birla Goa Campus for his encouragement and support that resulted in the inception of this project and inspiring me to strive towards obtaining a PhD degree.

I would like to express my sincere thanks to Prof. K.E. Raman, Director, BITS-Pilani K.K. Birla Goa Campus for his support, encouragement and for making available the necessary infrastructure & facilities so vital to the completion of this work.

My sincere thanks to Prof. L.K. Maheshwari, Vice-chancellor, BITS-Pilani, Prof. G. Raghurama, Deputy Director (Academic), and Prof. R.K. Mittal, Deputy Director (Administration) for their constant support and concern.

I acknowledge with due gratitude Prof. Ashis Kumar Das, Dean, Research and Consultancy Division, Prof. S.D. Manjare, Faculty In-charge, Research and Consultancy Division, Goa Campus, Prof. A.K. Sarkar, Dean, Instruction Division and Prof. A.P. Koley, Faculty In-charge, Instruction division for their constant support and help.

Deepest gratitude are also due to the members of the doctoral advisory committee, Dr. C.K. Ramesha and Dr. Sheron Figarado without whose knowledge and assistance this study would not have been successful.

Sincere thanks to Dr. K.R. Anupama, Group Leader, EEE/E&I Group, Prof. M.K. Deshmukh, Faculty In-charge (Administration), Prof. B.J.C. Babu, Faculty In-charge (SWD), Prof. V.K. Deshpande and Dr. Anita Agrawal for their contributions at various crucial stages of my work, constructive comments, motivation and collaboration. I thank them for their willingness to share their knowledge with me, which was very fruitful in shaping my ideas and research. I gratefully acknowledge their promptness in making available to me all the equipment to facilitate my research.

Collective and individual acknowledgements are due to all my colleagues and friends, within and outside of the BITS community, who have directly or indirectly helped me in my work. I also thank the large number of persons, family and friends, who have been praying me through the entire process and whose goodwill and moral support have kept my morale high. Sincere thanks to Dr. Saby John for her patient reading and appropriate amendment in the thesis.

Last but never the least, I wish to express my gratitude to my father Mr. A. Amala Raj, my mother Mrs. S. Cecily, my brothers Mr. A. Amalin Ugin, and Mr. A. Amalin Janet, who have been a constant source of encouragement and moral support during the entire period of my research work. My sister Dr. A. Amalin Kavitha and brother In-law Dr. K. Thomas Paul deserve special thanks for their support, motivation, suggestions, encouragement and for helping me obtain relevant literature for the study.

Amalin Prince A

ABSTRACT

Microelectromechanical Systems (MEMS) are miniaturized devices with high functionality. In recent years, MEMS products have become increasingly dominant in every aspect of the commercial market place. As the MEMS technology is in its infant stage and has several unique features compared to macro-scale products, it is faced with several challenges. For instance, design, fabrication, packaging, and materials knowledge is very intrigue and thus very difficult to access. Thus there is an urgent need for an effective computer supportive algorithm for the MEMS product development to evaluate the product at the conceptual stage.

An attempt has been made in this work to develop an integrated systems model for the complete structure of the MEMS product system in terms of its constituents as well as interactions between the constituents. The hierarchical tree structures of the MEMS system and its subsystems up to component level have been elucidated. For characterization, analysis and identification of MEMS product system, three different mathematical representations have been developed. These models and representations are associated with graph theory, matrix method and variable permanent function by considering the various subsystems, sub-subsystems up to component level, their connectivity and the interdependency of the MEMS product system.

An *n*-digit alphanumeric coding scheme is proposed herein. The coding scheme is a nomenclature and characterises the MEMS products on the basis of *n*-attributes. The situation and the need for group decision making are discussed. Typical crisp and fuzzy Multiple Attribute Decision Making (MADM) methods, which are suitable for multiple attributive group decision making problems in crisp and fuzzy environments, have been proposed to deal with the problem of ranking and selection of MEMS product alternatives. Techniques for Order Preference by Similarity to Ideal Solution (TOPSIS) and Fuzzy TOPSIS are the MADM and Fuzzy MADM techniques used. Graphical procedures in the form of line diagram and spider diagram have been presented.

A new MEMS product optimum design method, which supports the total product/device optimization and evaluation at the conceptual stage itself using Multiple Attribute Decision Making (MADM), has been developed. The new product development methodology has been compared with the traditional method. The

proposed new method has been found to take sufficiently less time for MEMS product development as has been presented herein using time charts.

The work also renews the need for an integrated product development methodology for MEMS products. Different subsystems of MEMS product developmental stage called X-abilities have been identified. To facilitate design of MEMS products simultaneously for all X-abilities in an integrated way, a concurrent design methodology using MADM approach and graph & matrix have been developed to show the interaction between subsystems. The advantages of the graph theory approach have been used to consider all the design aspects together in a single methodology with the help of a multinomial developed using matrix algebra. The design index developed using the proposed methodology, depicts the actual interaction among the subsystems and decides if the overall design is acceptable or not by considering all the aspects related to micromachined element design, microelectronics circuit design, fabrication, packaging, materials, environment etc.

This proposed concurrent MEMS product design methodology is aimed at reducing design and development time considerably and makes use of expertise of experts from different specialized fields for instance micromachined element design, microelectronics, materials, fabrication, package etc, in a single design team.

A Radio Frequency (RF) MEMS power sensor has been designed and the proposed methodology is elaborated herein. The power sensor has been simulated using MEMS Electronic Design Automation (EDA) tool for various design, materials and environment parameters. The simulated results have been used to validate the above models. The simulated results and the evaluation results of the models have been compared and a power sensor with Voltage Standing Wave Ratio (VSWR) of 1.08002 has been presented in this study.

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LIST OF ACRONYMS

AHP	Analytical Hierarchical Process
AM	Adjacency Matrix
CAD	Computer Aided Design
CE	Concurrent Engineering
CIM	Characteristic Interaction Matrix
CM	Characteristic Matrix
CMPDA	Concurrent MEMS Product Design Aspect
COS	Coefficient of Similarity
DFE	Design for Environment
DFF	Design for Fabrication
DFM	Design for Materials
DFMCD	Design for Microelectronics Circuit Design
DFMED	Design for Micromachined Element Design
DFP	Design for Packaging
DoD	Department of Defense
EDA	Electronic Design Automation
FEA	Finite Element Analysis
FNIS	Fuzzy Negative Ideal Solution
FPIS	Fuzzy Positive Ideal Solution
FST	Fuzzy Set Theory
GA	Genetic Algorithm
GDM	Group Decision Making
IC	Integrated Circuit

IF	Intermediate Frequency
IM	Interaction Matrix
LIGA	Lithographie Galvanoformung Abformung
MADM	Multiple Attribute Decision Making
MCDM	Multiple Criteria Decision Making
MEMS	Microelectromechanical Systems
MFS	Microfluidic Systems
MODM	Multiple Objective Decision Making
MOMES	Micro-Opto-Electromechanical Systems
MP	MEMS Products
NEMS	Nanoelectromechanical Systems
PE	Production Engineering
PES	Passive Electronic Systems
PMS	Passive Mechanical Systems
QoS	Quality of Service
QSAR	Quantitative Structure Activity Relationship
QSPR	Quantitative Structure Properties Relationship
RF	Radio Frequency
RIE	Reactive Ion Etching
SA	Simulated Annealing
SoC	System-on-Chip
SWOT	Strength Weakness Opportunities Threats
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VCIM	Variable Characteristic Interaction Matrix
VCM	Variable Characteristic Matrix
VCO	Voltage Controlled Oscillator

VDL	Variable Delay Lines
VLSI	Very Large Scale Integration
VPF	Variable Permanent Function
VPIM	Variable Permanent Interaction Matrix
VPM	Variable Permanent Matrix
VSWR	Voltage Standing Wave Ratio
μ TAS	Micro Total Analysis Systems

CHAPTER 1

INTRODUCTION

In its continuous progress towards ever higher levels of integration, the semiconductor industry has reached the point of embedding hundreds of millions of transistors into a single chip. Heterogeneous blocks can form part of these chips, including hardware and software. Hardware blocks can be rather different in nature, including digital, analog and mixed-signal and radio-frequency blocks. As a result of this enhanced level of complexity, this type of device is widely known as System-on-Chip (SoC). SoCs embedding sensors and actuators (or Microelectromechanical Systems) are also becoming a reality, leading to very powerful microsystems able to interact as microentities in different energy domains (mechanical, thermal, magnetic, radiant, chemical, biological, radiofrequency, etc). Microelectromechanical Systems (MEMS) are micro/nano systems which are constructed to achieve a certain engineering function or functions by electromechanical or electrochemical means (Hsu, 2002). MEMS is an emerging field of technology, which promises to have a major impact on our lives. Their small mass and size, low power consumption and potential for low cost production make them attractive in many sensors, actuators and control system applications. Particularly in automobile, aerospace and biomedical applications their research gives a detailed idea about the advantages of MEMS in the direction of scaling in various fields (Judy, 2001; Epen et al., 2006).

1.1 Introduction to Microelectromechanical Systems Products

The term MEMS refers to a collection of microsensors and actuators which can sense its environment and has the ability to react to changes in that environment with the use of a microelectronic circuit control. This includes, in addition to the conventional microelectronics packaging, integrating antenna structures for command signals into microelectromechanical structures for desired sensing and actuating functions. The system may also need micropower supply, micro relay and microsignal processing units.

Microcomponents make the system faster, more reliable, cheaper and capable of incorporating more complex functions.

In the beginning of the 1990's MEMS emerged with the aid of the development of Integrated Circuit (IC) fabrication process, where sensors and actuators and control functions are co-fabricated in silicon. Since then remarkable research progress has been achieved in MEMS thanks to strong capital promotions from both government and industry. In addition the commercialization of some less-integrated MEMS devices, such as microaccelerometers, inkjet printer heads, gyros, switches, phase shifters, micromirrors for projectors and optical routers, etc., the concepts and feasibility of more complex MEMS devices have been proposed and demonstrated for applications in such varied fields as microfluidics, aerospace, biomedicine, chemical analysis, wireless communications, data storage, display, optics etc. (Fujita, 1996; Fujita, 1998; Varadan et al., 2007).

Some branches like Micro-Opto-Electromechanical Systems (MOEMS), Micro Total Analysis Systems (µ TAS), etc., have attracted a great deal of research on account of their potential application market. By the end of the 1990's, most MEMS devices with various sensing or actuating mechanisms were being fabricated using silicon bulk micromachining, surface micromachining and Lithographie (lithography), Galvanoformung (electroplating), Abformung (moulding) (LIGA) process (Bustillo et al., 1998; Guckel, 1998; Kovacs et al., 1998). For more specific application requirements, for instance in biomedical devices, three dimensional microfabrication processes incorporating more materials were used, where wafer-to-wafer bonding is critical in the formation (Ikuta and Hirowatari, 1993; Stix, 1992).

1.2 MEMS Product Development Methodology

Current MEMS product design and development practice focuses on physical device and process development. A simplified design methodology is shown in Figure 1.1. Design concepts are implemented in a manual layout. The performance is analyzed using numerical analysis tools, usually resulting in iterations on both the layout and the underlying process. To present the state of-the-art in MEMS CAD relies on device-level extraction of macro-models in a limited set of energy domains for behavioral simulation

(Senturia et al., 1992). However, these numerical tools by themselves may not be practical for rapid iterative design since the physical layout (and perhaps the process) must be changed for each iteration without prior knowledge of changes that would best enhance the device performance. Currently, a self-consistent electromechanical analysis of a simple device requires many person-hours to create the 3-D geometry and perform a numerical analysis. This manual design cycle in MEMS has not decreased significantly over the past few years since knowledge from previous development efforts cannot be easily reused by future developers (Fedder, 1995).

The simulated micromachined element design is fabricated along with the necessary microelectronics circuit to get a complete MEMS product. The fabrication is a complex process which requires expert knowledge (Crary, 1995). The fabrication process is repeatable, so circuit and microstructure designs can be reused. The device improves as the process technology improves. The final fabricated product is suitably packaged and the prototype can be reproduced at any time.

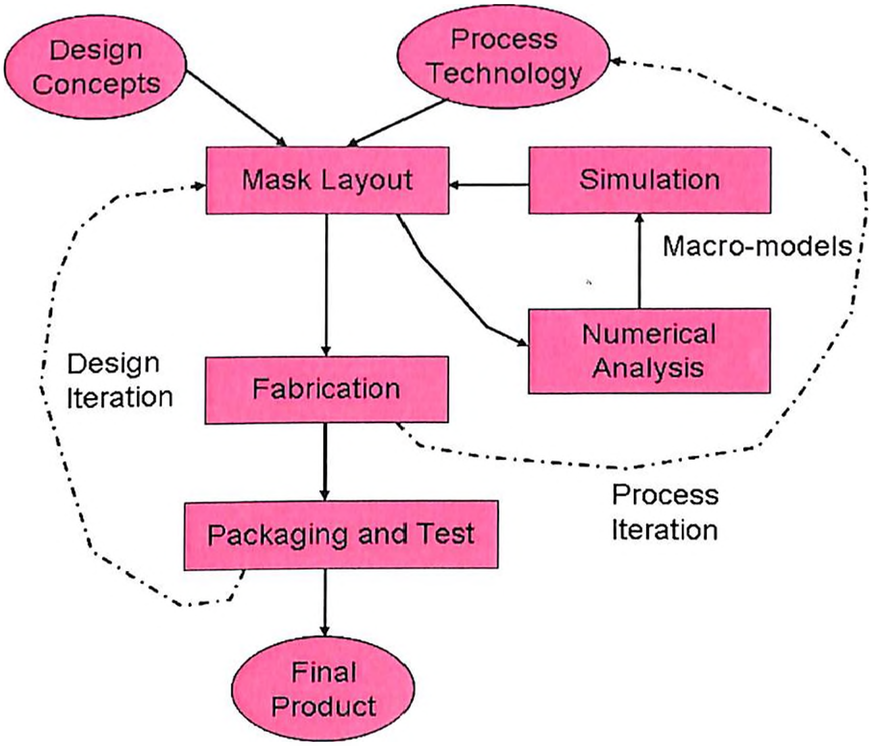


Figure 1.1: Flow chart of current MEMS product design (Fedder, 1995).

1.3 Concurrent Engineering

Concurrent Engineering (CE), or Integrated Product Development, or Parallel Engineering is a Department of Defense (DoD) initiative for the defense industry; it has also been used very successfully by commercial industries (Hoffman, 1998). CE is a systematic approach to the integrated concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule and user requirements (MIL-HDBK-59A, 1990).

CE considers the product from the conceptual stage to the disposal stage of the design (Kusiak, 1992). In fact, the term "Concurrent Product Development" was proposed, because not only technical people must be involved at the conceptual stage, but also economists, physicists, biologist, chemists, etc., must be considered while designing a product from the conceptual stage itself.

The number of stages in CE are minimized in the downstream stages of design, because every person who has a venture in the product's life cycle is involved in the design process from the very beginning. So, issues such as maintenance, manufacturing, and customer use, are addressed from the beginning of the process by the cross-functional design team. Since a cross-functional team is used and customers and suppliers are involved in the process from product definition, the entire development time is reduced significantly (Skalak, 2002).

1.4 Need for Concurrent Engineering in MEMS Product Development

According to iSuppli (Cheung, 2009), Microelectromechanical Systems are making major inroads in the consumer- and mobile-electronics worlds. As a result, shipments of MEMS for consumer and mobile electronics are expected to grow from $0.9 billion (2006) to $2.5 billion (2013). Figure 1.2 explains the consumer and mobile MEMS market by application from the year 2006 to 2013.

In order to satisfy the customer needs and competitive in the market, MEMS designers and manufacturers need to develop new methodologies to bring high quality and reliable low cost products into the market within less time. The MEMS products that have successfully achieved the performance and cost targets have taken, on an average, 4-10 years from concept to final volume production and market insertion (Da Silva et al., 2002; Schropfer et al., 2004). The most time consuming factor is the current design follows serial approach for MEMS product design. If a powerful top-down methodology is introduced with concurrent engineering practice for the design of MEMS product the design and manufacture will be faster (Da Silva et al., 2002; Schropfer et al., 2004). It is very important for the success of product development that many design concepts are developed and evaluated simultaneously so as to offer enough choices for a successful product. The key to develop several viable concepts is the ability to create and evaluate concepts rapidly.

The envisioned model will be able to choose the optimal technology, select and optimize mechanical and electrical components from which the system will be composed, and determine coupling among the components, including the degree of monolithic integration and packaging (Crary, 1995).

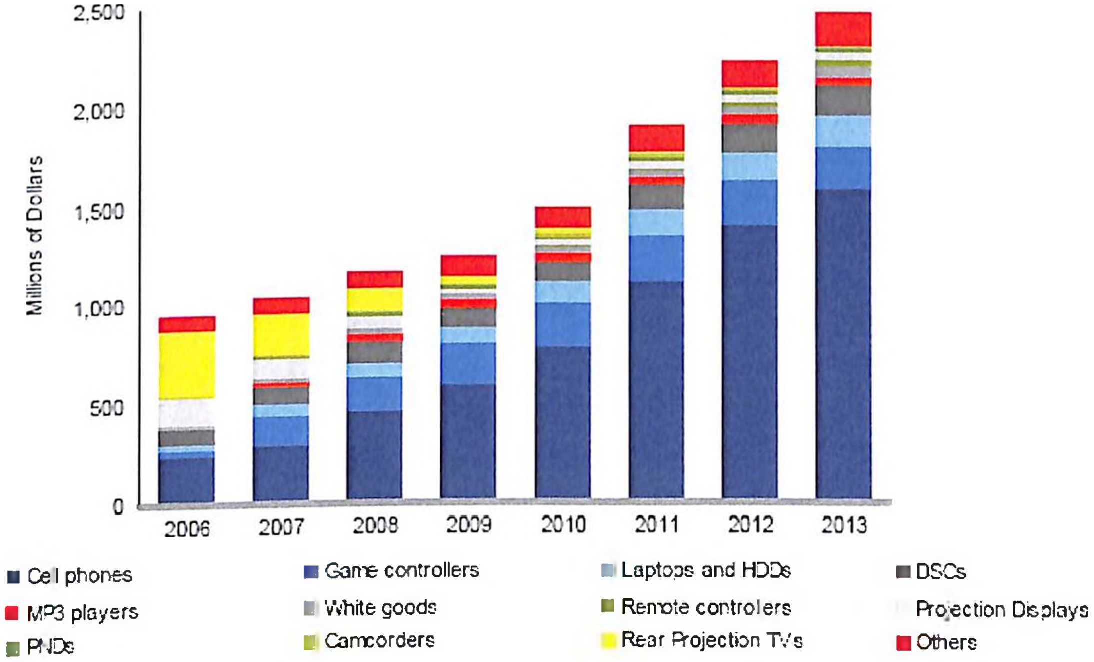


Figure 1.2: Consumer and mobile MEMS market by application (Bouchaud and Dixon, 2009).

1.5 Research Objectives, Scope and Significance

The following objectives were defied for this thesis study:

> ***Objective 1:*** *To analyze the MEMS product development process thoroughly by considering a MEMS product as a system in-toto, to identify subsystems as well as sub-subsystems up to component level as well as interactions among them which influence the overall performance of a MEMS product.*

The method applied to achieve this objective involved an in-depth literature study to identify unique features associated with a MEMS product development process and develop hierarchical tree structures of the MEMS product system and its subsystems up to component level. An integrated system model for the complete structure of the MEMS product system in terms of its constituents and interactions between constituents was developed using graph theory and matrix approach.

> ***Objective 2:*** *To characterize a better component level of the MEMS product system, collect the attributes pertaining to each subsystem of the MEMS product and also develop a simpler method to manage and manipulate the attributes by using a computer algorithm.*

An in-depth literature survey was conducted to identify the pertinent attributes which belong to each MEMS product subsystem. Another idea was to develop a coding scheme to handle the large number of attributes which facilitates the designer to store, retrieve and compare the attributes using computer.

> ***Objective 3:*** *To develop methodologies which can rank/compare/select the better MEMS product using the attributes under fuzzy or crisp situations, from component level to system level [i.e. bottom to top approach]. To develop computer algorithms which use the coded and stored attributes to select better MEMS product system.*

To achieve this objective, a conceptual model was developed which utilized the fuzzy and crisp attributes as inputs. An attributes based evaluation method called Multiple Attribute Decision Making (MADM) and Fuzzy Multiple Attribute Decision Making (Fuzzy MADM) were considered for the analysis.

> ***Objective 4:*** *To develop an improved MEMS product development method which can reduce the product development time by reducing the number of iterations involved in traditional MEMS product development and to evolve a method to reduce the number of iterations involved in the time consuming EDA tool simulation.*

To achieve this objective, a methodology was proposed which has very less number of iterations in MEMS product development by pre-evaluating the possible alternatives in each stage i.e. design of micromachined element, microelectronic circuit, fabrication, package etc. In order to validate the methodology a suitable MEMS product (RF MEMS power sensor) was designed and the performance characteristics were compared with MEMS EDA tool simulation results.

> ***Objective 5:*** *To develop a concurrent product development methodology for MEMS product design which can evaluate the product at the conceptual stage itself by considering inputs from all the stages of product development in an integrated manner.*

This objective was achieved by proposing a methodology which could consider inputs from all the stages of the MEMS product development and choose better alternatives at the conceptual stage of product development itself. MADM as well as Graph and matrix based approaches were used to achieve this model. A suitable MEMS product (RF MEMS power sensor) was developed to validate the proposed models with the existing product development methods.

1.6 Organization of the Thesis

The remainder of the thesis will be organized as follows:

Chapter-2 consists of a comprehensive literature review that further justifies the significance of the proposed work, particularly with respect to the research objectives delineated in Chapter 1. Literature on related fields like MEMS, RF MEMS, concurrent design, graph and matrix approach, MADM, MEMS EDA tools etc are also presented.

Chapter – 3 describes a unique methodology for the structural analysis of MEMS product system. To start with various subsystems and sub-subsystems were identified for analyzing the total MEMS product system upto the component level. Graph theoretical models and matrix based function index were developed. An illustrative example to show the structural variation and coefficient of similarity for two different MEMS products was studied. A step-by-step procedure to apply the structural model for a MEMS product was developed to assist the MEMS industry. The usefulness of the same has been highlighted in this chapter.

Chapter-4 describes a methodology for coding the attributes for easy storage and retrieval by a computer and an evaluation method to select the optimum subsystem. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), a Multiple Attribute Decision Making (MADM) approach, and Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS), a Fuzzy Multiple Attribute Decision Making (Fuzzy MADM) approach were used for evaluation and ranking. Two graphical methods (Line diagram and Spider diagram) were also introduced to compare the MADM results. The methodology was explained using an illustrative example.

Chapter-5 presents a new MEMS product optimal design and analysis method which reduces the number of iterations involved in the traditional manufacturing approach so as to shrink product development time. This method uses MADM for evaluation. An RF MEMS power sensor was designed and the proposed methodology has been explained in detail in this chapter.

Chapter-6 presents two concurrent product development methodologies for MEMS product development. This study proved that the concurrent methodology reduces the product development time tremendously when compared to traditional methodology and the methodology described in Chapter-5. The concurrent product development method uses MADM based modeling and Graph and matrix based modeling. The proposed methodologies are explained using RF MEMS power sensor as an example and it has been proved that the Graph and matrix based approach is more effective to handle the interaction among the subsystems.

Chapter-7 is a conclusion with recommendations for future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides further justification to the significance of the research setting developed in Chapter-1, in particular those related to research objectives. A critical review of related work reported in literature will fulfill this purpose. This chapter also provides background knowledge that facilitates subsequent discussions. Section 2.2 discusses the principle and application of MEMS, which is a foundation for understanding multiple domains in which MEMS is used. This section also highlights the fact that to develop MEMS product, experts from many field are required. Section 2.3 discusses the general concept of concurrent engineering and the initiation given by researches to implement concurrent engineering in the MEMS industry. In Section 2.4, studies on graph theory and matrix approach are reviewed, which also highlight how effectively the graph and matrix approaches are used to analyse complex systems in different industries. Section 2.5 discuss the importance of fuzzy and crisp multiple attribute decision making tools and their applications. Concluding remarks are presented in section 2.6.

2.2 Principle and Application of MEMS

Most phenomena need to be precisely measured and controlled in a timely predictive manner in order to overcome temporal and spatial limitations. The miniaturised systems have better response time, faster analysis and diagnosis, good statistical results, improved automation possibilities with decreased space, risk and costs. In the year 1959, Feynman envisioned the possibility of manufacturing ultraminiaturised systems for a variety of applications, to a level that would involve multiscale formulation methods that would enable manipulation of molecules and atoms (Mahalik, 2007). Sophisticated miniaturised components and systems can change products and equipments dramatically (Mahalik, 2005). Microelectromechanical Systems (MEMS) an advanced product and equipment design concept has emerged in order to cater the need for miniaturisation. Many industries in conjunction with academic institutions and R&D sectors have been investing good amount of money and resources in pursuing technological growth in this field. Currently, MEMS market demand is progressively being strengthened by time-based value engineering that meets the high industry demand (Helvajian, 2009). The design phases of MEMS are highly complex involving multiphysics and a strong interdisciplinary knowledge base (Mahalik, 2008). MEMS devices have already found significant applications in numerous sectors. They are used for controlling micromanipulators, microequipments, microgrippers and microrobots. Many MEMS devices are found in clock, ink-jet printer heads, colour projection and display systems, scanning probe microscopes, to name a few. MEMS technology is also found in the design of sensors such as pressure, temperature, vibration, etc. MEMS-based light reflectors, beam splitters, RF and optical switches are common. Broadly the application sectors are:

1. Aircraft and automotive industries
2. Chemical and manufacturing industries
3. Clinical, diagnostics, therapeutic devices, Pacemakers and pharmaceuticals
4. Defence and space applications
5. Environmental
6. Communications (wireless, optical)
7. Data storage devices
8. Consumer products
9. Display applications
10. Inertial navigation devices
11. Microfluidic applications
12. Industrial automation and control sectors, etc. (Mahalik, 2008)

2.2.1 Mother disciplines of MEMS and NEMS

The R&D activities on miniaturisation of systems broadly fall under two major categories such as MEMS and Nanoelectromechanical Systems (NEMS) (Mahalik, 2008). MEMS technology is considered as amalgamation of two subdomains such as ultra-precision microengineering and IC technology. MEMS and NEMS both are interdisciplinary, multiphysics, multiengineering platforms in which manufacturing of smaller parts, components, products and systems at the level of micro- and nanoscale with more functionalities and capabilities are realised (Denko and Endo, 2002). The former is more close to the mechanical machining processes, while IC technology corresponds to microelectronics design. NEMS groups of systems fall under the area of nanotechnology. To some extent, both MEMS and NEMS have been categorised under micromanufacturing, a sister branch of Production Engineering (PE). The synergistic integration of MEMS technology and intelligent control algorithm in the manufacture of products is called micromechatronics.

2.2.2 IC and MEMS

ICs are Very Large Scale Integrated (VLSI) semiconductor chips. A technology that considers manufacturing of microscale sensors, actuators, valves, gears, mirrors, switches and so on similar to semiconductor chips, are referred to as MEMS. MEMS design technology, an extended form of traditional IC fabrication, can fabricate capacitors and inductors as well as mechanical elements such as springs, gears, beams and diaphragms. It was impossible to fabricate these components utilising IC technology.

Fabrication Processes

The method of micromanufacturing of microelectronic devices is called fabrication. The important fabrication sequences are film growth, doping, lithography, etching, dicing and packaging. All these processes are performed on a substrate on which a thin film is grown. The properties of the layer are then modulated by appropriately introducing doped material in a controllable manner. The subsequent process is called lithography, which refers to creation and subsequent transformation of a masking pattern (Seo and Kim, 2007). Etching is a process of removing the portion of a layer of semiconducting material from the base by chemical or electrolytic means. Etching can be either physical or chemical or a combination (French and Sarro, 1998). Dicing is a process of cutting up the wafer into individual chips. Packaging is a complex process that involves physically locating, connecting and protecting a device (Liang et. al., 2006).

Micromachining refers to the fabrication of 3D MEMS structures with the aid of advanced lithography and etching techniques. Broadly, the processes fall into two categories: bulk and surface micromachining (Bag, 2005). Bulk micromachining refers to etching through both the sides (front and back) to form the desired structures. The structures are formed by wet chemical etching or by Reactive Ion Etching (RIE). The advantage of bulk micromachining is that substrate materials such as quartz or single crystal silicon are readily available and reasonably high aspect-ratio structures can be fabricated. It is also compatible to IC technologies. The disadvantages of bulk micromachining is that the process is pattern and structure sensitive and pattern distortion occurs due to different selective etch rates on different crystallographic planes. Surface micromachining is another method that is characterised in terms of fabrication of MEMS structures out of deposited thin films. The thin film may be composed of three layers of materials (Alper and Akin, 2000). LIGA process is well used for high aspect ratio 3D devices (Larson, 1999).

SoC Concept

MEMS is the integration of active and passive elements on a single silicon substrate. The active elements are sensors and actuators and the passive elements are Passive Electronic Systems (PES) such as signal conditioning circuits (amplifier, ADC, filter, isolators, etc.) and the Passive Mechanical Systems (PMS) such as gear, crank, bearing, etc. IC circuits can be thought of as the nervous system with sensors and actuators as the eyes and arms, respectively. MEMS promise to revolutionise most of the microproducts by combining microfabrication with micromachining process sequences on silicon making it possible to realise SoC (Richards and De Los Santos, 2001).

Next Generation MEMS

MEMS technology can allow the development of smart systems inheriting additional capability of perception and controlled attributes of microsensors and microactuators. For example, quite large numbers of sensors can be micromachined in a single platform as a sensor fusion device. Sensor fusion is a scheme usually applied in the field of industrial automation and control to ensure reliable operations. Instead of using a single sensor, multiple sensors are employed in order to detect the measurand. A single output is produced based on statistical manipulation. Since many sensors take part in generating a unified output, the sensor fusion scheme can eliminate error. The next generation MEMS device can accommodate decision-making capability with embedded soft computing algorithm. Moreover, prognostic measures in terms of sensor and actuator validation (Henry, 1995) can be achieved through this advanced design approach.

2.2.3 Classifications

Broadly, MEMS are classified based on the principle of sensing, actuation and application domains; accordingly we have Mechanical MEMS, Thermal MEMS, Magnetic MEMS, Micro-Opto-Electromechanical Systems (MOEMS), RF MEMS, Microfluidics and BioMEMS. Micromachined microsensors are designed by adopting various transduction principles such as thermoelectric, photoelectric, electromagnetic, magnetoelectric, thermoelastic, pyroelectric and thermomagnetic (Grimes et al., 2001).

Mechanical MEMS

Mechanical MEMS mostly emphasises on two classes of devices; mechanical structure based and piezoelectric material-based device. When the geometric structural configurations are exploited for sensing and actuating purpose then the MEMS design can be classified under the first category. Piezoelectric material-based mechanical sensors and actuators exploit the effect of piezoelectricity. Broadly, the mechanical MEMS mechanism utilises:

1. Cantilever beam sensor (Chui et al., 1998)
2. Capacitive sensing
3. Gyroscopes (Acar and Shkel, 2004) and
4. Piezoelectricity-based methods and principles.

Thermal MEMS

Thermal MEMS work on Peltier effect, thermoresistivity, pyroelectricity and shape memory effect. A voltage/current is developed in a loop containing two dissimilar metals, provided the two junctions are maintained at different temperatures. The effect is popularly known as Seebeck effect. The reversed Seebeck effect is Peltier effect. The materials which produce a large range of resistance value to a small range of temperature, are thermoresistive materials. The research areas under thermal MEMS include:

1. Thermodevices including thermocouple and thermopiles

2. Peltier heat pump and heat sink devices
3. Hotwire and microhotplate-based thermal flow sensors
4. Microthermo-vessels
5. Thermocouple probe for imaging, topography and data storage applications (Ho et al., 1999)

MOEMS

MOEMS are MEMS but they handle optical signals. MOEMS technology accommodates the principles of optics, electronics and mechanics. MOEMS show good performance with negligible signal degradation and better Quality of Service (QoS) compared to traditional optoelectronic devices. High operational bandwidth and low power consumption are the key features of MOEMS devices. Some of the important applications of MOEMS are (Sche and Wu, 2004; Mahalik, 2007):

1. Optical sources and photodetectors
2. Display and projection systems
3. Optical switches and routers
4. Microscanners (image processing, bar code reading, obstacle detection)

Magnetic MEMS

Soft ferromagnetic materials have found the most utility in microsensors and microactuators while hard magnetic materials are mostly used for data storage devices. Hard magnetic films with thickness of several microns are grown by the sputtering technique. Especially, Magnetoresistive (MR) materials are used for detecting the strength and direction of the magnetic field, which in turn can measure:

1. Distance
2. Proximity and position
3. Angle and rotational speed (Guo-Ming, 2004).

RF MEMS

RF MEMS add new capabilities and improve power efficiency. Devices used for RF communication are switches, inductors, varactors, filters, tuners and resonators: the important components of a typical mobile phone. MEMS versions of these components promise to make devices more reliable and power efficient (Jung et al., 2006; Lee et al., 2007). RF MEMS can be used for achieving:

1. Transmission and reception
2. Voltage Controlled Oscillator (VCO) tuning
3. RF band select filters and Intermediate Frequency (IF) filtering
4. Time delay for phased-arrays
5. Variable Delay Lines (VDL) and
6. Reconfigurable antennas (Schoebel et al., 2005).

Microfluidic Systems

Microdevices, which are used to transport and store fluid, are called Microfluidic Systems (MFS). Typically the MFS handle fluid volumes on the order of nanoliter. Some of the important building blocks of MFS are microchannel, micronozzles, micropumps, microvalves and microreservoirs (microvessels). Some important applications are:

1. Inkjet printing
2. Drug dispensing
3. Reaction analysis
4. Mixing and separation
5. Chemical synthesis and Detection of chemical species
6. Genetic analysis and
7. Semiconductor processing.

The advantages of MEMS compared to conventional fluidic systems are that the miniaturised system requires less reagent (species or samples) resulting in faster, accurate and reliable measurements (Hensel et al., 2006).

Bio and Chemo Devices

Microdevices used for analysis and detection of biomedical and industrial reagents are called bio and chemo-devices. Unlike MFS, bio and chemo-devices are diode-type, transistor-type or 3D cantilever structure. Some of the applications are:

1. Forensics and genetic screening
2. Antibodies gene expression in transgenic cells
3. Identification of patients with high tumour risk

4. Pathogens like throat bacteria and
5. Drug discovery (Grayson et al., 2004).

The development of DNA sensors is considered as the most innovative molecular biology technology (Liu and Lu, 2003).

2.2.4 MEMS packaging and design considerations

Much like IC packaging, MEMS packages must have the ability to meet some important criteria (Lee et al., 1998), such as:

1. Good isolation between the non-sensing and sensing areas of the device
2. No hindrance to the driving actions such as tilting, twisting, rotating, sliding or vibrating
3. Efficient coupling at the link, junction, anchor area
4. No unreliability issues due to contamination, fusing, sticking, clamping, static overload, de-lamination, creep and fatigue.

2.2.5 Modeling and simulation

Prior to the design, it is desirable to study the potential behaviour of the envisaged MEMS system. Simulation is performed by the use of computer-assisted tools. Computer-assisted simulation tools contain all types of mathematical building blocks so that the designer can formulate any kind of model equations looking at the system and can subsequently analyse and predict the behaviour of the MEMS system. Even the designer can incorporate the physical properties (bulk modulus, permittivity, coefficient of resistance, etc.) of the material into the model equations. Available popular simulation tools or Electronic Design Automation (EDA) tools for MEMS modeling and analysis are ANSYS, SUGAR, MEMCAD, IE3D etc. (Cole et al., 2003; Gilbert, 1998).

However, most MEMS devices are currently modeled using weak analytical tools, resulting in a relatively inaccurate prediction of performance behaviors (MEMS Exchange, 2008). The MEMS design process is usually performed in a trial-and-error fashion, which requires several iterations before the performance requirements of a given device are finally satisfied. This non-ideal design methodology combined with the length of time and high costs associated with MEMS prototyping results in a very inefficient and ineffective scenario for commercial product development. With the development of MEMS, advanced simulation and modeling tools for MEMS design are urgently needed. The design and manufacturing (design, fabrication, packaging, testing etc.) of MEMS as well as microelectronic devices and systems, need to improve considerably from their current primitive state (Mahalik, 2007). The advanced simulation and modeling tools for MEMS design must provide an advisory service so as to help the designer to select manufacturing processes and materials for MEMS devices (Zha and Du, 2000).

In order to achieve the optimum design solutions efficiently, several methods/techniques have been proposed by researchers. Design optimization for MEMS and their applications using Simulated Annealing (SA) method, optimization of the MEMS switch using cost function, optimal and robust design methods for a MEMS accelerometer using Genetic Algorithm (GA), optimal design of a new MEMS phase shifter using GA and Optimal design and fabrication of MEMS rotary thermal actuators using topology optimization have been studied (Ongkodjojo and Tay, 2006; Brenner et al., 2002; Coultate et al., 2008; Huang et al., 2001; and Heo and Kim, 2007). The primary drawback of the existing MEMS product development process is the lack of a procedure to integrate different aspects of the product development process in an integrated manner. A lacuna exists in research to analyse MEMS product development using systems approach. It therefore becomes imperative that an efficient method and system in a computer-aided concurrent collaborative environment for designers to use at the early stages of MEMS design be developed urgently.

2.3 Concurrent Engineering in MEMS

CE can be described as a systematic approach to design, engineering, and manufacturing that considers all elements of the product life cycle as an integrated arid harmonious process. Effective CE of products will require organizations to support a seamless design-to-manufacturing product cycle. At each phase of the cycle, personnel (designers, engineers, and manufacturing managers) must make complex decisions. These decisions will require, and the decision process itself will generate, a large volume of cost, design, manufacturing and product information (Hoffman, 1998).

In the past, few researchers had highlighted the need for concurrent design methodology for MEMS. Romanowicz et al. (2001) studied a methodology and tool-set which directly support such an integrated design process. Da Silva et al. (2002) presented the fundamental components of MEMS Design for Manufacturing (DFM) design methodology which may be broadly divided into design and manufacturing activities. Sadek and Moussa (2005) discussed a modeling framework to MEMS Design for Fabrication (DFF) and the frame work was applied to a micro gas sensor. A methodology for MEMS DFM was reported which focused on solid process and design qualification through systematic parametric modeling and testing, from initial development of specifications to volume manufacturing (Schropfer et al., 2004). A knowledge based methodology for design and simulation of MEMS devices was developed by Zha and Du (2002), and a web-based knowledge intensive support framework was built up to support concurrent collaborative design of MEMS. Further, as a part of concurrent collaborative design framework, an interface was designed to separate design from fabrication/packaging processes, which allowed the designer to use process independent design tools and methodologies (Zha and Du, 2003).

However, the field is still in its infancy because there were huge unsolved problems (summarized before, referring to packaging, testing and reliability, and reflected in design & simulation). It was difficult to solve the above mentioned problems using the classical approach (i.e. the sequential engineering approach) because of the high costs involved in re-engineering. CE appeared to be a better solution, because the field required involvement experts with significant scientific depth in a variety of disciplines. Also experts would be able to cover the development process at every scale, from molecular dynamics and system engineering to process engineering and product testing. Science, engineering, manufacturing and marketing would be brought together under the umbrella of CE. Bazu (2004), therefore, asserted that MEMS needs CE.

The literature reviewed above discusses the need and advantages of CE in MEMS product development. In spite of the advantage, there exits a critical gap in MEMS product development studies to integrate several design aspects (design for micromachined element design, design for microelectronics circuit design, design for fabrication, design for packaging, design for materials, design for cost, design for environment, design for testability etc.) simultaneously, taking into account the significant interactions and interrelations among the various product development aspects.

2.4 Graph Theory and Matrix Approach as a System Modeling Tool

The application of graph theory was known centuries ago, when the long-standing problem of the Konigsberg bridge was solved by Leonhard Euler in 1736 by means of a graph. Since then, graph theory has proved its mettle in various fields of science and technology such as physics, chemistry, mathematics, communication science, computer technology, electrical engineering, sociology, economics, operations research, linguistics, internet, etc. Graph theory has served an important purpose in the modeling of systems, network analysis, functional representation, conceptual modeling, diagnosis, etc. Graph theory is not only effective in dealing with the structure (physical or abstract) of the system, explicitly or implicitly, but also useful in handling problems of structural relationship. The theory is intimately related to many branches of mathematics including group theory, matrix theory, numerical analysis, probability, topology, and combinatorics. The advanced theory of graphs and their applications have been well documented (Harary, 1985; Wilson and Watkins, 1990; Chen, 1997; Deo, 2004; Jense and Gutin, 2000; Liu and Lai, 2001; Pemmaraju and Skiena, 2003; Biswal, 2005).

Venkatasamy and Agrawal (1995) developed a structural model for analyzing automobile vehicles using graph theoretic and matrix analysis. A methodology to analyze failure cause of a system using structural approach based on digraph and matrix method was developed by Gandhi and Agrawal (1996). Rao (2004) presented a digraph and matrix methods for evaluating environmentally conscious manufacturing programs. Prabhakaran et al. (2006a) developed a structural model to analyse composite product system using graph theory.

Since MEMS product system is a complex interdisciplinary system, the systems approach was found to be well suited for its analysis. Systems and sub-systems based analyses have not been attempted till now in the literature using graph and matrix approaches for MEMS product systems.

2.5 Multiple Attribute Decision- Making

Multiple Attribute Decision Making (MADM) methods are generally discrete, with a limited number of predetermined alternatives. MADM is an approach employed to solve problems involving selection from among a finite number of alternatives. An MADM method specifies how attribute information is to be processed in order to arrive at a choice. MADM methods require both inter- and intra-attribute comparisons, and involve appropriate explicit tradeoffs (Zeleny, 1982).

In the study of decision making, terms such as multiple objective, multiple attribute and multiple criteria are often used interchangeably. Here, the conceptual distinctions leading to the definition of the proposed MADM methods are provided. Multiple Objective Decision Making (MODM) consists of a set of conflicting goals that cannot be achieved simultaneously. It invariably concentrates on continuous decision spaces and can be solved with mathematical programming techniques. MODM generally deals with

(i) preferences relating to the decision maker's objectives and

(ii) the relationships between objectives and attributes.

An alternative could be described whether in terms of its attributes or in terms of the attainment of the decision maker's objectives. MADM deals with the problem of choosing an option from a set of alternatives which are characterized in terms of their attributes. MADM is a qualitative approach due to the existence of criteria subjectivity. It requires information on the preferences among the instances of an attribute, and the preferences across the existing attributes. The decision maker may express or define a ranking for the attributes as importance/weights. The aim of the MADM is to obtain the optimum alternative that has the highest degree of satisfaction for all of the relevant attributes (Ribeiro, 1996; Bellman and Zadeh, 1970).

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is one of the MADM techniques based on the concept that the chosen alternative should have the shortest Euclidean distance from the ideal solution and the farthest from the negative ideal solution (Hwang and Yoon, 1982). The papers reviewed in this literature survey that use TOPSIS include optimum selection of grippers (Agrawal et al., 1992), optimal material selection aided with decision making theory (Jee and Kang, 2000), computer aided selection of power plants (Garg et al., 2005), and optimum selection of composite product system (Prabhakaran et al., 2006b).

In MEMS system selection, the expert data may be fuzzy or imprecise. Fuzzy Multiple Attribute Decision Making (Fuzzy MADM) methods are proposed to solve problems that involve fuzzy data. Bellman and Zadeh (1970) were the first to relate fuzzy set theory to decision-making problems. Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS) is one of the Fuzzy MADM techniques. Recently, a few papers reporting on work in different areas using the Fuzzy MADM approach have been published.

Karray et al. (2000) proposed an integrated methodology using the fuzzy set theory and genetic algorithms to investigate the layout of temporary facilities in relation to the planned buildings in a construction site. It identifies the closeness relationship values between each pair of facilities in a construction site using fuzzy linguistic representation. Grobelny (1987; 1997) explored the use of a fuzzy approach to facilities layout problems using a fuzzy criterion to determine the closeness relationship among departments; and then to determine the final optimum design. Evans et al. (1987) and Dweiri and Meier (1996) used a similar concept that employed the theory of fuzzy sets to solve a block layout design problem. Yang and Hung (2007) proposed multiple-attribute decision making methods for plant layout design problem in an IC packaging company.

The study presented in this thesis uses MADM and Fuzzy MADM methodology, considering various subsystems related to MEMS product development, to evaluate a MEMS product alternative. In existing literature MADM and Fuzzy MADM methods are used to select best product alternatives or to solve decision making problems. The presented study uses these methodologies to design, develop and pre-evaluate the products at the outset, so MEMS product alternatives are evaluated using these methods at the conceptual stage itself.

From the above literature review, it is clear that despite major concerns and efforts on the part of researchers, methodologies involving a systems approach that could incorporate all the attributes primarily involved in producing a MEMS product system using optimum selection procedures are scare. No mathematical method is available for optimum selection and no coding scheme is available for better understanding, storage and retrieval. To date the proposed methodology have not been applied in MEMS field particularly taking into consideration the attributes that are primarily related to sub-systems like design, fabrication, environment, packaging and materials of MEMS product system. Thus the work presented herein is particularly relevant and necessary in the current MEMS application scenario.

2.6 Conclusions

In general the area of MEMS design and product development has been subject of intense research and novel application for many years. Few important issues that become apparent through the literature review are listed below

- Structural models which could give a detailed understanding of MEMS product from system level to component level had not been reported.
- A model which represents the interactions and dependencies between different components of MEMS product system which would influence the final MEMS product performance had not been envisaged.
- There was a need to develop a methodology which could effectively handle the attributes pertaining to different system level components of MEMS product development. These attributes could be coded and stored so that a computer algorithm could retrieve it easily. Also a methodology which utilises these attributes (crisp or fuzzy or imprecise) to rank and evaluate the MEMS products had to be developed.
- CE approach had not been applied to MEMS product development in an integrated manner. New MEMS product design and development methodology was required which could consider parameters of various design and development aspects at the conceptual stage to bring high quality MEMS product in to market rapidly and with less cost.

A study on methodology which would fulfill the above requirements directly benefit designers, manufacturers and users. Hence, this work planned and evaluated with the aim, to consider the dependencies and interrelations among several MEMS product development aspects to improve the quality, reliability and to reduce the product development time.

CHAPTER 3

STRUCTURAL MODELING AND INTEGRATIVE ANALYSIS OF MEMS PRODUCTS

3.1 Introduction

MEMS are a hybrid of electronics, mechanical elements, sensors, and actuators on a common silicon substrate through the utilization of microfabrication technique with common package. Since the complexity of MEMS increases, it is becoming increasingly important to design and optimize the coupling between the micromachined elements, the microelectronics circuits that control them and condition the signal and the constraints due to packaging. The package IC die is part of the complete system and should be designed as the MEMS chip is designed, with the specific and many times custom package in mind. The chip, package, and environment all must function together and must be compatible with each other (Yufeng et al., 2005). This determines which materials and what design considerations and limitations become important. One of the main scientific challenges of MEMS is the issue of material properties. The properties of the materials depend on how they are used, processed, the heat treatments to which the materials are subjected, and even the specific pieces of equipment used during fabrication. Not all the materials used react the same to these parameters, so compromises must be made. Some materials may be hard to obtain with R&D production run numbers. Low quantities of materials are used, and suppliers are reluctant to sell small quantities or develop new products for limited markets (Monk and Shah, 1996). One good point about the materials used in microsystems is that the material properties generally get better at the microscale. This is due to a decrease in the number of defects encountered in the materials.

Researcher Lucyszyn (2004) has given a unique roadmap that shows how the enabling technologies, RF MEMS components, RF MEMS circuits and RF Microsystems packaging are linked together; leading towards enhanced integrated subsystems. Mechels et al. (2003) discussed the 1-D MEMS based wavelength switching subsystem. Due to design and fabrication complexity the development of MEMS devices still relies on knowledge and experience of MEMS experts. It is difficult to understand the trade-offs inherent in the system and achieve an optimal structure without any MEMS-related insight. MEMS product development is too slow because iterative structural analysis, layout and testing are necessary to achieve complete structures. Also MEMS researchers need to design structures under some MEMS fabrication limitations. Thus MEMS designers tend to pursue just a few primary characteristics without consideration of the total system performance. This time consuming product development process is unavoidable while bringing MEMS to market (Mamiya et al., 2004).

The present work has the capability to consider the interactions/interdependence and connectivities in an integrated way. It gives a detailed understanding of MEMS product system and its subsystem interconnections.

3.2 Identification of Structural Constituents of MEMS Product System

To develop the systems mathematical model of the structure of the MEMS products, it is very much necessary to identify the structural components, manufacturing process, process parameters, materials and the application/usage. Five subsystems have been identified namely design, fabrication, materials, packaging and environment. These subsystems may vary and depend on the product and the process of manufacturing. The proposed methodology is capable of considering any such variation and is suitable for modeling any particular MEMS product structure. The importance of the identified subsystems is discussed in the following section.

3.2.1 Design subsystem

MEMS design is a complex process, because it is important to design and optimize the coupling between the micromachined elements and the microelectronics circuits that control them and condition the signal (Schropfer et al., 2004). The micromachined element designer should be an expert from the design type/domain in which he is working and the sensing & actuation technique used for the design (Liu, 2006; Senturia, 2001). For example if the design is an RF switch, the micromachined element designer should be an RF domain expert and the possible actuation technique is electrostatic. Microelectronics circuit designer has to consider the design of signal conditioning circuit and signal processing circuits in a structured way. On the basis of critical literature review (Girbau et al., 2006; Jeong et al., 2004; Museau et al., 2007), different subsystems for MEMS product system were identified. Subsystems of a typical MEMS product system and sub-subsystems of design subsystem are shown in Figure 3.1.

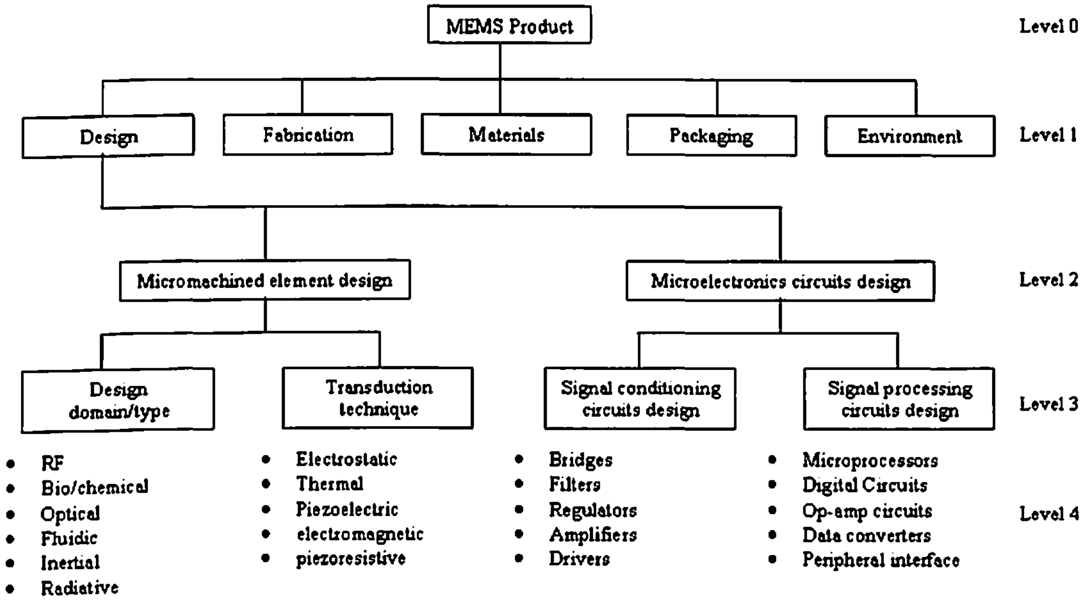


Figure 3.1: Subsystems of a typical MEMS product system and sub-subsystems of design subsystem

3.2.2 Fabrication subsystem

While the microelectronic circuits are fabricated using IC process sequences, the micromechanical components are fabricated using compatible micromachining process that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and/or electromechanical products (Zha and Du, 2003). The fabrication subsystem experts have to identify the process requirements, fabrication technique and the fabrication process equipment/tools. Different sub-subsystems identified for fabrication subsystem are shown in Figure 3.2 (Museau et al., 2007; Zha and Du, 2003; Kovacs et al., 1998; Bustillo et al., 1998; Schmidt, 1998).

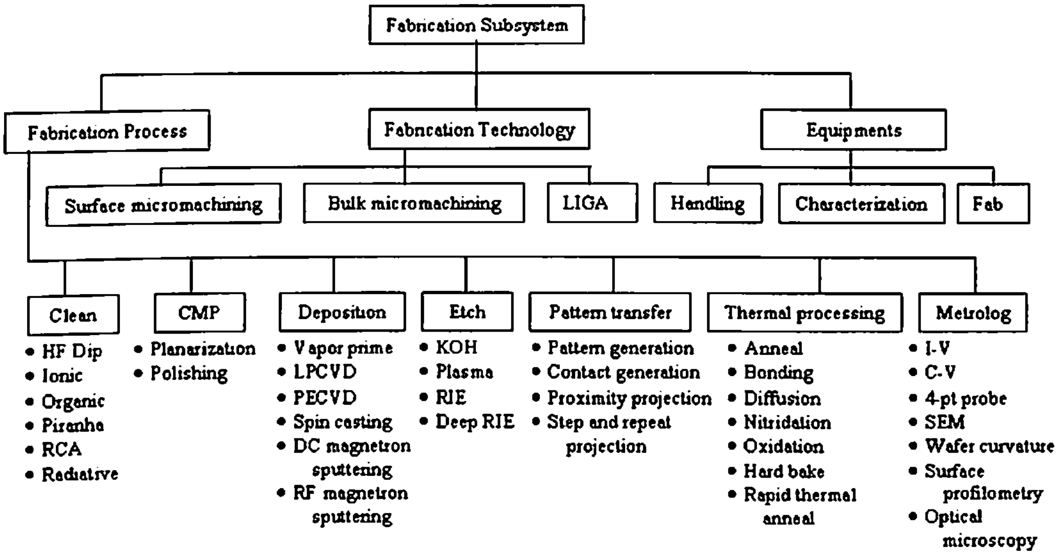


Figure 3.2: Sub-subsystems of fabrication subsystem

3.2.3 Material subsystem

The material property can change the performance of the MEMS product. Since MEMS devices are essentially mechanical, it is required to characterize all the material properties. The material property characteristics and structure help us to understand the electrical, mechanical, optical or magnetic properties of the materials. The usage level of each material can also be structured in a systematic way to understand its use in substrate level or package level or doping level etc. The material subsystem may also have information about the type and availability of materials. Different sub-subsystems identified for materials subsystem are shown in Figure 3.3 (Liu, 2006; Zha and Du, 2003; Judy and Myung, 2002; Gilleo, 2005).

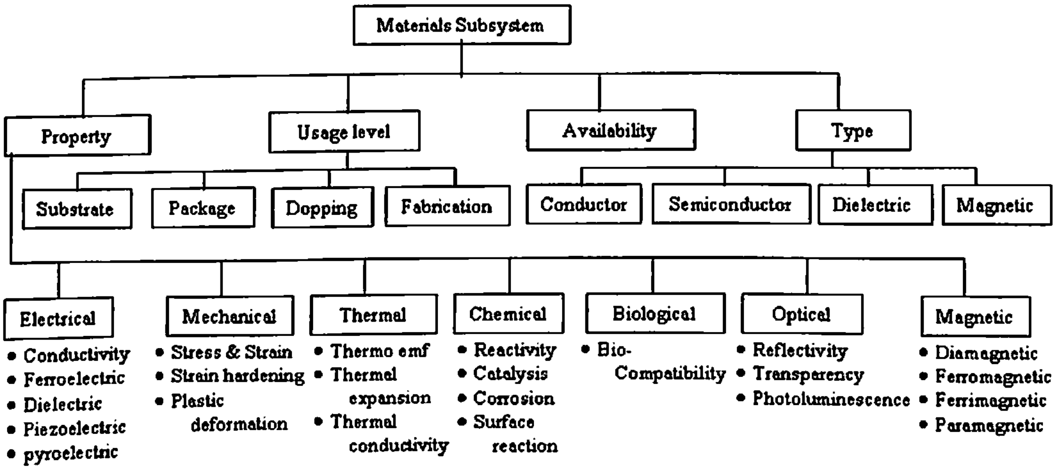


Figure 3.3: Sub-subsystems of materials subsystem

3.2.4 Packaging subsystem

A clear understanding of the package level is required: it may be system level (micromechanical elements and microelectronic circuits), device level (transduction element and signal mapping circuits) or die level (sensing and/or actuation element). The package may provide protection to the MEMS product from the environment or electrical and mechanical disturbances. Packaging process is again a complex structure; it is to be done in coordination with the design and fabrication experts to have better compatibility. Different sub-subsystems were identified for the packaging subsystem and these are shown in Figure 3.4 (Yufeng et al., 2005; O'Neal et al., 1999; Gilleo, 2005; Hsu, 2004).

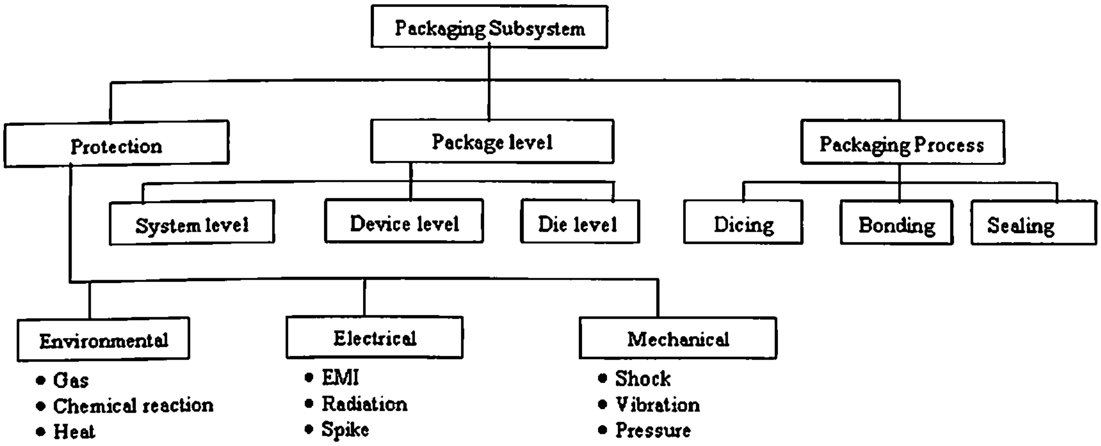


Figure 3.4: Sub-subsystems of packaging subsystem

3.2.5 Environment subsystem

Environment is also a part of the MEMS product system (Mir et al., 2006; Persson and Boustedt 2002). The micromachined element is required to interact with the environment to sense/activate, but at the same time it is to be protected from the environment. The microelectronics circuits are also very sensitive to the environment. It is thus necessary to understand the MEMS product interface domain, the possible noise/disturbance and the compatibility of the chip for the designed environment. Different sub-subsystems were identified for the environment subsystem and these are shown in Figure 3.5 (Mir et al., 2006; Persson and Boustedt, 2002; Tanner et al., 2000; Shea, 2006).

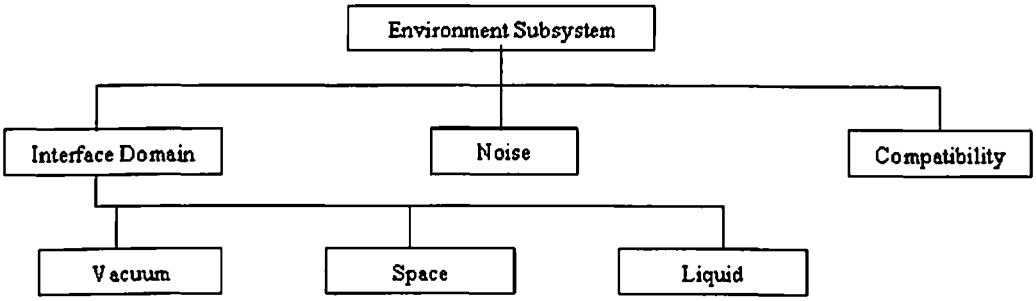


Figure 3.5: Sub-subsystems of environment subsystem

3.3 Hierarchical Structure of MEMS Product System

The hierarchical tree structure helps to understand and analyse the MEMS product system in top-down or bottom-up fashion. Different elements of the system, subsystems, sub-subsystems etc., at each level are identified up to component level. This tree structure helps the industry to develop the product from component level to the system level in the hierarchical order. Normally the tree structure may have (n+1) levels as given below:

Level 0: Total system
Level 1: Subsystems
Level 2: Sub-subsystems
Level 3: Sub-sub-subsystems
|
|
|
|
Level n: Components

A five level tree structure of MEMS product as proposed in Figure 3.1 can be described as:

Level 0: MEMS product system (Total)
Level 1: Design, Fabrication etc. (Subsystems)
As an example for design subsystem (Figure 3.1)
Level 2: Micromachined element design, Microelectronics circuit design (Sub-subsystems)
Level 3: Design type, Transduction technique etc. (Sub-sub-subsystems)
Level 4: RF, Optical etc. (Components)

3.4 Interaction in the Subsystems of the MEMS Product System

The subsystems are interrelated and interdependent on each other in a number of ways. For example, the product designer should consider the environment in which the product is going to be used, the suitable fabrication technique for the design and the package compatible for the product. Materials used in the product fabrication and package should retain their properties under environmental conditions.

Though the tree diagram in Figure 3.1-3.5 developed above represents all the subsystems of the MEMS product system, it fails to include the interdependencies and connectivity among different subsystems. So, a schematic diagram was developed as shown in Figure 3.6. This is an exhaustive schematic diagram, but it was developed to explain the proposed methodology.

Figure 3.6 incorporates all the interactions mentioned above and is in good accord with recent findings regarding interrelationship between subsystems. The design system depends on the kind of environment the product is designed to perform in. The design team has to bother about the fabrication limitation. All the designs may not be able to fabricate with the required tolerance. The package should also be designed along with the product (O'Neal et al., 1999; Velten et al., 2005).

The fabrication subsystem directly depends on the design and from the design specifications the fabrication process can be selected. Packaging schemes should be designed and incorporated into the device fabrication process itself (Chiao and Lin, 2004).

Materials used are to be stable for the operating environmental conditions. The materials used in fabrication and packaging are to be investigated for compatibility, for example in Bio-chip design the materials used must be biocompatible (Grayson et al., 2004).

The package plays a key role in ensuring long-term reliability of a MEMS product and it is to be designed along with the MEMS design. It is ensured that the materials used for the package are studied to give the required protection and isolation from the environment.

The MEMS product communicates with the environment to sense or activate. The environment is more transparent for required parameter monitoring and it should not be harmful to the package. Environment can also change the materials property and product performance.

The interconnection and interaction between these subsystems distinguish one MEMS product from the others and is the cause for their performance variations

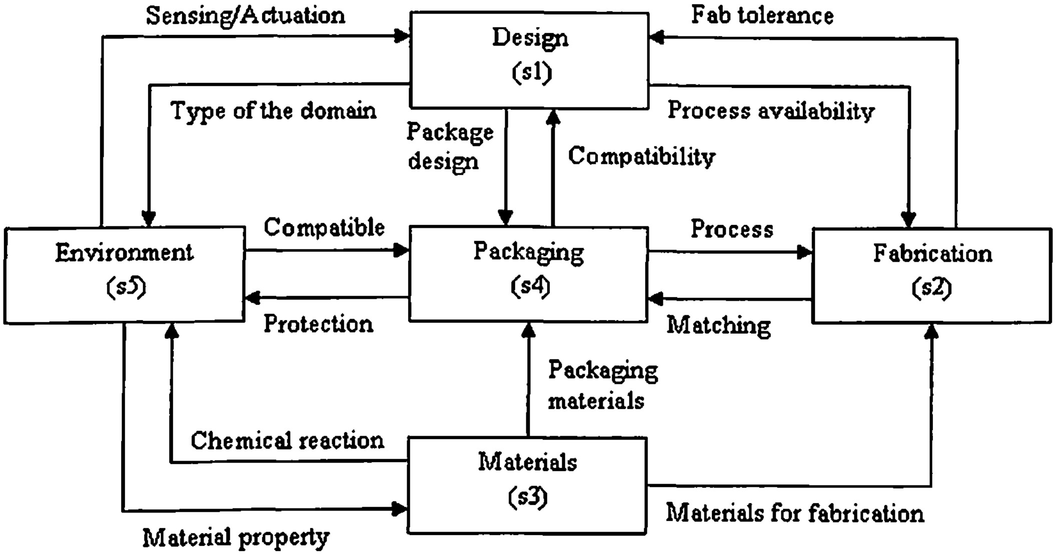


Figure 3.6: Schematic representation of the structure of MEMS product system

3.5 Graph Theoretic Modeling and Analysis of the MEMS Product System

The MEMS product subsystems are connected to each other through different forms of bonding and interactions. The constituents and interactions forming a MEMS product are shown in Figure 3.6. Blocks show the constituents, lines show the connectivity and arrows show the direction of dependency. Though, the schematic diagram is a good representation of the MEMS product structure, it is not a mathematical entity. Hence it is not possible to derive/develop different results as no mathematical operation can be carried out. Mathematical modeling is done using graph theory for systems like power plants, composite industry and manufacturing system (Mohan et al., 2003; Prabhakaran et al., 2006a; Singh and Agrawal, 2008). Thus, for modeling of the MEMS product systems it is meaningful to use the graph theory and matrix algebra (Jurkat and Ryser, 1966).

A MEMS product system may be considered to be a system $[M,I]$of its constituent set $\{M\}=\{M_1,M_2,...,M_n\}$ and interconnection set $\{I\}=\{I_1,I_2,...,I_n\}$, where M_i represents the i^{th} constituent while I_j corresponds to j^{th} interconnection between two corresponding constituents of the MEMS product (Deo, 2004). A graph G has been defined as a function of vertex set and edge set as $G = f\{V,E\}$, where V corresponds to a set of vertices $\{V\} = \{V_1, V_2, ..., V_n\}$ and E corresponds to a set of edges $\{E\} = \{E_1, E_2, ..., E_n\}$ joining different vertices.

For MEMS product system, let vertices corresponds to subsystems (S_i) and the edges (e_{ij}) corresponds to interconnection/connectivity from subsystem S_i to S_j . If the assumption is that all the five subsystems are interacting with each other and have general directional characteristics, the MEMS product has a graph theoretic representation with $e_{ij} \neq e_{ji}$. If the directional property is not significant, the MEMS product is represented by an undirected graph, in this case $e_{ij} = e_{ji}$. The MEMS product graph developed is shown in Figure 3.7. This graph is a useful mathematical entity and is highly useful for the total understanding of the MEMS product for visual analysis. To have a better mathematical representation and information storage MEMS product graph can be represented in the form of various matrix models as discussed in the next section.

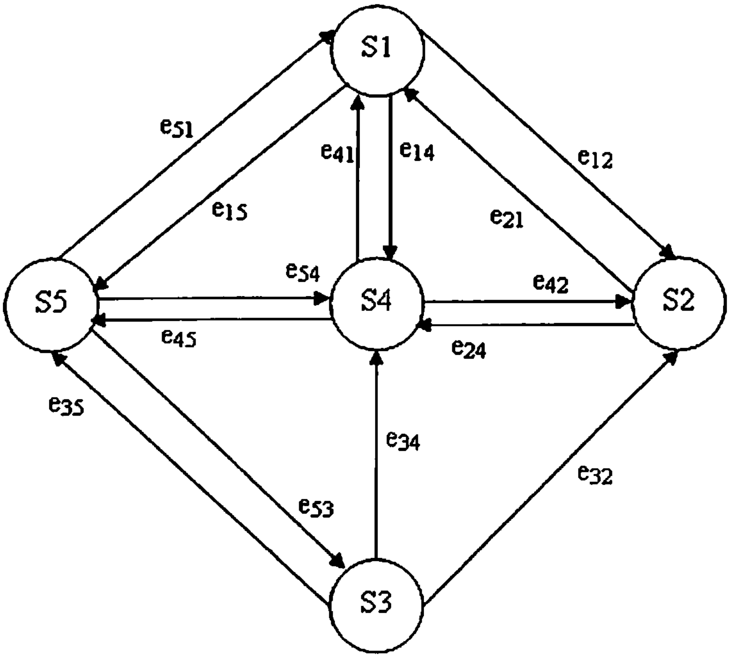


Figure 3.7: MEMS product system graph

3.5.1 Matrix representation for the MEMS product system

Adjacency Matrix (AM-MP)

An alternative to the incidence matrix, it is more convenient to represent a graph by its adjacency matrix/connectivity matrix (Bonchev, 1983). The adjacency matrix of the graph G with five nodes is a five order binary (0, 1) square matrix, $A=[a_{ij}]$ such that:

$$a_{ij}=\begin{cases} 1, & \text{if subsystem } i \text{ has an influence on subsystem } j \\ 0, & \text{if } i \text{ and } j \text{ are not connected} \end{cases}$$
$$\text{where } i,j \in \{1,2,3,4,5\} \text{ and } i \neq j.$$

The MEMS product system Adjacency Matrix (AM-MP), A for the Graph can be written as equation (3.1)

$$\begin{array}{rcl} & \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} & \text{subsystems} \\ A= & \left[\begin{array}{ccccc} 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 \end{array}\right] & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \end{array} \tag{3.1}$$

Characteristic Matrix (CM-MP)

Since the adjacency matrix represents the interrelationships only, in order to represent the MEMS product system characteristic also, another matrix B called Characteristic Matrix (CM-MP) (Deo, 2004) is derived and is given in equation (3.2).

$$\begin{array}{rcl} & \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} & \text{subsystems} \\ B=[\lambda I-A]= & \left[\begin{array}{ccccc} \lambda & -1 & 0 & -1 & -1 \\ -1 & \lambda & 0 & -1 & 0 \\ 0 & -1 & \lambda & -1 & -1 \\ -1 & -1 & 0 & \lambda & -1 \\ -1 & 0 & -1 & -1 & \lambda \end{array}\right] & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \end{array} \tag{3.2}$$

Where λ represents invariant Eigen values of the system; I is the identity matrix of same order as A. The determinant of the MEMS product system characteristics matrix B will lead to an invariant of this matrix and is given in equation (3.3).

$$Det(B)=\lambda^5-6\lambda^3-5\lambda^2 \tag{3.3}$$

The solution of equation (3.3) will give Eigen spectrum i.e. invariant Eigen values.

Interdependencies between the subsystems have been assigned values of 0 and 1 depending on whether they exist or not. However this does not represent varying degree of influence of one subsystem over the other subsystems. To consider this, another matrix called the MEMS product system Variable Characteristic Matrix (VCM-MP) is proposed.

Variable Characteristic Matrix (VCM-MP)

From matrix B , another matrix C , called as MEMS product system variable characteristic matrix is developed as given in equation (3.4).

Consider a five order square matrix E with off-diagonal elements e_{ij} representing known levels of interactions between the subsystems. Another matrix D, a diagonal matrix with diagonal elements representing five different subsystems is defined. The matrix C (VCM-MP) can be given as below:

$$C=[D-E]=\begin{array}{cc} \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} & \text{subsystems} \\ \begin{bmatrix} S_1 & -e_{12} & 0 & -e_{14} & -e_{15} \\ -e_{21} & S_2 & 0 & -e_{24} & 0 \\ 0 & -e_{32} & S_3 & -e_{34} & -e_{35} \\ -e_{41} & -e_{42} & 0 & S_4 & -e_{45} \\ -e_{51} & 0 & -e_{53} & -e_{54} & S_5 \end{bmatrix} & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \end{array} \tag{3.4}$$

The above matrix C permits us to represent complete information about all the five subsystems and interactions amongst them of any industrially useful MEMS product. This information is useful for analysis, design, and development of new MEMS products at conceptual stage or for optimization purposes.

The determinant of the matrix C , is the variable characteristic MEMS product multinomial. It carries both positive and negative signs with some of its terms. The symbolic terms in the multinomial has complete information of the MEMS product system. The complete information in the MEMS product system will not be obtained as some will be lost due to the addition and subtraction of numerical values of the diagonal and off-diagonal elements. Thus the multinomial of the matrix, C in equation (3.4) does not provide complete information concerning the MEMS product system under certain conditions. i.e. when numerical values of e_{ij} and S_i are substituted.

In order to avoid the loss of structural information during mathematical processing, another matrix MEMS product Variable Permanent Matrix (VPM-MP) is proposed.

Variable Permanent Matrix (VPM-MP)

Let the permanent matrix of five-subsystem MEMS product be defined as

$$\begin{array}{cc} & \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & \text{subsystems} \end{array} \\ F= & \left[\begin{array}{ccccc} S_1 & e_{12} & e_{13} & e_{14} & e_{15} \\ e_{21} & S_2 & e_{23} & e_{24} & e_{25} \\ e_{31} & e_{32} & S_3 & e_{34} & e_{35} \\ e_{41} & e_{42} & e_{43} & S_4 & e_{45} \\ e_{51} & e_{52} & e_{53} & e_{54} & S_5 \end{array}\right]\begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \end{array} \qquad (3.5)$$

The above matrix is the most general matrix representation for a MEMS product modeled as five-subsystem MEMS product system. Thus the VPM-MP which corresponds to the five variable subsystems as shown in Figure 3.7 is given in equation 3.6.

$$\begin{array}{cc} & \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & \text{subsystems} \end{array} \\ F= & \left[\begin{array}{ccccc} S_1 & e_{12} & 0 & e_{14} & e_{15} \\ e_{21} & S_2 & 0 & e_{24} & 0 \\ 0 & e_{32} & S_3 & e_{34} & e_{35} \\ e_{41} & e_{42} & 0 & S_4 & e_{45} \\ e_{51} & 0 & e_{53} & e_{54} & S_5 \end{array}\right]\begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \end{array} \qquad (3.6)$$

In the matrix, the diagonal elements represent the contribution of the five subsystems and off-diagonal elements represent interdependencies of subsystems in producing a MEMS product. This model permits the representation of the contribution of each subsystem and interconnection quantitatively without any loss of information in multinomial representation as permanent function.

3.5.2 Permanent function representation for the MEMS product system

Both diagraph and matrix representations are not unique as these models change by changing the labeling of nodes. In order to develop a unique representation of MEMS products, a permanent function of the matrix VPM-MP is proposed. Permanent is a standard matrix function and is used in combinational mathematics (Jurkat and Ryser, 1966; Marcus and Minc, 1965). Procedures for deriving determinant and permanent from the respective matrices are identical except that no negative signs appear in permanent at any stage of its calculation. Thus, permanent function is a unique and complete structural representation of the MEMS product system with the added advantage of using numerical values of each term without any chance of loosing important information in the total numerical index.

The VPM for a MEMS product modeled as five subsystem MEMS product system can be derived from the matrix representation shown in equation (3.6) is given in equation (3.7).

The permanent function for the matrix equation (3.6) corresponding to Figure 3.7, has 28 terms. Because the values of the variables $e_{13}, e_{23}, e_{25}, e_{31}, e_{43},$ and e_{52} are 0 which means interactions are absent, so terms reduce from 120 (5!) to 28. The terms are arranged in six groups in the standard manner. The second group is always absent as self group is not present.

$$\begin{aligned} per(F) = {} & S_1S_2S_3S_4S_5 + (S_1S_2S_3e_{45}e_{54} + S_1S_2S_4e_{53}e_{35} + S_1S_3S_5e_{42}e_{24} + S_3S_4S_5e_{21}e_{12} + S_2S_3S_5e_{41}e_{14} \\ & + S_2S_3S_4e_{51}e_{15}) + (S_1S_2e_{53}e_{34}e_{45} + S_3S_5e_{21}e_{42}e_{14} + S_3S_5e_{41}e_{12}e_{24} + S_2S_3e_{41}e_{15}e_{54} \\ & + S_2S_3e_{51}e_{14}e_{45}) + (S_1e_{32}e_{53}e_{24}e_{45} + S_1e_{42}e_{53}e_{24}e_{35} + S_3e_{21}e_{12}e_{45}e_{54} + S_4e_{21}e_{12}e_{53}e_{35} \\ & + S_4e_{21}e_{32}e_{53}e_{15} + S_3e_{21}e_{42}e_{15}e_{54} + S_2e_{41}e_{53}e_{14}e_{35} + S_2e_{41}e_{53}e_{15}e_{34} + S_3e_{51}e_{12}e_{24}e_{45} \\ & + S_3e_{51}e_{42}e_{15}e_{24}) + (e_{21}e_{12}e_{53}e_{34}e_{45} + e_{21}e_{32}e_{53}e_{14}e_{45} + e_{21}e_{42}e_{53}e_{14}e_{35} + e_{21}e_{42}e_{53}e_{15}e_{34} \\ & + e_{41}e_{12}e_{53}e_{24}e_{35} + e_{41}e_{32}e_{53}e_{15}e_{24}) \end{aligned} \tag{3.7}$$

The loops and dyads (interaction loop between two subsystems) in equation (3.7) are written in a more convenient way in equation (3.8). Here, in place of e_{ij}, e_{ji} the dyad (two subsystem loop) between subsystems S_i and S_j is represented as a loop L_{ij}. A loop between subsystems S_i, S_j and S_k i.e. $e_{ij}e_{jk}e_{ki}$ has been represented as L_{ijk} and the loops $e_{ij}e_{jk}e_{kl}e_{li}$, and $e_{ij}e_{jk}e_{kl}e_{lm}e_{mi}$ are represented by L_{ijkl} and L_{ijklm} respectively. Thus, equation (3.7) has been arranged and written as shown in equation (3.8).

$$\begin{aligned} per(F) = {} & [S_1S_2S_3S_4S_5] + [S_1S_2S_3L_{45} + S_1S_2S_4L_{35} + S_1S_3S_5L_{24} + S_3S_4S_5L_{12} + S_2S_3S_5L_{14} + S_2S_3S_4L_{15}] \\ & + [S_1S_2L_{345} + S_3S_5L_{214} + S_3S_5L_{412} + S_2S_3L_{415} + S_2S_3e_{514}] + [\{S_1L_{24}L_{35} + S_3L_{12}L_{45} \\ & + S_4L_{12}L_{35} + S_2L_{14}L_{35} + S_3L_{15}L_{24}\} + \{S_1L_{3245} + S_4L_{2153} + S_3L_{2154} + S_2L_{4153} + S_3L_{5124}\}] \\ & + [\{L_{12}L_{534} + L_{35}L_{214} + L_{35}L_{412}\} + \{L_{21453} + L_{21534} + L_{41532}\}] \end{aligned} \tag{3.8}$$

The above multinomial consists of distinct subsystems S_i , dyads L_{ij} and loops $e_{ij}e_{jk}...e_{mi}$. The complete permanent function has been written in a systematic manner for the unique representation. In short, it can be represented as:

$$\begin{aligned} per(F) &= f(S_i, L_{ij}, L_{ijk}, L_{ijkl}, L_{ijklm}) \\ &= f(\text{Vertices, dyads, loops}) \\ &= f(\text{structural components}) \end{aligned}$$

The multinomial equation (3.8) is the structural model of the MEMS product system, Figure 3.7 consists of various structural components such as S_i, which represents the characteristic structural features of the i^{th} unconnected subsystem. Similarly L_{ij} is interpreted as 2-subsystem structural dyad and L_{ijk} is 3-subsystem interaction loop. Each term of the multinomial is considered as a set of different structural components. The terms $S_1, S_{2,} S_3, S_4$ and S_5 are considered as a set of five S_i's and the term $S_1S_2S_3$ and L_{45} is read as a collection of three S_i's and one L_{ij}. The terms of the multinomial are expressed in $(N+1)$ groups with $N=5$ in the example; present an exhaustive way of analysis of a MEMS product at different levels. It helps in identifying different constituents, process parameters, design attributes, and the interaction among various subsystems of MEMS product system up to component level.

The terms in the permanent are grouped in to six groups as follows:

Group 1: 1 term

Group 2: 0 term

Group 3: 6 terms

Group 4: 5 terms

Group 5: (5+5) =10 terms

Group 6: (3+3) =6 terms

(1) The first group consists of a single term representing a set of five subsystems singularly representing each subsystem and that is $S_1, S_{2,} S_3, S_4$ and S_5.

(2) The second group terms, if existing should have four singular subsystems and a subsystem dependent on itself (self loop). Such a condition is non-existent in the MEMS product system. Thus the second group is absent. The second group will appear in the presence of self loops i.e. when a subsystem connects itself.

(3) The third group has six terms, each term is a set of three singular subsystems and a dyad (L_{ij}).

(4) The fourth group consists of five terms, which is a set of three subsystem interaction loops (L_{ijk}) and 2-subsystem characteristic structural features.

(5) The fifth group has two subgroups. Each term of the first subgroup is a collection of two 2-subsystem interaction dyads (L_{ij} and L_{kl}) and 1-subsystem characteristic structural features. Each term of the second subgroup is a collection of a 4-subsystem interaction loop (L_{ijkl}) and 1-subsystem characteristic structural features.

(6) The sixth group also has two subgroups. Each term of the first subgroup is a product of 2-element MEMS product subsystem interaction loop (L_{ij}) and 3-element MEMS product subsystem interaction loop (L_{klm}). Each term of the second subgroup consists of a 5-component MEMS product subsystem interaction loop (L_{ijklm}).

The diagonal elements (S_i) were obtained from the subsystem structure graphs. The above procedure analyses the system thoroughly from the perspective of its structure. Since the performance of the MEMS product is dependent on its structure, it can be claimed that its structural analysis and modeling is an indirect way of performance analysis. It is therefore possible for the designer as well as the manufacturer to carry out Strength-Weakness-Opportunities-Threats (SWOT) analysis of their MEMS product system and take strategic decisions to their advantage as per policy.

The diagonal elements of the matrix in equation (3.6) correspond to the five subsystems that constitute a MEMS product system. The values of these diagonal elements $S_1, S_{2,} S_3, S_4$ and S_5 were calculated as

$$S_1 = per(FS_1);\ \ S_2 = per(FS_2);\ \ S_3 = per(FS_3);\ \ S_4 = per(FS_4);\ \ S_5 = per(FS_5)$$

Where FS_1, FS_2, FS_3, FS_4 and FS_5 are the variable permanent matrices (functions or function values) for five subsystems of the MEMS product system. The procedure for calculating $S_1, S_{2,} S_3, S_4$ and S_5 is the same as for calculating $per(F)$ of equation (3.6). For this purpose the subsystems of MEMS product system were considered, and the procedure given below was followed.

(1) The schematic of these subsystems were drawn separately taking into consideration their subsystems values.

(2) The degree of interactions, interconnections, dependencies, connectivity etc., between different sub-subsystems were identified.

Digraph representations like Figure 3.7 of five subsystems were drawn first separately to obtain their matrix equations like equation (3.6). The permanent function of these variable permanent structure matrices gives the values of the corresponding S_i. The off-diagonal elements of the matrix give the interactions between systems. For getting exact degree of dependencies, connectivity, interactions etc., between subsystems or sub-subsystems, it was necessary to consider the views of experts from design, fabrication, packaging, material science, chemistry etc. Thus, the methodology may be applied in a bottom-up approach where in the analysis proceeds from the lowest level to the total MEMS product system level and gives the complete structural evaluation of the MEMS product system as a single index.

3.5.3 Graphical representation of permanent function

The multinomial in equation (3.8) models the structure of MEMS product system completely. The representation can be related to set theory. The complete structure represents a full set; every term of the permanent therefore represents one subset of the full set and has a physical meaning. So every term represents a collection of subsystems of MEMS product system. Graphical representation of the terms of the permanent is given in Figure 3.8. Terms of any group or subgroup represent all possible subsets of the given type shown in Figure 3.8. Each structural subset can be used to develop tests for analyzing structure, design, performance, reliability and quality of the given MEMS product system. The analysis based on this will lead to better understanding and the development of high performance MEMS product system.

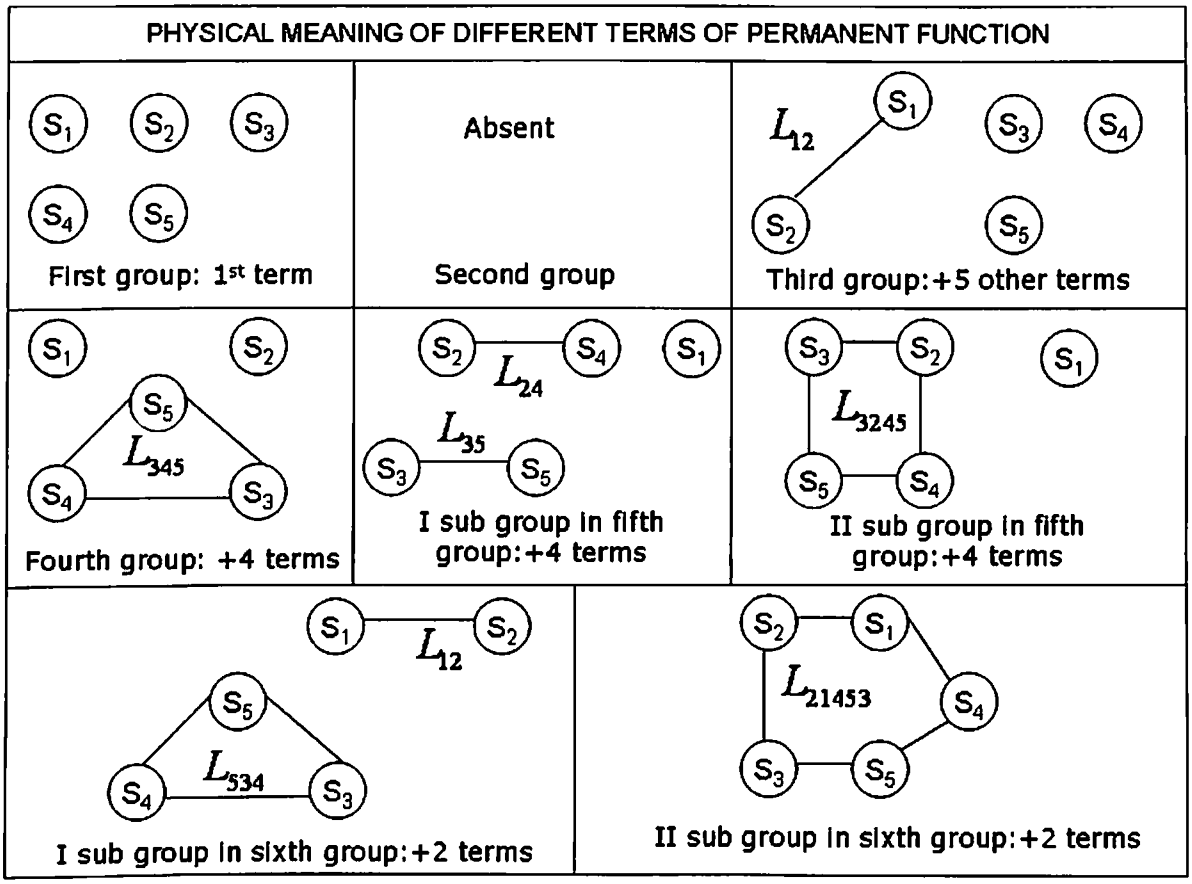


Figure 3.8: Graphical representation of permanent function for MEMS product system

3.5.4 Generalization of the methodology

For a general MEMS product system with N subsystems, the MEMS product system characteristic and interdependence permanent matrix, G may be written as shown in equation (3.9).

$$\begin{array}{ccc} & \begin{array}{ccccc} 1 & 2 & 3 & \ldots & N \end{array} & \text{subsystems} \\ G= & \left[\begin{array}{ccccc} S_1 & e_{12} & e_{13} & \cdots & e_{1N} \\ e_{21} & S_2 & e_{23} & \cdots & e_{2N} \\ e_{31} & e_{32} & S_3 & \cdots & e_{3N} \\ \vdots & \vdots & \vdots & \ldots & \vdots \\ e_{N1} & e_{N2} & e_{N3} & \cdots & S_N \end{array}\right] & \begin{array}{c} 1 \\ 2 \\ 3 \\ \vdots \\ N \end{array} \end{array} \qquad (3.9)$$

For a general N subsystem with all the subsystems linked together, the total number of terms of the permanent function shall be equal to $N!$. Permanent for the above matrix $per(G)$ can be written in sigma form as shown in equation (3.10).

$$
\begin{aligned}
per(G) = {} & \prod_{a=1}^{N} S_a + \sum_i \sum_j \sum_k \cdots \sum_N (e_{ij}e_{ji}) S_k S_l S_m \cdots S_N \\
& + \sum_i \sum_j \sum_k \cdots \sum_N (e_{ij}e_{jk}e_{ki} + e_{ik}e_{kj}e_{ji}) S_l S_m \cdots S_N \\
& + \Bigg[\sum_i \sum_j \sum_k \cdots \sum_N (e_{ij}e_{ji})(e_{kl}e_{lk}) S_m S_n \cdots S_N \\
& + \sum_i \sum_j \sum_k \cdots \sum_N (e_{ij}e_{jk}e_{kl}e_{li} + e_{il}e_{lk}e_{kj}e_{ji}) S_m S_n \cdots S_N \Bigg] \\
& + \Bigg[\sum_i \sum_j \sum_k \cdots \sum_N (e_{ij}e_{ji})(e_{kl}e_{lm}e_{mk} + e_{km}e_{ml}e_{lk}) S_n S_o \cdots S_N \\
& + \sum_i \sum_j \sum_k \cdots \sum_N (e_{ij}e_{jk}e_{kl}e_{lm}e_{mi} + e_{im}e_{ml}e_{lk}e_{kj}e_{ji}) S_n S_o \cdots S_N \Bigg] \\
& + \ldots
\end{aligned} \tag{3.10}
$$

This form of permanent multinomial has been derived from the fact that the terms in the permanent multinomial observe a regular pattern. It may be noted that a permanent function will contain $N!$ terms only, provided the e_{ij}'s are not zero.

3.6 Structural Identification and Comparison of MEMS Product System

In the previous section the MEMS product is represented as a system consisting of five subsystems, which affect property and performance of the final product. This five-subsystem product is represented/modeled as a multinomial, a permanent function. MEMS products are manufactured and used for different applications and will have a different number of terms in different groups and subgroups of their permanent function. By comparing their permanents, similarity and dissimilarity between different MEMS product system can be obtained. Using the proposed methodology, identification of a MEMS product and its comparison with other MEMS product is based on the analysis carried out with the help of VPF-MP. From subsystems and its interactions viewpoint, two MEMS products may be similar if their digraphs are isomorphic. Two MEMS products digraphs are isomorphic if they have identical VPF-MP. This shows that not only the terms are same but also the values are same. On this basis, MEMS product identification can be written as in (3.11):

$$[(J_1 / J_2 / J_3 / J_4 / J_{51} / J_{52} / J_{61} / J_{62} / \ldots)] \qquad (3.11)$$

Where J_i is the total number of terms in the *ith* grouping J_{ij} is the total number of terms in the j^{th} subgroup of i^{th} grouping. If there is no subgrouping, then J_{ij} is same as J_i. The subgroups are arranged in decreasing order of size i.e. based on number of elements in the loop.

A comparison is carried out on the basis of the coefficient of similarity. The coefficient is derived from the structure, i.e. VPF-MP and compares two MEMS products or a set of MEMS products on the basis of similarity and dissimilarity. If the number of distinct terms in the j^{th} grouping of VPF-MP of two MEMS product system under consideration are denoted by J_{ij} and $J_{ij}^{'}$, then three criteria are proposed as follows (Marcus and Minc, 1965).

Criterion 1: The coefficient of dissimilarity C_{d-1} is proposed as

$$\begin{aligned} C_{d-1} &= \frac{1}{Y_1}\sum_i\sum_j \phi_{ij} \\ \text{where } Y_1 &= \max\left[\sum_i\sum_j J_{ij} \text{and} \sum_i\sum_j J_{ij}^{'}\right] \end{aligned} \qquad (3.12)$$

When subgroupings are absent $J_{ij} = J_i$ and $J_{ij}^{'} = J_i^{'}$. When the subgrouping exists $\phi_{ij} = \left|J_{ij} - J_{ij}^{'}\right|$, and when the subgroupings are absent $\phi_{ij} = \left|J_i - J_i^{'}\right|$. Though the criterion 1 developed above present relatively simple method of quantifying the structural difference between the MEMS product system but this may cause loss of comparison information in the coefficient of dissimilarity. This is because ϕ_{ij} is difference of J_{ij} and $J_{ij}^{'}$ depending upon the structural difference in the MEMS product system under consideration. As a result, the subtraction operation may be involved and may cause limitation in the coefficient of similarity. To improve the differentiating power, criterion 2 is proposed.

Criterion 2: The coefficient of dissimilarity C_{d-2} is proposed as

$$C_{d-2} = \left[\frac{1}{Y_2}\sum_i\sum_j \phi_{ij}^2\right]^{1/2}$$
$$\text{where } Y_2 = \max\left[\sum_i\sum_j (J_{ij})^2 \text{and} \sum_i\sum_j (J'_{ij})^2\right] \tag{3.13}$$

When subgroupings are absent $J_{ij} = J_i$ and $J'_{ij} = J'_i$. When the subgrouping exists $\phi_{ij} = \left|J_{ij} - J'_{ij}\right|$, and when the subgroupings are absent $\phi_{ij} = \left|J_i - J'_i\right|$. To increase further the differencing power, criterion 3 is proposed.

Criterion 3: the coefficient of dissimilarity C_{d-3} is proposed as

$$C_{d-3} = \frac{1}{Y_3}\sum_i\sum_j \phi'_{ij}$$
$$\text{where } Y_3 = \max\left[\sum_i\sum_j (J_{ij})^2 \text{and} \sum_i\sum_j (J'_{ij})^2\right] \tag{3.14}$$

When subgroupings are absent $J_{ij} = J_i$ and $J'_{ij} = J'_i$. When the subgrouping exists $\phi'_{ij} = \left|J_{ij}^2 - J_{ij}'^2\right|$, and when the subgroupings are absent $\phi'_{ij} = \left|J_i^2 - J_i'^2\right|$. It is clear that ϕ'_{ij} is larger than ϕ_{ij} .

Using the above three equations, the coefficient of similarity is given as

$$C_{s-1} = 1 - C_{d-1}; \quad C_{s-2} = 1 - C_{d-2}; \quad C_{s-3} = 1 - C_{d-3} \tag{3.15}$$

Where C_{s-1}, C_{s-2} and C_{s-3} are the coefficients of similarity between two MEMS products under considerations based on Criteria 1, 2 and 3. It may be noted that the coefficients of similarity and dissimilarity lie in the range between 0 and 1.

3.6.1 Illustrative example

Two MEMS product systems can be compared using the coefficient of similarity/dissimilarity. Two high performance MEMS motion sensors from Colibrys^{TM} (Colibrys, 2008a) were studied for this purpose. Colibrys^{TM} Motion sensors are ideal products for a wide range of applications in the domains of inertial and tilt /inclination sensing. The robust and low power design combined with an excellent bias stability, guarantee the superior reliability of the MEMS motion sensor. The Colibrys^{TM} MEMS motion sensor is a MEMS capacitive sensor, based upon a bulk micro-machined silicon element, a low power ASIC for signal conditioning, a micro-controller for storage of compensation values and a temperature sensor. The product is low power, calibrated, robust and stable and the electronic configuration provides a solid power on reset and a full protection against brown-out. Long-term stability of bias and scale factor are typically less than 0.1% of full-scale range. For the ± 2g version, typical bias temperature coefficient is 100 μg/°C and scale factor temperature coefficients 100 ppm/°C (Colibrys, 2008a; Colibrys, 2008b). Based on this study the design subsystem up to four levels was identified and is shown in Figure 3.9. This helps the design experts to determine their role in the complete MEMS product design.

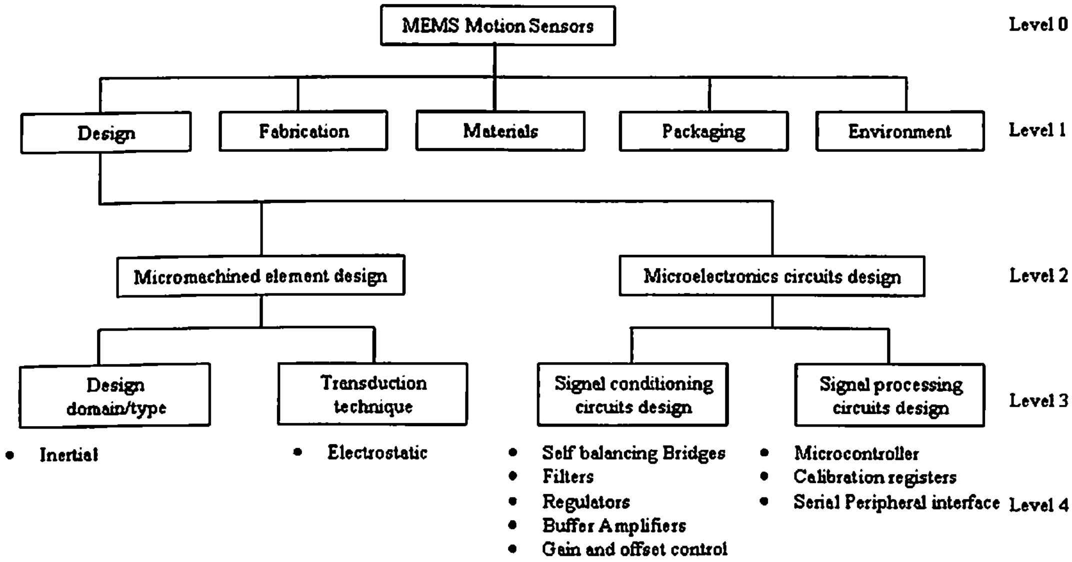


Figure 3.9: Subsystems of MEMS product system and sub-subsystems of design subsystem for MEMS motion sensors.

MEMS Product System 1

MEMS motion sensors are used for seismic sensing, vibration sensing, inertial sensing, tilt sensing etc. Let us consider the MEMS motion sensor FS300L from Colibrys^{TM} designed for seismic sensing (Colibrys, 2008b). This can be used in earthquake detection, geophysics, homeland and border security, structural monitoring, strong motion and railway technology. For applications like earthquake detection, the environment to be sensed is so hazardous that the environment subsystem may affect the product. For such MEMS products the schematic developed in Figure 3.6 is the appropriate representation to show the interaction between the subsystems. The structural identification of this MEMS product system can be given as:

$$J_1/J_2/J_3/J_4/J_{51}/J_{52}/J_{61}/J_{62}/=1/0/6/5/5/5/3/3/.$$

MEMS Product System 2

Let us consider the MEMS motion sensor MS8000.D from Colibrys^{TM} designed for inertial sensing (Colibrys, 2008c). This can be used in automobiles to release the airbag automatically in case of any accident. This MEMS product is not under hazardous environment and the concern of the environment subsystem experts is less in product development. For such MEMS product the interaction between the material subsystem & the environment subsystem is negligible. The new permanent function was obtained after substituting the terms containing element $e_{35}, e_{53} = 0$. The structural identification of this MEMS product system can be given as:

$$J_1/J_2/J_3/J_4/J_{51}/J_{52}/J_{61}/J_{62}/=1/0/5/4/2/2/0/0/.$$

The values of the coefficient of similarity and dissimilarity based on structure by criteria 1, 2 and 3 are written below.

$$\begin{array}{lll} C_{d-1}=0.5; & C_{d-2}=0.54; & C_{d-3}=0.6153 \\ C_{s-1}=0.5; & C_{s-2}=0.46; & C_{s-3}=0.3847 \end{array} \tag{3.16}$$

The above result shows that Criterion 3 has much larger value when compared with Criterion 2 and 1. When two systems are compared with the same number of nodes and difference in edges, changes in the structural complexity occur. Structural complexity is directly reflected in the similarity/dissimilarity coefficient calculated as shown in (3.16).

Since the coefficient lies between 0 and 1, if two systems are structurally similar they are isomorphic, their coefficient of similarity is 1 or dissimilarity is 0. Similarly, in case the two systems are completely dissimilar, their coefficient of similarity is 0 or dissimilarity is 1.

For comparison of two or more MEMS product system or a given family of systems, they are ranked based on the increasing or decreasing value of coefficient of similarity or dissimilarity. Using this, selection of the MEMS product system with desired structure is possible among different alternatives. Structural similarity/dissimilarity is an indirect measure of performance similarity/dissimilarity. Because of this manipulation of structure is a way to develop high performance MEMS product system.

3.7 Usefulness to MEMS Product Industry

The proposed methodology is extremely versatile in nature. It helps the MEMS product industry to provide optimum system characteristics under different applications. The methodology is useful to analyze a MEMS product in the conceptual stage as a large number of alternative solutions based on different designs of sub and sub-subsystems can be generated and evaluated without incurring any cost. The MEMS industry can select their own subsystems for the analysis of their specific product. The decisions at this stage have a very large impact on the final product performance. The methodology can be used to select the optimum MEMS product based on available subsystem, sub-subsystem off-the-shelf from the global market. Since it selects the process, package type, equipment etc. according to user requirement, it is useful for the designer and manufacturer at conceptual stage, design stage and at failed stages of the product development.

The methodology also assists MEMS product industry to compare different products in terms of its characteristics and rate them for particular applications. The methodology may lead the research in a new direction towards global projects of Quantitative Structure Activity Relationship (QSAR) and Quantitative Structure Properties Relationship (QSPR) (Liu et al., 2004; Katritzky et al., 1997). This procedure gives a comprehensive knowledge to the user, designer, manufacturer etc., about the MEMS product selection with right technology at right time and right cost from the market to the right environment. This study can be used to correlate the structure of the system with different performance parameters like reliability, quality, compatibility, cost etc.

3.8 Step-by-Step Procedure to Develop and Use Graph Theoretic Structural Model

The proposed methodology is written in the form of a step-by-step procedure and can be implemented by any existing MEMS industry in developing the graph theoretic model to have a comprehensive understanding of the MEMS product.

Step 1: Consider the desired MEMS product system. Study the complete system and identify subsystem, sub-subsystem up to component level along with their interactions.

Step 2: With the necessary assumptions, develop a hierarchical tree structure of the MEMS product system and interactions.

Step 3: Develop a graph theoretic model of the total system with subsystems as nodes and edges for interaction between nodes (Figure 3.7).

Step 4: Develop the CM-MP matrix and VCM-MP matrix representations.

Step 5: Develop the VPM-MP matrix and permanent functions of distinct subsystems and repeat steps from 2 to 4 for each subsystem.

Step 6: Identify interconnections at different levels of hierarchy of the MEMS product system (i.e. systems, subsystems, sub-subsystems etc.) by grouping the terms of permanent functions.

Step 7: Represent each term as per Figure 3.8 and use it for analysis, evaluation, comparison and optimum selection.

Step 8: Calculate the coefficients of similarity and coefficient of dissimilarity based on structure, between different alternative MEMS product systems.

The above procedure is flexible and capable of meeting the requirements of the industry.

3.9 Conclusions

The following contributions were made forwards structural modeling and integrative analysis of MEMS products:

- To understand the system better and to obtain quality products a MEMS product system consisting of subsystems and sub-subsystems was presented up to component level in the form of hierarchical tree diagram.
- Mathematical models like graph theoretic model, matrix models and permanent models of MEMS product system were developed, which enable us to derive and exploit a number of results that are useful to designers and manufacturers of the system.
- It is brought out clearly that, how the terms of the permanent function can be represented as different subsets of MEMS product system and also can help us

to generate and analyse a large number of design solutions before selecting an optimum system.

- Structural identification set and the coefficients of similarity and dissimilarity were developed and are useful to select optimum set of subsystems up to component level to finally achieve high quality MEMS products in less cost and time by comparing their structures.
- The proposed methodology is explained with an example to distinguish two structurally different MEMS product systems.
- In brief, the proposed structural graph theoretic methodology is comprehensive enough to deal with different structural and performance issues of MEMS product system at different levels of its life cycle.

CHAPTER 4

CODING EVALUATION COMPARISON RANKING AND OPTIMUM SELECTION OF MEMS PRODUCTS

4.1 Introduction

This chapter describes a new methodology that aids the MEMS industry, designer and manufacturer in deciding the subsystems as well as MEMS product system selection. It helps in achieving expected quality and properties of final MEMS product with the help of integrated systems approach and also a decision-making approach based on the attributes identification.

This chapter addresses a number of issues like coding, evaluation, comparison, ranking and optimum selection of MEMS products. Coding/Characterization/Specification of MEMS is proposed to carry out using an exhaustive set of attributes related to design, manufacturing etc. The issues related to evaluation, comparison, ranking and optimum selection fall under three categories viz. Multiple Attribute Decision Making (MADM), Multiple Criteria Decision Making (MCDM) and Multiple Objective Decision Making (MODM). In each of these categories a number of techniques in original forms and their modifications are available. Optimum selection of a particular technique is carried out on the basis of

(i) type of information available

(ii) application e.g. designing a product, manufacturing a product, decision making in social sciences, management, operation research etc.

The selection of a suitable technique for given application (decision making in social sciences, operations research & management etc.) is given in a hierarchical form by Hwang and Yoon (1982). Analytical Hierarchical Process (AHP)-a MCDM approach is recommended for decision making in social sciences, management, etc. while Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)- a MADM approach is recommended for attribute based design evaluation, generation of design alternatives, sensitivity analysis, etc. The main advantages of TOPSIS are:

(i) a sound logic that represents the rationale of human choice

(ii) a scalar value that accounts for both the best and worst alternatives simultaneously

(iii) a simple computation process that can be easily programmed into a spreadsheet, and

(iv) the performance measures of all alternatives can be visualized on a polyhedron, at least for any two dimensions.

These advantages make TOPSIS a major MADM technique as compared with other related techniques such as AHP and ELECTRE etc. (Shih et al., 2007). TOPSIS has been applied successfully in a variety of other disciplines (Agrawal et al., 1992; Bhangale et al., 2004; Jee and Kang, 2000; Prabhakaran et al., 2006b; Satapathy and Bijwe, 2004; Tong et al., 2003; Venkatasamy and Agrawal, 1994; Wang et al., 2000). Deng et al. (2000) has used modified TOPSIS for inter company comparison using entropy measure for weight evaluation. Also a number of modifications in original TOPSIS have been suggested and published (Rao, 2007; Shih et al., 2007; Ren et al., 2007). On the basis of its suitability to address design and manufacturing issues, TOPSIS in the original form was selected in this work for design evaluation of MEMS products. Though AHP enables the decision maker to represent interaction of many factors in a complex unstructured situation, judgments based on observations are fed into AHP for each attribute and sub attribute for all levels of hierarchy. As this type of information and situation does not arise in MEMS design evaluation based on a given set of attributes, TOPSIS is preferred over AHP.

The above techniques consider only crisp attributes and parameters as inputs. But real problems involve vagueness and fuzziness, thus the need to propose a new methodology which can also handle fuzzy parameters/attributes. The TOPSIS approach is efficient in handling multi-domain crisp as well as fuzzy attributes for MEMS product evaluation. In this chapter the methodology for group decision making is further extended because the experts work in teams while designing the product. The proposed approach is based on the attributes for various subsystems.

A decision maker (or expert) is often faced with the problem of ranking/selecting an optimal product from a given set of finite number of alternatives. The chosen alternative is the best product or a compromise option that meets certain predefined objectives/goals.

In MEMS product system selection decision problem, where ranking optimum selection and evaluation is required, MADM situations are characterised by the following interrelated problems: the problems involve vagueness and fuzziness and the decision maker has the difficult task of choosing among the many alternatives to specify the best alternative. The imprecision comes from a variety of sources such as

(i) unquantifiable information

(ii) incomplete information and

(iii) nonobtainable information (Chen and Hwang, 1992).

In many cases the decision maker has inexact information about the alternatives with respect to an attribute.

The classical MADM methods cannot effectively handle problems with such imprecise information. These classical methods, both deterministic and random processes, tend to be less effective in conveying the imprecision and vagueness characteristics. This has led to the development of Fuzzy Set Theory (FST) by Zadeh (1965), who proposed that the key elements in human thinking are not numbers but labels of fuzzy sets. FST is a powerful tool to handle imprecise, incomplete data and fuzzy expressions that are more natural for humans than rigid mathematical rules and equations.

It is obvious that much knowledge in the real world is fuzzy rather than precise. In MEMS product system ranking/selection problems, decision data of MADM problems are usually fuzzy, crisp, or mixture of them. Hence, a useful decision model would incorporate the ability to handle both fuzzy and crisp data. Most of the decision problems in MEMS design involve the work of a team of experts or specialists related to sub-systems say design, fabrication, environment, packaging and materials of MEMS product system and are focused on analysis and evaluation of attributes of the decision-making process. Human opinions often conflict because of group decision-making in fuzzy environment. Consequently, they are, in fact, cases of fuzzy multiple attributive Group Decision Making (GDM) problems. The important challenge of fuzzy multiple attributive GDM is to aggregate conflicting opinions.

Normally, the importance of each expert against an attribute may not be equal. Sometimes there are important experts in decision group, such as the design manager, or some experts who are more experienced than others; the final decision is influenced by the degree of importance of each expert. Therefore, a good method of aggregating multiple expert opinions must consider the attribute-based assigned degree of importance of each expert in the aggregation procedure.

Therefore, this research was devoted to evolving a useful and rational decision making model that provided the ability to handle the aforementioned problems. The primary objective of this research was to contribute to the development of an MADM method with multiple decision makers, capable of working in a fuzzy environment for selecting an optimum MEMS product system.

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and fuzzy TOPSIS have been applied to solve a variety of applications, and are proven methodology in solving MADM and Fuzzy MADM problems (Yoon and Hwang, 1995; Yang and Chou, 2005).

The present study explored the use of TOPSIS and fuzzy TOPSIS to solve the proposed MEMS product system problem. A conceptual model for the proposed methodology has also been explained. Graphical methods like line graph and spider diagram methods have been used successfully to MEMS product system by considering its pertinent attributes in totality. The graphical method is not only the original contribution for design evaluation, comparison and optimum selection of MEMS product, it is very useful when milestones are set to improve the MEMS product design and ultimately to achieve the bench mark product. It is useful for visual analysis of design process at different stages of product development along with comparison with TOPSIS and Fuzzy TOPSIS. The proposed methodology has been explained with the help of an illustrative example for the optimum selection of a micromirror for an optical scanner. Ranking and selection procedure was explained for one subsystem selection i.e. design subsystem for MEMS system. The step-by-step procedure to apply this methodology in MEMS industry and usefulness to MEMS industry has also been addressed.

4.2 Conceptual Model

MADM and fuzzy MADM methods were proposed to overcome aforementioned difficulties. A new algorithm was developed by following three major states along with the conceptual model shown in Figure 4.1. The conceptual model was helpful in understanding the selection procedure in three stages. In the first stage attributes related to the five subsystems to be proposed say design, fabrication, environment, packaging and materials were collected. The sources of these attributes would result from experimental results, group discussion, questionnaires, experience and expert opinions (or performance ratings) about alternatives with respect to subjective attributes. These ratings would generally be in the fuzzy data form. The fuzzy data could be in the form of linguistic or verbal assessments. This kind of qualitative data could be better modeled using fuzzy numbers. Quantitative attributes give crisp values.

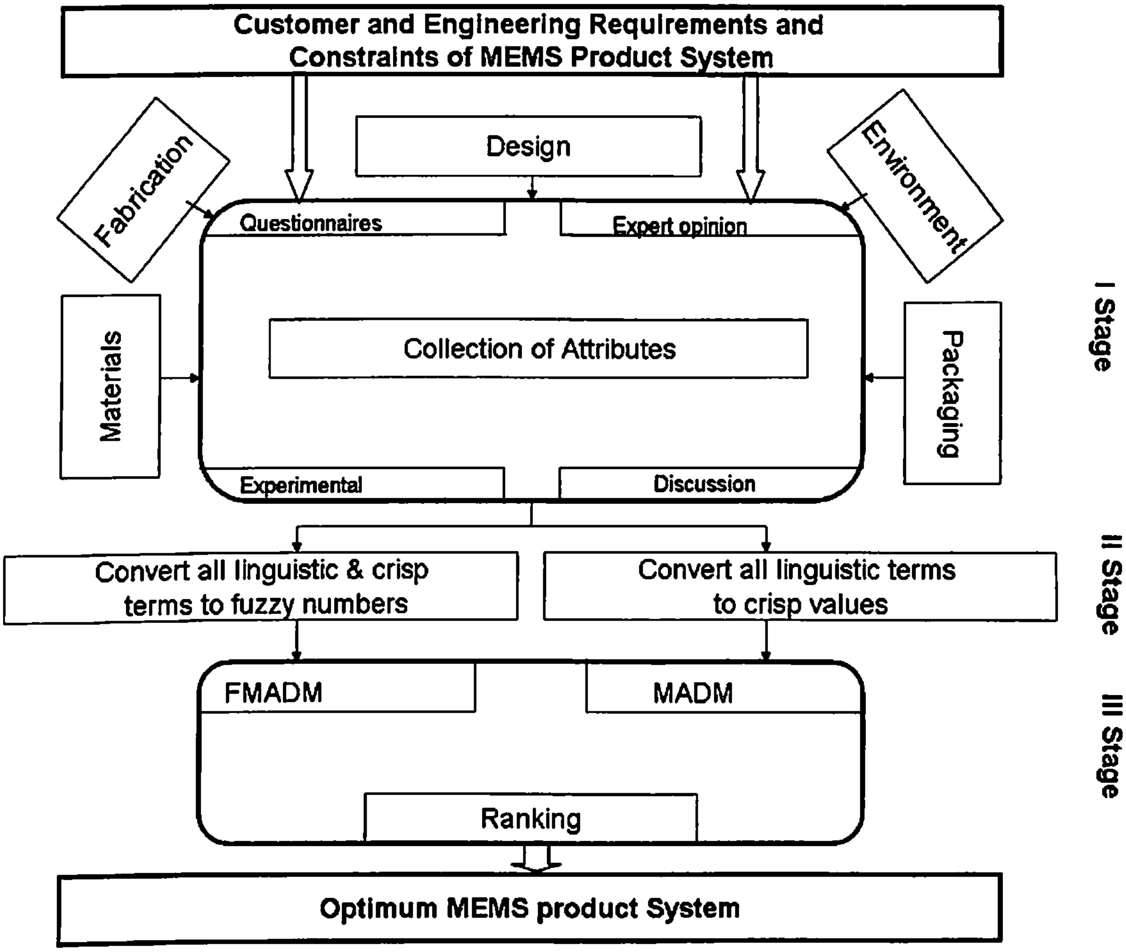


Figure 4.1: The conceptual model for evaluation, ranking and optimum selection of MEMS products

In the second stage, the decision maker could choose MADM (TOPSIS) or fuzzy MADM (fuzzy TOPSIS) method for selecting the optimum product. To apply MADM all linguistic terms would be converted to crisp values and for fuzzy MADM all linguistic and crisp terms would be converted to fuzzy numbers. In the third stage the required method for the best optimum product selection would be applied. It is important to note that the specific methods employed in this particular solution development are for convenience only. The methodology remains valid and representative of actual decision making process even when alternative specific methods are employed.

4.3 Identification of Attributes

Proper identification of relevant attributes is critically important to compare and select a particular MEMS product. A long list of attributes related to total MEMS product system has been developed on the basis of published literature in the form of research papers, books, manufacturer's catalogues, websites etc. It cannot be claimed that this is an exhaustive complete list of attributes or that all these attributes are useful and should be considered by all users of this methodology. The attributes are identified on the basis of the broad area of sub-systems say design, fabrication, environment, packaging and materials of MEMS by considering MEMS product as a system in totality. These attributes play a significant role in selection of suitable design subsystem, fabrication subsystem, environment subsystem, packaging subsystem and materials subsystem.

The attributes are of two types: quantitative/deterministic and qualitative/fuzzy/subjective. Quantitative attributes can be determined or calculated using mathematical models or using experimental methods. Qualitative attributes are subjective in nature and imprecise information is available. It is desirable to evaluate the inheritance/presence of qualitative attributes on one of the several interval scales e.g.0-5, 0-7, etc., for uniformity. Alphabets are used to represent those attributes that cannot be represented by numbers. As different quantitative attributes are measured in different units having different magnitudes, it is difficult to carry out sensitivity analyses to identify critical attributes. So, it is recommended that quantitative attributes be transformed, again on a common interval scale (e.g.0-5 or 0-7) as used in the case of qualitative attributes.

The attributes may be fuzzy in nature where imprecise information is available. Different types of fuzzy functions e.g. triangular, trapezoidal etc. have been reported in literature (Yang and Hung, 2007; Yang et al., 2007).

The quantification procedures of many of these attributes are not readily available from the manufacturers. A team of experts from relevant disciplines would be required to codify all the attributes related to a particular MEMS product. Examples shown in Table 4.1 illustrate the proposed coding for quantitative and qualitative attributes. For example the 0-5 interval scale was used for fill factor (in %): unspecified was assigned as 0, between 0 and 80 as 1, between 81 and 85 as 2, between 86 and 90 as 3, between 91 and 95 as 4 and last greater than 95 was assigned as 5. The qualitative attribute shape was coded as unknown was assigned to 0, circular as CR, rectangular as RR, square as SR , polygon as PN and oval as OL.

Table 4.1: Illustration of coding

Quantitative attributes				**Qualitative Attributes**			
Coding of actuation voltage		***Coding of Fill factor***		***Coding of micromirror shape***		***Coding of type of energy conversion***	
Actuation voltage (V)	**Code**	**Fill Factor (%)**	**Code**	**Shape**	**Code**	**Type**	**Code**
Un-specified	0	Un-specified	0	Unknown	0	Unknown	0
Up to 60	1	Up to 80	1	Circular	CR	Mechanical to other domain	MO
61 to 90	2	81 to 85	2	Rectangular	RR	Electrical to other domain	EO
91 to 120	3	86 to 90	3	Square	SR	Chemical to other domain	CO
121 to 150	4	91 to 95	4	Polygon	PN	Thermal to other domain	TO
Above 150	5	Above 95	5	Oval	OL	Radiative to other domain	RO

Some attributes are common to more than one subsystem and they are grouped into the most relevant subsystem. The design parameters are generally associated with the customer requirements to create an optimum product. Design subsystem attributes (i.e. Shell No: 1-48 in Table 4.2) are very important in determining the performance and specification of a MEMS product (Sasaki et al., 2006; Shin et al., 1997; Seo et al., 1996; Chiou and Lin, 2003; Yee et al., 2000; Lee and Lin, 2004; Ji et al., 2006; Singh et al., 2006; Jain and Xie, 2006; Michalicek and Bright, 2001; Yu and Chen, 2006; Niklaus and Stemme, 2003; Cheng et al., 2005). Attributes related to the fabrication subsystem (i.e. Shell No: 49-68 in Table 4.2) play an important role in product manufacturing (Jain and Xie, 2006; Michalicek and Bright, 2001; Yu and Chen, 2006; Niklaus and Stemme, 2003; Kouma et al., 2005; Hao et al., 2003; Lim and Kim, 1999; Tung and Kurabayashi, 2005). Attributes in the environment subsystem listed in Table 4.2 (i.e. Shell No: 69-82) are to be considered seriously because the MEMS product is interacting with the environment (Cheng et al., 2005; Tung and Kurabayashi, 2005; Boustedt et al., 2002; Bhushan, 2007; Persson and Boustedt, 2002). Packaging is an integral part of the MEMS product and the attributes related are listed under packaging subsystem (i.e. Shell No: 83-91 in Table 4.2) (Wang, 2004; O'Neal et al., 1999). Selection of materials subsystem is another important aspect in MEMS industry. Selection of the appropriate materials based on attributes like conductivity, biocompatibility, coefficient of thermal expansion etc., contribute significantly in improving the quality and performance of MEMS products. The attributes related to materials subsystem are defined in Table 4.2 (i.e. Shell No: 92-101) (Liu, 2006; Velten et al., 2005; Grayson et al., 2004).

Table 4.2: Alphanumeric coding for the design of micromirror for optical scanner applications

Shell No.	Attribute	Information	Code
1.	Pull-in voltage	3 V	2
2.	Maximum rotation angle	7.3°	3
3.	Resonant frequency	670 Hz	3
4.	Actuation voltage	5 V	1
5.	Area of the mirror	$100\times100\ \mu m^2$	3
6.	Resolution	-----	0
7.	Threshold deflection	26.5 μm	2
8.	Settling time	-----	0
9.	Surface reflectivity	85 %	4
10.	Cross axis coupling	-----	0
11.	Actuation accuracy	-----	0
12.	Mirror flatness	-----	0
13.	Light coupling efficiency	-----	0
14.	Radius of curvature	200 cm	3
15.	Power consumption	-----	0
16.	Active area	91%	4
17.	Response time	10 μs	2
18.	DC bias voltage	50	2
19.	Sensitivity	0.01 μm/v	2
20.	Output noise	-----	0
21.	Insertion loss	-----	0
22.	Noise factor	-----	0
23.	SNR	100 dB	3
24.	Phase shift	-----	0
25.	Power loss	-----	0
26.	Switching energy	-----	0
27.	Switching speed	0.1 mSec	3
28.	Pull in angle	2.96°	2
29.	Type of energy conversion	Electrical to other	EO
30.	Form factor	-----	0
31.	Bandwidth	100 KHz	4
32.	Gap between electrodes and	------	0

	mirror		
33.	Frame length	-----	0
34.	Inter electrode gap	79.5 μm	3
35.	Width of electrodes	------	0
36.	Sample size	------	0
37.	Detection limit	-----	0
38.	Rotation angle tolerance	± 0.1°	4
39.	Operating range	------	0
40.	Channel pass band shape	Low pass	LPF
41.	Gain	-----	0
42.	Frequency of oscillation	100 KHz	5
43.	Data rate	-----	0
44.	Phase noise	-----	0
45.	Q-Factor	-----	0
46.	Shape	Oval	OL
47.	Array pitch	2 mm	2
48.	Width of electrodes	-----	0
49.	Fabrication Process type	Bulk-Micromachining	BM
50.	Fill factor	80 %	1
51.	Aspect ratio	10	4
52.	Thickness of the poly silicon	------	0
53.	Fabrication tolerance	±0.2 μm	2
54.	Positional error	-----	0
55.	Alignment accuracy	-----	0
56.	RMS roughness	-----	0
57.	Coefficient of microscale friction	-----	0
58.	Adhesion	-----	0
59.	Surface to volume ratio	-----	0
60.	Deposition rate	-----	0
61.	Etching selectivity	-----	0
62.	Processing temperature	400°K	3
63.	Etch uniformity	-----	0
64.	Sensitivity to over-time etch	-----	0
65.	Surface finish	Good	GD
66.	Surface defects	------	0
67.	Safety of etchants	High	HI
68.	Coast of etchants	Medium	ME
69.	Crosstalk	Very Less	VL
70.	Temperature	100 °K	2
71.	Moisture	-----	0
72.	Vibration	-----	0
73.	Shock	-----	0
74.	Electromagnetic interference	-----	0
75.	Velocity	-----	0
76.	Viscosity	-----	0
77.	Type of energy conversion	Electrical to other	EO
78.	Pressure	------	0
79.	Mechanical Stress	------	0
80.	Gas	-----	0

81.	Corrosion	-----	0
82.	Particles	Non-radiative	NR
83.	Life time	200 month	3
84.	Product volume	1000	2
85.	Release	-----	0
86.	Stiction	-----	0
87.	Dicing	-----	0
88.	Out gassing	-----	0
89.	Thermal expansion	0.01%	3
90.	Extrinsic parasitic effect	-----	0
91.	Thermal conductivity	-----	0
92.	Heat capacity	------	0
93.	Dielectric constant	-----	0
94.	Biocompatibility	Bio-Compatible	BC
95.	Conductivity	10^8	2
96.	Residual stress	------	0
97.	Knoop hardness	-----	0
98.	Young's modulus	168	3
99.	Poisson ratio	-----	0
100.	Melting point	-----	0
101.	Density	8.9	4

4.4 Coding Scheme

A MEMS product system incorporating these 101-attributes was characterized. Each attribute was allotted a serial numbered box (shell no.) in the coding scheme for identification by the computer. Each box was filled by a code/value/number, which represented the presence or inheritance of that particular attribute in a particular MEMS product system. In order to facilitate the selection of pertinent attributes for the application, the attributes were required to be evaluated and coded for range of values. This coding was alphanumeric in nature.

The overall performance of the out-coming product of the MEMS industry directly depends on the proper choice of all these subsystems. The MEMS product should be specified, characterized, processed and evaluated with the help of identified attributes. The attributes were identified based on the selection of five subsystems for a MEMS product system. They are listed in Table 4.2. The first column in this table contains the shell No. while the second, third and fourth columns contain name of attributes, information and codes respectively for the 101-attribute alphanumeric coding scheme as given in Table 4.3.

Table 4.3: An alphanumeric attribute identification coding scheme of a typical MEMS product system-micromirror for optical scanner

Design Subsystem (Shell No: 1-48)	2	3	3	1	3	0	2	0	4	0
	0	0	0	3	0	4	2	2	0	0
	0	0	0	0	0	0	3	2	0	0
	0	0	0	3	0	0	0	4	0	LPF
	0	5	0	0	0	OL	2	0		
Fabrication Subsystem (Shell No: 49-68)	BM	1	4	0	2	0	0	0	0	0
	0	0	0	3	0	0	GD	0	HI	ME
Environment Subsystem (Shell No: 69-82)	VL	2	0	0	0	0	0	0	EO	0
	0	0	0	NR						
Packaging Subsystem (Shell No: 83-91)	3	2	0	0	0	0	3	0	0	
Transduction Subsystem (Shell No: 92-101)	0	0	BC	2	0	0	3	0	0	4

4.5 A Three-Stage Selection Procedure

Though 101 attributes have been identified, all of them would not be equally important while selecting the MEMS product for a particular application. A three-stage selection procedure for optimum selection of candidate from the available large database of alternative candidates was designed for the MEMS industry.

4.5.1 Algorithm of selection process

Stage 1. Elimination Search

This could be achieved by scanning the database for the set of the pertinent attributes, one at a time, to eliminate the MEMS alternatives which have one or more pertinent attribute value that fall short of the minimum required (Threshold) values. Pertinent attributes along with their threshold values would be selected based on application and performance requirements of intermediate subsystems and final system. At the end of this stage all candidates would be feasible. To facilitate this search procedure an identification system has been made for all the MEMS products in the database. This would reduce the unmanageable list of alternatives into a manageable mini-database. A large list of candidate would thus be reduced to a compact list of eligible candidates by using the set of pertinent attributes for a given application as indicated in the method described in the first stage.

Stage *2. Evaluation and Ranking Procedure*

TOPSIS and fuzzy TOPSIS methods were suggested at the second stage for attribute-based evaluation of candidates. The procedure as been elaborated in sections 4.7 and 4.8.

Stage 3. Optimum Selection

The final decision would be taken by the decision makers of the industry for a given application of a MEMS product system after considering other factors which have not been taken into account earlier during evaluation by TOPSIS or Fuzzy TOPSIS, such as cost, human factors, know how, etc. This is necessary, as a computer cannot altogether replace human brain i.e. age-old practice of using experience in selecting subsystems for developing MEMS product system in an industrial environment. The third stage ensures complete flexibility to the industry to take concrete decisions based on the preference list developed at the second stage.

4.6 The Case Study: Illustrative Example

To illustrate the proposed methodology briefly, the optimum selection of a micromirror for a MEMS optical scanner has been considered. Hundred and one attributes have been collected based on five subsystems i.e. design, fabrication, packaging, environment and materials. Of these, forty eight attributes have been identified for design subsystem. Following an elimination search, the design subsystem based attributes that were considered for the selection of a micromirror for a MEMS optical scanner were:

1. Mirror area in μm^2 (X1)
2. Resonant frequency in Hz for Y axis (X2)
3. Max rotation angle in degrees for Y axis (X3)
4. Actuation voltage in Volt (X4)
5. Radius of curvature in cm (X5)
6. Surface reflectivity in % (X6)
7. Rotation angle tolerance in % (X7)

Four mirrors were considered for this example, DuraScan™ mirror developed for low-speed beam scanning application (Mirror1) (Colibrys, 2003), Digital-8™ mirror for optical telecommunication applications (Mirror2) (Colibrys, 2003), Micromirror for a optical scanner in a laser scanning microscope (Mirror3) (Miyajima et al., 2002) and an electrostatically actuated bi-axial micromirror (Mirror4) (Parrain et al., 2005). From the database generated, following an elimination search the manageable number of candidates and their pertinent attributes were identified. They are as listed in Table 4.4.

Table 4.4: Design subsystem decision matrix for the MEMS micromirror

Alternatives/Attributes	X1	X2	X3	X4	X5	X6	X7
Mirror1(M1)	9×10^6	50	12	330	800	96	0.08*
Mirror2 (M2)	2.25×10^6	318	1.8	11	150	96	0.01
Mirror3 (M3)	12.6×10^6	4100	16	200*	244	85	0.1
Mirror4 (M4)	3.15×10^6	500	2	200	200	95	0.05*

* Assumed value

This research explored the use of TOPSIS and fuzzy TOPSIS in solving the proposed micromirror MEMS product system selection problem. The TOPSIS uses specific values for MADM problem, while the fuzzy TOPSIS was applied to the instances of imprecise and fuzzy performance ratings.

The overall objective and sub-functions of the MEMS product were developed based on customer specification and engineering requirements. Alternative concepts satisfying required attributes, functions and objectives were generated using the morphological chart shown in Figure 4.2.

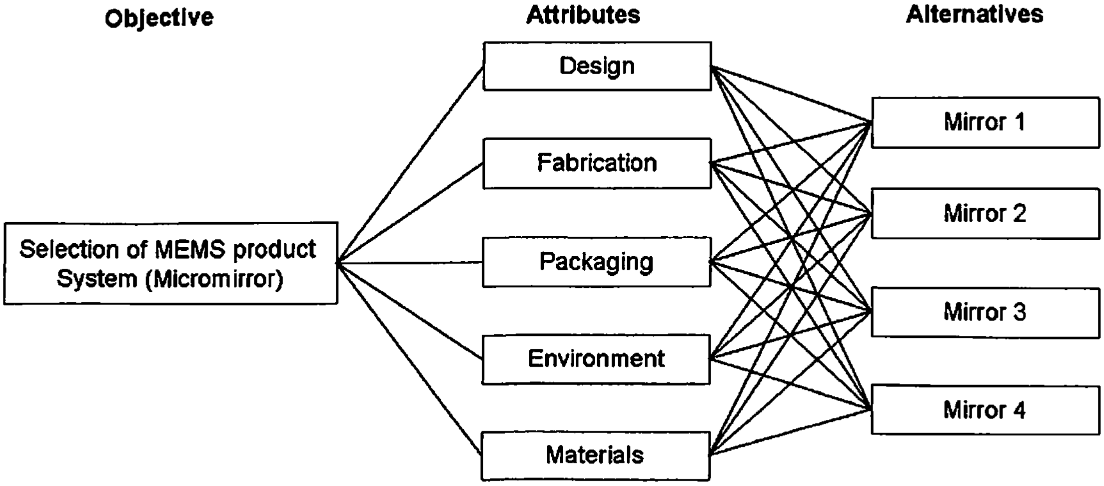


Figure 4.2: Objective-Attribute-Alternative relationship of MEMS micromirror product system

4.7 TOPSIS: An MADM Approach

4.7.1 Principles of TOPSIS

A MADM problem starts by expressing data in the decision/data matrix format, in which columns indicate attributes considered in a given problem; and in which rows list the competing alternatives. Specifically, a MADM problem with *m* alternatives $(\mathrm{M}_1, M_2, ..., M_m)$ that are evaluated by n attributes $(X_1, X_2, ..., X_n)$ can be viewed as a geometric system with m points in n-dimensional space.

Step 1: The mini-database comprises satisfying solutions i.e. alternatives which have all attributes satisfying the acceptable levels of aspiration. All the information available in the database which were satisfying solutions were represented in the matrix form. Such a matrix is called as decision matrix, $D = [d_{ij}]$, where row "i" corresponds to the i^{th} option (i.e. i^{th} MEMS product) and column"j"corresponds to the j^{th} attribute of the i^{th} MEMS product.

$$D = \begin{bmatrix} d_{11} & d_{12} & d_{13} & \cdots & d_{1n} \\ d_{21} & d_{22} & d_{23} & \cdots & d_{2n} \\ d_{31} & d_{32} & d_{33} & \cdots & d_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ d_{m1} & d_{m2} & d_{m3} & \cdots & d_{mn} \end{bmatrix} \tag{4.1}$$

Step 2: TOPSIS allows consideration of the effect of real life applications of the MEMS product during evaluation, comparison and ranking of different alternatives. With the change in the application and the requirements, the relative importance of different attributes also change. To fulfill this need a relative importance matrix $A = [a_{ij}]$ for a given application was proposed. Where

$$a_{ij} = \frac{\text{importance of } i\text{th attribute}}{\text{importance of } j\text{th attribute}} = \frac{w_i}{w_j} \tag{4.2}$$

Where w_i and w_j are the importance weight of the i^{th} and j^{th} attributes respectively. This matrix was prepared by a cross functional team of relevant/subject experts involved from the conceptual stage of this product (Keeney and Raiffa, 1976). The method allowed consideration of the relative importance of a pair of attributes at a time, for the given application only. Only the upper triangular matrix was filled by the experts considering all the needs of the application. The lower triangular matrix terms

$\left(a_{ji}\right)$ were taken as reciprocal of the upper triangular matrix terms $\left(a_{ij}\right)$. All the diagonal elements were unity as the i^{th} attribute was compared with the i^{th} attribute only. A team of experts to the best of their knowledge and experience in application domain would decide the relative importance of each pair of attributes independently (Allen, 2001).

Step 3: Some discrepancy/inconsistency in the relative importance matrix data could be envisaged as only two attributes were compared at a time. To overcome this discrepancy, Eigen value formulation $(A-\lambda I)W=0$ was proposed to find out the weight vector $W=\left\{w_1, w_2, w_3, ..., w_n\right\}$ subject to $\sum w_i = 1$. Maximum Eigen value "λ" was obtained from the Eigen vector $\lambda = \{\lambda_1, \lambda_2, ..., \lambda_{\max}, ..., \lambda_n\}$, using this value of "$\lambda_{\max}$" the vector W was determined (Olson, 2004), where W represents the weights of each attribute as

$$(A-\lambda I)W=0 \tag{4.3}$$

where $W=\left\{w_1, w_2, w_3, ..., w_n\right\}^T$

Step 4: Normalized specification matrix, $N=[n_{ij}]$ was constructed from the decision matrix, $D=[d_{ij}]$. An element n_{ij} of the normalized matrix N could be calculated as

$$n_{ij} = {d_{ij}}\Big/{\left(\sum_{i=1}^{m} d_{ij}^2\right)^{1/2}} \tag{4.4}$$

where $i=1,2,...,m$ and $j=1,2,...,n$. n_{ij} is an element of the normalized decision matrix. It was necessary became different attributes have different units and magnitudes. This put all the attributes in the range 0 to 1.

Step 5: The weighted normalized decision matrix $V=[v_{ij}]$ was determined. It indicated the true comparable values of the attributes based on normalization and application.

$$V=W*N \text{ or } v_{ij}=w_{ij}n_{ij} \tag{4.5}$$

Step 6: It is desirable to compare different alternative MEMS product with some bench marked solutions. Based on benefit/quality criteria and cost/error criteria, positive ideal and negative ideal values of different attributes were identified from available normalized and weighted database of feasible solutions. These solutions were taken as bench marked solutions. The positive ideal V^+ and negative ideal V^- solution were determined using the relation.

$$V^+ = \left[\left(\max_j v_{ij} \Big/ j \in J \right), \left(\min_j v_{ij} \Big/ j \in J', i = 1,2,...,m \right) \right]$$

$$V^+ = \left[v_1^+, v_2^+, ..., v_n^+ \right]^T \tag{4.6}$$

where $J = \{ j = 1,2,3,...,n \}$, $.J'$ is associated with benefit/quality criteria, J is associated with cost/error criteria.

$$V^- = \left[\left(\min_j v_{ij} \Big/ j \in J \right), \left(\max_j v_{ij} \Big/ j \in J', i = 1,2,...,m \right) \right]$$

$$V^- = \left[v_1^-, v_2^-, ..., v_n^- \right]^T \tag{4.7}$$

Step 7: In an attempt to develop an index for ranking, different candidates were represented on an n-dimensional attribute space. Their distances from positive and negative ideal solutions were used to calculate the desired index for ranking. The separation measure S_i^+ and S_i^- were calculated, where a separation from positive-ideal is given by

$$S_i^+ = \left[\sum_{j=1}^{n} \left(v_{ij} - v_j^+ \right)^2 \right]^{1/2} \quad (i = 1,2,...,m) \tag{4.8}$$

and separation from negative-ideal is given by

$$S_i^- = \left[\sum_{j=1}^{n} \left(v_{ij} - v_j^- \right)^2 \right]^{1/2} \quad (i = 1,2,...,m) \tag{4.9}$$

A two attribute (normalized and weighted normalized) representation of the procedure has been illustrated in Figure 4.3.

Step 8: The relative closeness to the positive ideal solution is defined in equation (4.10). The relative closeness to the positive benchmark MEMS, C^+, which is a measure of suitability of the MEMS product for the chosen application on the basis of attributes considered, was calculated. The MEMS product with the largest C^+ was preferred.

$$C_i^+ = S_i^- \Big/ \left(S_i^+ + S_i^- \right) \text{ where } i = 1,2,...,m \tag{4.10}$$

Step 9: C_i^+ varies between 0 and 1. $C_i^+ = 1$ implies that the candidate coincides with positive ideal solution and $C_i^+ = 0$ means that the candidate coincides with negative ideal solution. Then the candidate with the largest C_i^+ was most preferred for a given application. The alternatives were ranked in the decreasing order of suitability/goodness index C^+, indicating the most preferred and the least preferred feasible optimal solutions. The described procedure is illustrated in Figure 4.3 where candidates v_{ij} are represented by two attributes in two-attribute space.

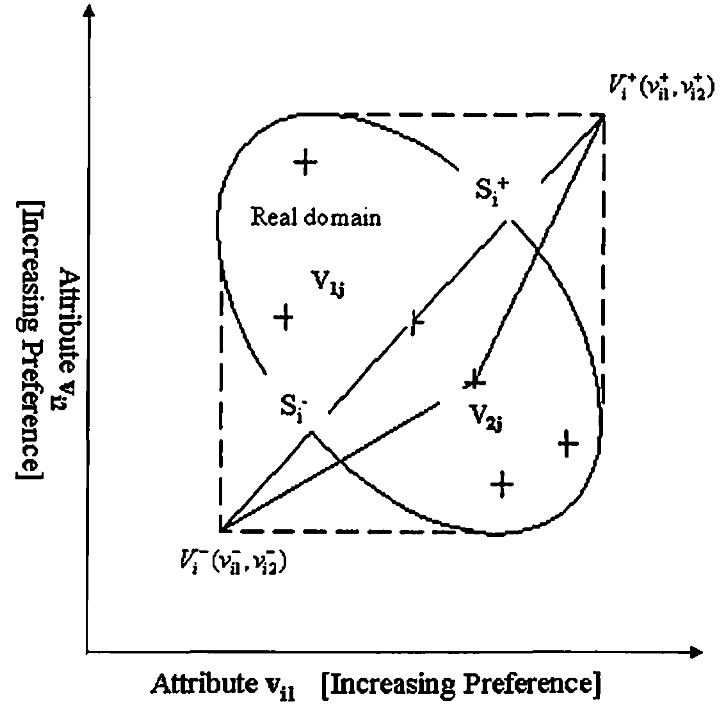


Figure 4.3: A two-attribute (normalized and weighted normalized) representation of a candidate C_i

4.7.2 Empirical illustration for TOPSIS method

Step 1: Formation of a decision matrix also called a data base matrix, "D" from Table 4.4.

$$D = \begin{bmatrix} 9\times10^6 & 50 & 12 & 330 & 800 & 96 & 0.08 \\ 2.25\times10^6 & 318 & 1.8 & 11 & 150 & 96 & 0.01 \\ 12.6\times10^6 & 4100 & 16 & 200 & 244 & 85 & 0.1 \\ 3.15\times10^6 & 500 & 2 & 200 & 200 & 95 & 0.05 \end{bmatrix} \qquad (4.11)$$

Step 2: Construction of a relative importance matrix A. A group of subject experts would determine the relative importance of the attributes with respect to each other for a given application. The symmetric terms would be reciprocal to each other.

$$A=\begin{bmatrix} 1 & 1 & 2 & 0.5 & 1 & 2 & 0.5 \\ 1 & 1 & 2 & 1 & 0.5 & 2 & 1 \\ 0.5 & 0.5 & 1 & 2 & 1 & 0.5 & 1 \\ 2 & 1 & 0.5 & 1 & 2 & 1 & 0.5 \\ 1 & 2 & 1 & 0.5 & 1 & 0.5 & 1 \\ 0.5 & 0.5 & 2 & 1 & 2 & 1 & 1 \\ 2 & 1 & 1 & 2 & 1 & 1 & 1 \end{bmatrix} \tag{4.12}$$

Step 3: Eigen value is formulated and the Eigen spectrum $(\lambda_1, \lambda_2, \ldots.., \lambda_n)$ would be obtained. $\lambda_{\max}$ would be determined and the weight vector W would be calculated from $(A-\lambda_{\max} I)W = 0$. The weight vector obtained using largest Eigen value is $W = \{w_1, w_2, w_3, \ldots.., w_n\}^T$ i.e. satisfying $\sum w_i = 1$.

$$W=\begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ w_5 \\ w_6 \\ w_7 \end{bmatrix} = \begin{bmatrix} 0.14250 \\ 0.154196 \\ 0.119404 \\ 0.145659 \\ 0.130239 \\ 0.141957 \\ 0.166044 \end{bmatrix} \tag{4.13}$$

Where the largest Eigen Value is 7.757943

Step 4: The normalized data matrix (N) would be calculated using equation (4.4),

$$N=\begin{bmatrix} 0.5639 & 0.0121 & 0.5946 & 0.75903 & 0.9164 & 0.5155 & 0.5804 \\ 0.1409 & 0.0768 & 0.0892 & 0.0253 & 0.1718 & 0.5155 & 0.0725 \\ 0.7894 & 0.9896 & 0.7928 & 0.46002 & 0.2795 & 0.4564 & 0.7255 \\ 0.1974 & 0.1207 & 0.0991 & 0.46002 & 0.2291 & 0.5101 & 0.3627 \end{bmatrix} \tag{4.14}$$

Step 5: The weighted normalized decision matrix $[V]$ would be calculated using equation (4.5),

$$V=\begin{bmatrix} 0.08035 & 0.001861 & 0.071003 & 0.11056 & 0.119356 & 0.073177 & 0.096369 \\ 0.02009 & 0.011836 & 0.010650 & 0.003685 & 0.022379 & 0.073177 & 0.012046 \\ 0.11249 & 0.152599 & 0.094671 & 0.067006 & 0.036403 & 0.064792 & 0.120461 \\ 0.02812 & 0.018609 & 0.011834 & 0.067006 & 0.029839 & 0.072415 & 0.060230 \end{bmatrix} \tag{4.15}$$

Step 6: The positive and negative ideal solution would be determined using equations (4.6) & (4.7),

$$V^{+} = \begin{bmatrix} 0.112495 & 0.152599 & 0.094671 & 0.11056 & 0.119356 & 0.073178 & 0.120461 \end{bmatrix} \tag{4.16}$$

$$V^{-} = \begin{bmatrix} 0.020089 & 0.001861 & 0.010651 & 0.003685 & 0.022379 & 0.064792 & 0.0120461 \end{bmatrix} \tag{4.17}$$

Step 7: The separation measure S_i^{+} and S_i^{-} would be calculated using equations (4.8) & (4.9),

$$S_i^{+} = \begin{bmatrix} 0.157784 \\ 0.260755 \\ 0.094066 \\ 0.213242 \end{bmatrix} \tag{4.18}$$

$$S_i^{-} = \begin{bmatrix} 0.187834 \\ 0.013031 \\ 0.232983 \\ 0.080329 \end{bmatrix} \tag{4.19}$$

Step 8: The relative closeness to the ideal solution would be established. The relative closeness to the positive benchmark subsystem C^{+} , which is a measure of the suitability of the subsystem for the chosen application on the basis of attributes considered, would then be calculated using equation (4.10),

$$\begin{aligned} C_1^{\bullet} &= \frac{S_1^{-}}{S_1^{\bullet} + S_1^{-}} = 0.543473 \\ C_2^{+} &= \frac{S_2^{-}}{S_2^{+} + S_2^{-}} = 0.047595 \\ C_3^{+} &= \frac{S_3^{-}}{S_3^{+} + S_3^{-}} = 0.712379 \\ C_4^{+} &= \frac{S_4^{-}}{S_4^{+} + S_4^{-}} = 0.278741 \end{aligned} \tag{4.20}$$

Step 9: The alternative would be ranked in accordance with the decreasing values of indices C_i^{+} , indicating the most preferred and least preferred feasible optional solutions. In this case, the third candidate having highest relative closeness value 0.712379 would be most preferred and the second candidate with lowest relative closeness value 0.047595 is least preferred. The summarized results obtained from TOPSIS are given in Table 4.5.

Table 4.5: TOPSIS analysis results for MEMS micromirror product design subsystem

Alternatives/Results	v_{i1}	v_{i2}	v_{i3}	v_{i4}	v_{i5}	v_{i6}	v_{i7}	S_i^+	S_i^-	C_i^+
M_1	0.08035	0.001861	0.071003	0.11056	0.119356	0.073177	0.096369	0.157784	0.187834	0.543473
M_2	0.02009	0.011836	0.010650	0.003685	0.022379	0.073177	0.012046	0.260755	0.013031	0.047595
M_3	0.11249	0.152599	0.094671	0.067006	0.036403	0.064792	0.120461	0.094066	0.232983	0.712379
M_4	0.02812	0.018609	0.011834	0.067006	0.029839	0.072415	0.060230	0.213242	0.080329	0.278741
v_j^+	0.11249	0.152599	0.094671	0.11056	0.119356	0.073177	0.120461			
v_j^-	0.02009	0.001861	0.010650	0.003685	0.022379	0.064792	0.012046			
W	0.14250	0.154196	0.119404	0.145659	0.130239	0.141957	0.166044			

4.8 Fuzzy TOPSIS: A Fuzzy MADM Approach

4.8.1 Principles of fuzzy TOPSIS

It is often difficult for a decision-maker to assign a precise performance rating/ranking to an alternative for the attributes under consideration. The advantage of using a fuzzy approach is to assign the relative importance of attributes using fuzzy numbers instead of precise numbers. This section extends the TOPSIS to the fuzzy environment. The proposed method is particularly suitable for solving the group decision-making problem under fuzzy environment. The rationale of fuzzy theory before the development of fuzzy TOPSIS is briefly as follows:

A fuzzy set $\tilde{a}$ can be uniquely defined by a membership function $\mu_{\tilde{a}}(x)$, where x is an element in a universe of discourse X. This function can relate with each element x, a real number in the interval [0, 1]. The grade of this membership of element x in $\tilde{a}$ is given by the function value $\mu_{\tilde{a}}(x)$ (Zadeh, 1965). The present analysis is done using triangular fuzzy numbers. For example, a triangular fuzzy number $\tilde{a}$ can be expressed by a triplet $(a_1,\ a_2,\ a_3)$. The mathematical form of this triplet and its conceptual schema are depicted in equation (4.21) (Kaufmann and Gupta, 1985).

$$\mu_{\tilde{a}}(x)=\begin{cases}0, & x\leq a_{1,}\\ \dfrac{x-a_1}{a_2-a_1}, & a_1<x\leq a_2,\\ \dfrac{a_3-x}{a_3-a_2}, & a_2<x\leq a_3,\\ 0, & x>a_3,\end{cases} \tag{4.21}$$

Let $\tilde{a}=(a_1,a_2,a_3)$ and $\tilde{b}=(b_1,b_2,b_3)$ be two triangular fuzzy numbers, then the vertex method is defined to calculate the distance between them, as equation (4.22):

$$d(\tilde{a},\tilde{b})=\sqrt{\frac{1}{3}[(a_1-b_1)^2+(a_2-b_2)^2+(a_3-b_3)^2]} \tag{4.22}$$

Property1: Assuming that both $\tilde{a}=(a_1,a_2,a_3)$ and $\tilde{b}=(b_1,b_2,b_3)$ are real numbers, then the distance measurement $d(\tilde{a},\tilde{b})$ is identical to the Euclidean distance (Chen, 2000).

Property2: Let $\tilde{a},\tilde{b}$, and $\tilde{c}$ be three triangular fuzzy numbers. The fuzzy number $\tilde{b}$ is closer to fuzzy number $\tilde{a}$ than the other fuzzy number $\tilde{c}$ if, and only if, $d(\tilde{a},\tilde{b}) < d(\tilde{a},\tilde{c})$.

The basic operations on fuzzy triangular numbers are as follows:

$$\tilde{a}\times\tilde{b} = (a_1\times b_1, a_2\times b_2, a_3\times b_3) \text{ for multiplication} \tag{4.23}$$

$$\tilde{a}+\tilde{b} = (a_1+b_1, a_2+b_2, a_3+b_3) \text{ for addition} \tag{4.24}$$

Fuzzy MADM can be concisely expressed in matrix format as decision matrix and weight vector as given in equations (4.25) and (4.26) using the fuzzy theory briefed above.

$$\tilde{D} = \begin{bmatrix} \tilde{d}_{11} & \tilde{d}_{12} & \tilde{d}_{13} & \cdots & \tilde{d}_{1n} \\ \tilde{d}_{21} & \tilde{d}_{22} & \tilde{d}_{23} & \cdots & \tilde{d}_{2n} \\ \tilde{d}_{31} & \tilde{d}_{32} & \tilde{d}_{33} & \cdots & \tilde{d}_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \tilde{d}_{m1} & \tilde{d}_{m2} & \tilde{d}_{m3} & \cdots & \tilde{d}_{mn} \end{bmatrix} \tag{4.25}$$

$$\tilde{W} = [\tilde{w}_1, \tilde{w}_2, \ldots, \tilde{w}_n] \tag{4.26}$$

where $\tilde{d}_{ij}, i = 1,2,\ldots,m, j = 1,2,\ldots,n$ and $\tilde{w}_j, j = 1,2,\ldots,n$ are linguistic triangular fuzzy numbers, $\tilde{d}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ and $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$. $\tilde{d}_{ij}$ is the performance rating of the i^{th} alternative, M_i, with respect to the j^{th} attribute, X_j and $\tilde{w}_j$ represents the weight of the j^{th} attribute, X_j.

The normalized fuzzy decision matrix $\tilde{R}$ is given in equation (4.27):

$$\tilde{R} = [\tilde{r}_{ij}]_{m\times n} \tag{4.27}$$

The weighted fuzzy normalized decision matrix is shown as equation (4.28):

$$\tilde{V} = \left[\tilde{v}_{ij}\right] = \begin{bmatrix} \tilde{w}_1\tilde{r}_{11} & \tilde{w}_2\tilde{r}_{12} & \cdots & \tilde{w}_j\tilde{r}_{1j} & \cdots & \tilde{w}_n\tilde{r}_{1n} \\ \tilde{w}_2\tilde{r}_{21} & \tilde{w}_2\tilde{r}_{22} & \cdots & \tilde{w}_j\tilde{r}_{2j} & \cdots & \tilde{w}_n\tilde{r}_{2n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \tilde{w}_1\tilde{r}_{i1} & \tilde{w}_2\tilde{r}_{i2} & \cdots & \tilde{w}_j\tilde{r}_{ij} & \cdots & \tilde{w}_n\tilde{r}_{in} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \tilde{w}_1\tilde{r}_{m1} & \tilde{w}_2\tilde{r}_{m2} & \cdots & \tilde{w}_j\tilde{r}_{mj} & \cdots & \tilde{w}_n\tilde{r}_{mn} \end{bmatrix} \tag{4.28}$$

Given the above fuzzy theory, the proposed fuzzy TOPSIS procedure was then defined as follows:

Step 1: The linguistic attribute ratings $(\tilde{d}_{ij}, i = 1,2,...,m, j = 1,2,...,n)$ for alternatives with respect to criteria and the appropriate linguistic variables ($\tilde{w}_j, j = 1,2,...,n)$ for the weight of the criteria would be chosen.

The fuzzy linguistic rating $(\tilde{d}_{ij})$ preserves the property that the ranges of normalized triangular fuzzy numbers belong to [0, 1]; thus, there is no need for a normalization procedure. For this instance, the $\tilde{D}$ defined by equation (4.25) is equivalent to the $\tilde{R}$ defined by equation (4.27).

Step 2: The weighted normalized fuzzy decision matrix would be constructed. The weighted normalized value $\tilde{V}$ is calculated by equation (4.28).

Step 3: The positive ideal (V^+) and negative ideal (V^-) solutions would be identified. The Fuzzy Positive-Ideal Solution (FPIS, V^+) and the Fuzzy Negative-Ideal Solution (FNIS, V^-) are shown as equations (4.29) and (4.30):

$$V^+ = \left[\left(\max_j v_{ij} \Big/ i = 1,2,...,m \right), j = 1,2,...,n \right]$$

$$V^+ = \left[\tilde{v}_1^+, \tilde{v}_2^+, ..., \tilde{v}_n^+ \right]^T \tag{4.29}$$

$$V^- = \left[\left(\min_j v_{ij} \Big/ i = 1,2,...,m \right), j = 1,2,...,n \right]$$

$$V^+ = \left[\tilde{v}_1^-, \tilde{v}_2^-, ..., \tilde{v}_n^- \right]^T \tag{4.30}$$

Step 4: Separation measures would be calculated. The distance of each alternative from (V^+) and (V^-) could be currently calculated using equations (4.31) and (4.32).

$$d_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^+), i = 1,2,...,m \tag{4.31}$$

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-), i = 1,2,...,m \tag{4.32}$$

Step 5: Similarities to the ideal solution would be calculated. This step solves the similarities to an ideal solution by equation (4.33):

$$CC_i^+ = \frac{d_i^-}{d_i^+ + d_i^-} \tag{4.33}$$

Step 6: The preference order would be ranked. An alternative with maximum CC_i^+ or rank alternatives would be chosen according to CC_i^+ in descending order.

4.8.2 Fuzzy membership function

Linguistic variables are used by decision makers to evaluate the importance of attributes and the ratings of alternatives with respect to various attributes. The present MEMS product design subsystem selection study has only precise values for the performance ratings and for the attribute weights. In order to illustrate the idea, the existing precise/crisp values are deliberately transformed to five-level fuzzy linguistic variables very low (VL), low (L), medium (M), high (H) and very high (VH). The purpose of the transformation process is:

(i) to illustrate the proposed fuzzy TOPSIS method and

(ii) to benchmark the empirical results with other precise value methods in the later analysis.

Among the commonly used various fuzzy numbers, triangular and trapezoidal fuzzy numbers are likely to be the most adoptive ones. Triangular and trapezoidal fuzzy numbers are mostly used due to their simplicity in modeling and easy of interpretation. Both triangular and trapezoidal fuzzy numbers are applicable to the present MEMS product system selection study. Since a triangular fuzzy number can be effectively used to represent the five-level fuzzy linguistic variables and thus, is used for the analysis hereafter.

As a rule of thumb, each rank is assigned an evenly spread membership function that has an interval of 0.30 or 0.25. Based on these assumptions, a transformation table can be developed as shown in Table 4.6. For example, the fuzzy linguistic variable Very Low is associated with the triangular fuzzy number with minimum of 0.00, mode of 0.10 and maximum of 0.25. The same definition is then applied to the other fuzzy variables Low, Medium, High and Very High. Figure 4.4 illustrates the fuzzy membership function.

Table 4.6: Transformation for triangular fuzzy membership function

Rank	Attribute grade	Membership functions
Very low (VL)	1	(0.00, 0.10, 0.25)
Low (L)	2	(0.15, 0.30, 0.45)
Medium (M)	3	(0.35, 0.50, 0.65)
High (H)	4	(0.55, 0.70, 0.85)
Very High (VH)	5	(0.75, 0.90, 1.00)

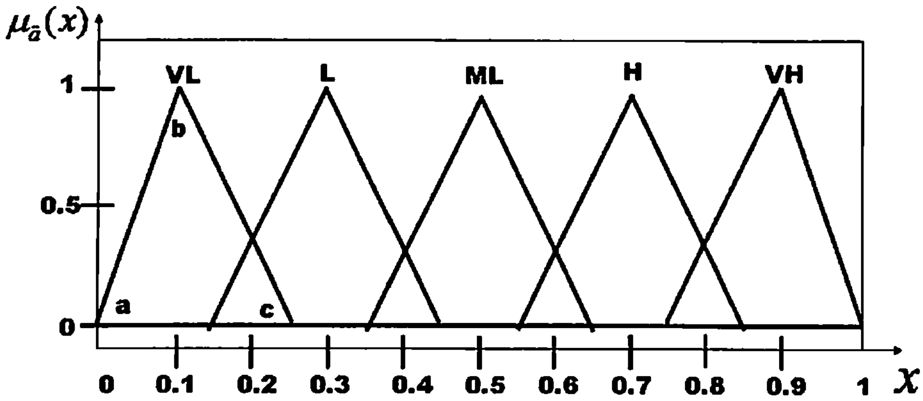


Figure 4.4: Fuzzy triangular membership function

4.8.3 Empirical illustration for fuzzy TOPSIS method

Numeric performance ratings were adapted again from Table 4.4 for the fuzzy TOPSIS analysis. In order to convert the performance ratings to fuzzy linguistic variables, the performance ratings in Table 4.4 were normalized between the range 0 and 1 using equation (4.34).

$$r_{ij} = \frac{x_{ij}}{\max\{x_{ij}\}} \tag{4.34}$$

Table 4.7 tabulates the results of the transformation discussed above.

Table 4.7: Normalized decision matrix for fuzzy TOPSIS analysis

Alternatives/Attributes	X1	X2	X3	X4	X5	X6	X7
M1	0.71	0.01	0.75	1.0	1.0	1.0	0.8
M2	0.18	0.08	0.11	0.03	0.19	1.0	0.1
M3	1.0	1.0	1.0	0.61	0.31	0.89	1.o
M4	0.24	0.12	0.13	0.61	0.25	0.98	0.5
w_j	0.82	0.88	0.70	0.88	0.76	0.82	1.0

Step 1: The fuzzy triangular membership function would be used to transform Table 4.7 into Table 4.8 as explained by the following example. If the numeric rating is 0.24, then its fuzzy linguistic variable is "L". This transformation is also applied to the attribute weights also. Then, the resulting fuzzy linguistic variables are given in Table 4.8.

Table 4.8: Decision matrix using fuzzy linguistic variables

Alternatives/Attributes	X1	X2	X3	X4	X5	X6	X7
M1	H	VL	H	VH	VH	VH	H
M2	VL	VL	VL	VL	VL	VH	VL
M3	VH	VH	VH	H	L	VH	VH
M4	L	VL	VL	H	L	VH	M
W	VH	VH	H	VH	H	VH	VH

The fuzzy linguistic variable would then be transformed into a fuzzy triangular membership function as shown in Table 4.9. The fuzzy attribute weight may also be calculated in Table 4.9.

Step 2: Analysis would be carried to find the weighted fuzzy decision matrix, using the fuzzy multiplication equation (4.23). The fuzzy weighted decision matrix obtained is shown as Table 4.10

According to Table 4.10, the elements $\tilde{v}_{ij}$, $\forall i, j$ are normalized positive triangular fuzzy numbers and they range between the closed interval 0 and 1.

Step 3: The fuzzy positive-ideal solution (FPIS, V^{+}) and the fuzzy negative-ideal solution (FNIS, V^{-}) would be defined as; $\tilde{v}_j^{+} = (1,1,1)$ and $\tilde{v}_j^{-} = (0,0,0), j = 1,2,...,n.$

Step 4: The distance of each alternative from V^{+} and V^{-} could be calculated using equations (4.31) and (4.32).

Step 5: The similarities to an ideal solution would be solved by equation (4.33). The resulting fuzzy TOPSIS analyses are summarized in Table 4.11.

Table 4.9: Fuzzy decision matrix and fuzzy attribute weights for MEMS micromirror

Alternatives/ Attributes	X1	X2	X3	X4	X5	X6	X7
M1	(0.55,0.70,0.85)	(0.00,0.10,0.25)	(0.55,0.70,0.85)	(0.75,0.90,1.00)	(0.75, 0.9, 1.00)	(0.75,0.90,1.00)	(0.55,0.70,0.85)
M2	(0.00,0.10,0.25)	(0.00,0.10,0.25)	(0.00,0.10,0.25)	(0.00,0.10,0.25)	(0.00,0.10,0.25)	(0.75,0.90,1.00)	(0.00,0.10,0.25)
M3	(0.75,0.90,1.00)	(0.75,0.90,1.00)	(0.75,0.90,1.00)	(0.55,0.70,0.85)	(0.15,0.30,0.45)	(0.75,0.90,1.00)	(0.75,0.90,1.00)
M4	(0.15,0.30,0.45)	(0.00,0.10,0.25)	(0.00,0.10,0.25)	(0.55,0.70,0.85)	(0.15,0.30,0.45)	(0.75,0.90,1.00)	(0.35,0.50,0.65)
W	(0.75,0.90,1.00)	(0.75,0.90,1.00)	(0.55,0.70,0.85)	(0.75,0.90,1.00)	(0.55,0.70,0.85)	(0.75,0.90,1.00)	(0.75,0.90,1.00)

Table 4.10: Fuzzy-weighted decision matrix characterizing micromirror

Alternatives/ Attributes	X1	X2	X3	X4	X5	X6	X7
M1	(0.41,0.63,0.85)	(0.00,0.09,0.25)	(0.30,0.49,0.72)	(0.56,0.81,1.00)	(0.41,0.63,0.85)	(0.56,0.81 1.00)	(0.11,0.27,0.45)
M2	(0.00,0.09,0.25)	(0.00,0.09,0.25)	(0.00,0.07,0.21)	(0.00,0.09,0.25)	(0.00,0.07,0.21)	(0.56,0.81,1.00)	(0.00,0.09,0.25)
M3	(0.56,0.81,1.00)	(0.56,0.81,1.00)	(0.41,0.63,0.85)	(0.41,0.63,0.85)	(0.08,0.21,0.38)	(0.56,0.81,1.00)	(0.56,0.81,1.00)
M4	(0.11,0.27,0.45)	(0.00,0.09,0.25)	(0.00,0.07,0.21)	(0.41,0.63,0.85)	(0.08,0.21,0.38)	(0.56,0.81,1.00)	(0.26,0.45,0.65)

Table 4.11: Fuzzy TOPSIS analysis results for MEMS micromirror product design subsystem

Alternatives/ Results	$\tilde{v}_{i1}$	$\tilde{v}_{i2}$	$\tilde{v}_{i3}$	$\tilde{v}_{i4}$	$\tilde{v}_{i5}$	$\tilde{v}_{i6}$	$\tilde{v}_{i7}$	d_i^+	d_i^-	CC_i^+
M_1	(0.41, 0.63,0.85)	(0.00, 0.09,0.25)	(0.30, 0.49,0.72)	(0.56, 0.81,1.00)	(0.41, 0.63,0.85)	(0.56, 0.81 1.00)	(0.11, 0.27,0.45)	3.5231	3.9297	0.52727
M_2	(0.00, 0.09,0.25)	(0.00, 0.09,0.25)	(0.00, 0.07,0.21)	(0.00, 0.09,0.25)	(0.00, 0.07,0.21)	(0.56, 0.81,1.00)	(0.00, 0.09,0.25)	5.6664	1.6828	0.22898
M_3	(0.56, 0.81,1.00)	(0.56, 0.81,1.00)	(0.41, 0.63,0.85)	(0.41, 0.63,0.85)	(0.08, 0.21,0.38)	(0.56, 0.81,1.00)	(0.56, 0.81,1.00)	2.7064	4.8111	0.63999
M_4	(0.11, 0.27,0.45)	(0.00, 0.09,0.25)	(0.00, 0.07,0.21)	(0.41, 0.63,0.85)	(0.08, 0.21,0.38)	(0.56, 0.81,1.00)	(0.26, 0.45,0.65)	4.5768	2.7963	0.37925
v_j^+	(1.00, 1.00,1.00)	(1.00, 1.00,1.00)	(1.00, 1.00,1.00)	(1.00, 1.00,1.00)	(1.00, 1.00,1.00)	(1.00, 1.00,1.00)	(1.00, 1.00,1.00)			
v_j^-	(0.00, 0.00,0.00)	(0.00, 0.00,0.00)	(0.00, 0.00,0.00)	(0.00, 0.00,0.00)	(0.00, 0.00,0.00)	(0.00, 0.00,0.00)	(0.00, 0.00,0.00)			
W	(0.75, 0.90,1.00)	(0.75, 0.90,1.00)	(0.55, 0.70,0.85)	(0.75, 0.90,1.00)	(0.55, 0.70,0.85)	(0.75,0.90, 1.00)	(0.75, 0.90,1.00)			

The calculation of CC_1 is used as an example to illustrate calculations from Steps 4 and 5 and is as follows:

$$d_1^+ = \sqrt{\frac{1}{3}[(1-0.41)^2+(1-0.63)^2+(1-0.85)^2]} + \sqrt{\frac{1}{3}[(1-0.00)^2+(1-0.09)^2+(1-0.25)^2]}$$
$$+\sqrt{\frac{1}{3}[(1-0.30)^2+(1-0.49)^2+(1-0.72)^2]} + \sqrt{\frac{1}{3}[(1-0.56)^2+(1-0.81)^2+(1-1.00)^2]}$$
$$+\sqrt{\frac{1}{3}[(1-0.41)^2+(1-0.63)^2+(1-0.85)^2]} + \sqrt{\frac{1}{3}[(1-0.56)^2+(1-0.81)^2+(1-1.00)^2]}$$
$$+\sqrt{\frac{1}{3}[(1-0.11)^2+(1-0.27)^2+(1-0.45)^2]} = 3.5231$$

$$d_1^- = \sqrt{\frac{1}{3}[(0-0.41)^2+(0-0.63)^2+(0-0.85)^2]} + \sqrt{\frac{1}{3}[(0-0.00)^2+(0-0.09)^2+(0-0.25)^2]}$$
$$+\sqrt{\frac{1}{3}[(0-0.30)^2+(0-0.49)^2+(0-0.72)^2]} + \sqrt{\frac{1}{3}[(0-0.56)^2+(0-0.81)^2+(0-1.00)^2]}$$
$$+\sqrt{\frac{1}{3}[(0-0.41)^2+(0-0.63)^2+(0-0.85)^2]} + \sqrt{\frac{1}{3}[(0-0.56)^2+(0-0.81)^2+(0-1.00)^2]}$$
$$+\sqrt{\frac{1}{3}[(0-0.11)^2+(0-0.27)^2+(0-0.45)^2]} = 3.9297$$

$$CC_1 = \frac{d_1^-}{d_1^+ + d_1^-} = \frac{3.9297}{3.5231+3.9297} = 0.52727$$

Step 6: From Table 4.11, the preferences for the four MEMS product design subsystem alternatives would be as follows: $M_3 > M_1 > M_4 > M_2$.

In this section, in order to illustrate the concept of proposed fuzzy-based method the existing precise/crisp values were deliberately transformed to fuzzy linguistic variables. This illustrates the feasibility of the fuzzy-based method for fuzzy inputs, which is justified by the empirical results.

4.9 Graphical Methods

TOPSIS method is suitable to carry out attribute-based evaluation using computer, as it's a mathematical procedure. To develop a basic understanding of MADM approach, graphical methods were also proposed for evaluation of candidates. Graphical representations help in enhancing the insight and better understanding of the available subsystems and systems. The graphical representation methods used for this purpose were line graph and spider diagram.

4.9.1 Line graph representation

Let the data base matrix D, normalized matrix N and weighted normalized data matrix V , containing information about various pertinent attributes of various alternatives be chosen for study. These candidates can be represented graphically using a line graph by plotting the magnitude of their attributes on the vertical axis and the attribute number on the horizontal axis. For those attributes whose minimum values are preferred such as accuracy, repeatability, cost, etc., it would be better to use the reciprocals of the magnitudes to plot, so that there exists a consistency where all the attributes are to be maximized in order to reach the best possible solution. The values for different candidates were plotted to obtain the line graph for each of them. These graphs were distinct for all types of candidates and could be used as a basis for comparison. The area under the line graph could be used for quantification purpose and to compare different kinds of subsystems with each other, and to benchmark the best selection of candidates for the given application, which is to be defined later.

These line graphs can be plotted for original, normalized and weighted data for all the candidates as well as the benchmarked candidates. The area under the curve is a measure of suitability/goodness of the MEMS product. The larger the area under the curve, the better the product would be. The area under the curve can be estimated as follows.

Let the width between the two parameters on horizontal axis be unity and $d_{ij}, n_{ij,}$ and v_{ij} are the elements of D, N and V matrices on the vertical axis. The area AD_i^L under the line graph of decision matrix for i^{th} alternative can be found out as summation of all trapezium areas A_i under line graph.

$$AD_i^L = \sum_{i=1}^{n} i.A_i A_{i+1}.(i+1) \tag{4.35}$$

$$AD_i^L = \left(d_{i,1} + 2\left(d_{i,2} + \ldots + d_{i,n-1}\right) + d_{i,n}\right)/2 \tag{4.36}$$

Similarly area under the graph of normalized and weighted normalized specifications of the ith alternative, i.e., AN_i^L and AV_i^L can be estimated using their respective elements. Figure 4.5 shows the line graph diagram for seven attributes of four candidate design subsystem as given in illustrative example.

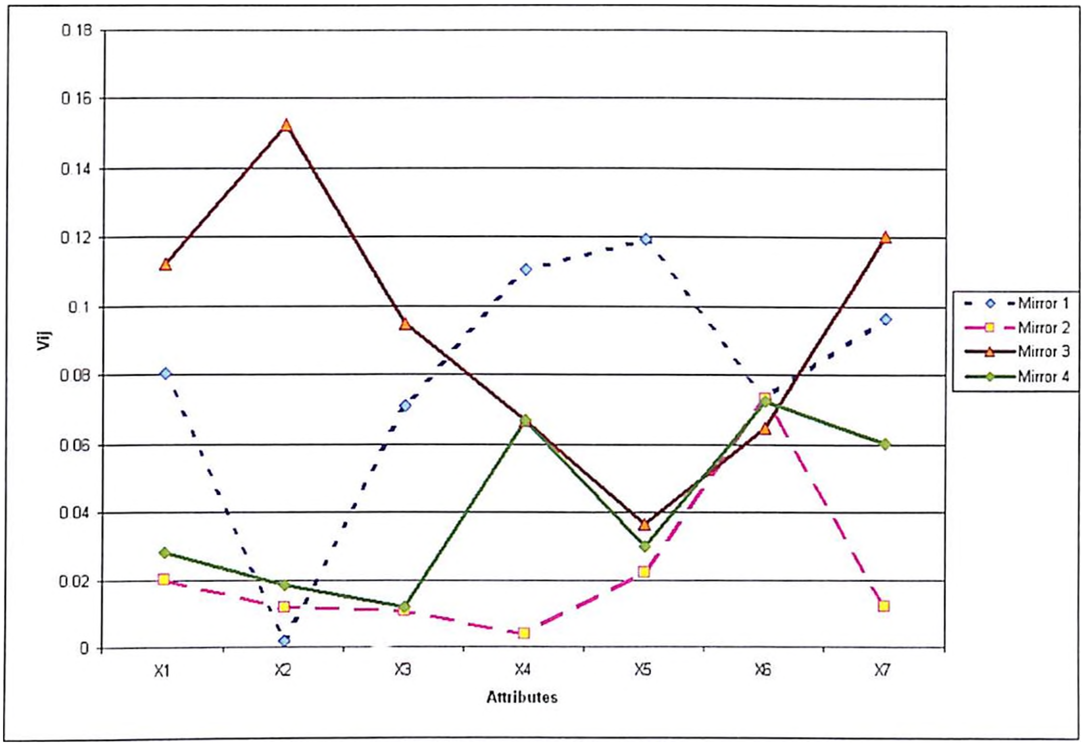


Figure 4.5: Line graph for 7-attribute weighted normalized data matrix

4.9.2 Spider diagram representation

In this method, the attributes have been visualized as forming the spider diagram. So the angle θ between the attribute axes passing through a common point O can be calculated as $\theta = 2\pi/n$, where n is the number of attributes under consideration. The original attributes data d_{ij}, normalized n_{ij} data and weighted normalized v_{ij} data are plotted along the attribute axes θ_i to obtain the spider diagram, also known as polar diagram.

The area enclosed by the polygon formed by joining attribute points on corresponding attribute axes on the spider diagram is the indication of the candidate capabilities/suitability. All the attributes of candidates would be reduced to this single index. The area enclosed by the polygon of the i^{th} candidate can be calculated as follows: In the spider diagram, $\theta = 2\pi/n$, where n is the number of attributes, X_i, $i = 1,2,...,n$.

Let d_{ij} represents the original data value of j^{th} attribute in the i^{th} candidate along θ_i.

Let n_{ij} represents the normalized value of the j^{th} attribute in the i^{th} candidate along θ_i.

Let v_{ij} represents the weighted normalized value of the j^{th} attribute in the i^{th} candidate along θ_i.

The area of spider diagram AD_i^S is calculated as:

$$AD_i^S = \frac{\sin\theta}{2}\sum_{j=1}^{n} d_{ij}d_{i,j+1}; \text{ where } d_{i,n+1} = d_{i,1} \tag{4.37}$$

Similarly for normalized and weighted normalized specifications, areas enclosed by polygons, i.e., AN_i^S and AV_i^S respectively can be calculated. Figure 4.6 shows spider diagram for seven attributes X_i, $i = 1,2,...,7$ based on weighted normalized data matrix for four candidate design subsystem as given in the illustrative example.

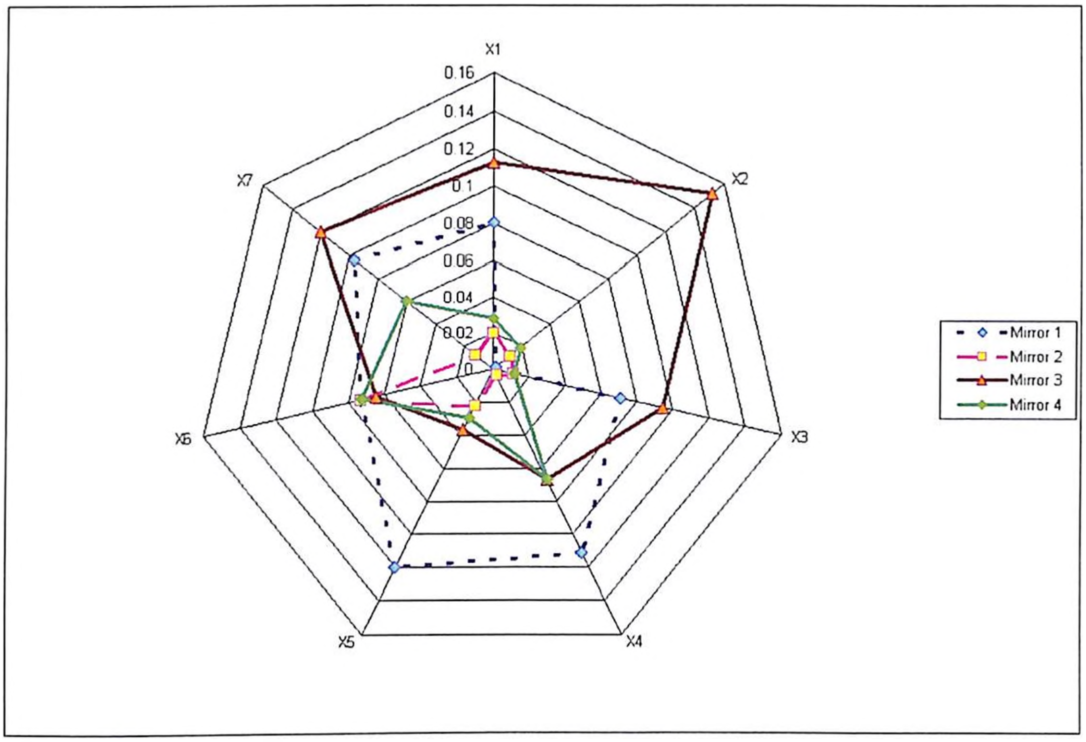


Figure 4.6: Spider diagram polygon for 7-attribute weighted normalized data matrix

4.9.3 Identification and graphical representation of the benchmark design subsystem

The same positive benchmark design subsystem, defined earlier, is used here for the comparison of the candidate design subsystem for the ranking purpose. The areas under the line graph for positive benchmark design subsystem, i.e., AD_B^L, AN_B^L, and AV_B^L would be calculated. The areas enclosed by the polygon of spider diagram for benchmark design subsystem, i.e., AD_B^S, AN_B^S, and AV_B^S would also be determined. All the candidate design subsystems would be compared with the positive benchmark design subsystem for evaluation purposes. This would indicate suitability of the system for the particular task. Let $A_i, i = 1,2,...,m$ be the enclosed areas of 'm' number of candidates. The larger the enclosed area, the better the candidate would be in comparison with the benchmark design subsystem.

4.9.4 Coefficient of similarity

The evaluation and ranking of the MEMS design subsystem using the novel graphical methods was carried out by assessing their similarity to the positive benchmark design subsystem. Let the Coefficient of Similarity (COS) be the ratio of area under the curve or enclosed by the polygon for the candidate to that of the benchmark MEMS design subsystem. The value of COS is a positive fraction $(0 \le \mathrm{COS} \le 1)$ and is a measure of the closeness of candidate MEMS design subsystem with the benchmark one. The candidate with COS magnitude closer to unity would be preferable, since it indicates greater closeness to the positive benchmark MEMS system.

COS based on the decision matrix:

$$COS_j^D = AD_j / AD_l \tag{4.38}$$

Where AD_j is the area for j^{th} design subsystem and AD_l for the benchmark design subsystem.

COS based on the normalized data matrix:

$$COS_j^N = AN_j / AN_l \tag{4.39}$$

Where AN_j is the area for j^{th} design subsystem and AN_l for the benchmark design subsystem.

COS based on the weighted normalized data matrix:

$$COS_j^V = AV_j / AV_l \tag{4.40}$$

Where AV_j stands for the j^{th} design subsystem and AV_l for the benchmark design subsystem.

Thus the COS calculations would be made for all the n number of candidate MEMS design subsystem and for both graphical methods, viz., line graph and spider diagram methods using the weighted normalized data matrices. These also give a basic understanding and insight from the selection point of view. They indicate how the preferences would change during the normalization and weight application process. This could be used for monitoring the process.

4.10 Discussion

Ranking of the design subsystem alternatives are summarized in Table 4.12. All the methods lead to the choice of M_3 design subsystem as the optimum solution. When precise performance ratings are available, the TOPSIS method is considered to be a viable approach in solving a MEMS product system selection problem. In the presence of imprecise or vague performance ratings, the fuzzy TOPSIS is a preferred choice in solving the proposed design problem. M_3 was identified as the best suitable mirror for a MEMS optical scanner application. A micromirror with design subsystem as M_3 was designed, fabricated and tested and the proposed mirror is already in use for scanner application (Miyajima, et al., 2002).

Table 4.12: Evaluation and ranking of the candidate design subsystem using various methods

Method\Design subsystem	M_1	M_2	M_3	M_4
TOPSIS – Closeness to the +ve benchmark design C^+	0.5435	0.0476	0.7124	0.2736
Rank Based on C^+	2	4	1	3
Fuzzy TOPSIS – Closeness to the +ve benchmark design CC_i^+	0.52727	0.22898	0.63999	0.37925
Rank Based on CC_i^+	2	4	1	3
COS Based on Line graph COS^{VL}	0.464317	0.137795	0.531947	0.243878
Rank Based on COS^{VL}	2	4	1	3
COS Based on Spider diagram COS^{VS}	0.009727	0.000704	0.013901	0.002548
Rank Based on COS^{VS}	2	4	1	3

Where COS^{VL} is COS based on the weighted normalized data matrix for line diagram and COS^{VS} is COS based on the weighted normalized data matrix for spider diagram.

4.11 Usefulness to MEMS Industry

- Attribute based characterization of MEMS products is useful for better understanding of its strength, weakness, opportunities and threats (SWOT) to designers, manufacturers, and end users in general.
- Industry can prepare a large database of alternative design solutions of different MEMS products and can reduce development cost and time to market.
- SWOT analysis of existing product helps in improving the product as per market and manufacturing strategies.
- Design for different environments and applications differ in terms of attributes only. Fine refinement of these attributes can be done as per the policy of top management.
- MEMS product system consists of all the subsystems and their related variables, which dictate overall performance, cost etc. This knowledge helps designers & manufacturers to take right decision at right time.
- Attribute based evaluation helps to develop highly customized MEMS product for highly specialized applications with highest quality standards.

4.12 Step-by-Step Procedure

A typical MEMS industry may apply this methodology either for design of new product, analysis of existing product for improvement or to carry out root cause analysis of failed product as follows:

Step 1: Identify aims and objectives, vision, mission and immediate business and manufacturing strategies and purpose of this application.

Step 2: Identify subsystems, sub-sub systems up to component level suitable for the MEMS product under consideration.

Step 3: Identify attributes-structural, performance, cost, reliability etc necessary to satisfy the goal.

Step 4: Develop the desired n-digit alphanumeric code.

Step 5: Develop Decision matrix, Relative importance matrix, Eigen value formulation for weight vector, hypothetical positive and negative ideal solution etc. as per TOPSIS or fuzzy TOPSIS.

Step 6: Find out suitability/goodness index and arrange the candidate MEMS products/solutions in order of preference.

Step 7: Make a decision regarding the generation of optimum product or improvement of existing product or identification of root cause of failed product or minor adjustment/refinement in attributes of existing product to improve competitiveness can be taken.

Step 8: Conduct a sensitivity analysis to identify critical parameters for unique selling proposition.

4.13 Conclusions

This chapter presented effective MADM and fuzzy MADM methods, which are very suitable for solving the multiple attributive GDM problems in a crisp and fuzzy environment where the information available is subjective and imprecise. Mathematical treatment of subjectivity and vagueness through fuzzy numbers was also discussed. A real MEMS design subsystem case study of micromirror was carried out to exemplify the proposed approach.

The main novel elements of the proposed method were as follows:

- Different subsystems, sub-sub systems up to element levels of MEMS product clearly identify all the parameters, which control its design, performance, reliability, cost etc. The adjustment in the critical parameters can make the product highly competitive and reliable.
- Proposed n-digit alphanumeric code is a comprehensive nomenclature of the MEMS products and is very useful for better understanding of the system.
- Coding scheme is very useful for comparison, sensitivity analysis and minor adjustment of parameters for improving its competitiveness.
- TOPSIS and fuzzy TOPSIS approaches carry out attribute-based evaluation of MEMS product. Industry can select a typical set of attributes depending upon their performance and business strategy.
- The identified hypothetically best and worst solutions help industry to set their target and bottom line. In steps resources can be pooled up to improve certain features in the set time.

- The methodology is useful not only for attribute based characterization and evaluation but also for comparison, ranking and optimum selection.
- Graphical procedures-Line diagram and Spider diagram are not only good for visual analysis and evaluation but are used for validating TOPSIS procedure. These diagrams represent original data matrix, normalized data matrix and weighted normalized data matrix to consider subjectivity as well as application. Also positive and negative ideal solutions can be represented by Line & Spider diagrams.

CHAPTER 5

A NEW MEMS PRODUCT OPTIMAL DESIGN AND ANALYSIS USING MADM

5.1 Introduction

Low-cost MEMS product designs are targeted for high-volume applications. These markets include automotive accelerometers, gyroscopes, pressure sensors, ink-jet print heads, optical and RF switching networks, data storage, and disposable chemical analysis systems. Smaller markets for MEMS sensors and actuators that need custom design are ignored due to the high non recoverable cost of design. Today, custom MEMS product design and development involves designers who need to be experts in MEMS processing, MEMS product design, system integration, as well as the final application domain. As in-depth expertise in each of these span field and breath across these domains is extremely difficult to acquire, few custom designs are attempted. Therefore MEMS continues to be dominated by high-volume markets (Mukherjee, 2003; Fedder, 1999). Development of MEMS product/device is slow because MEMS product design, fabrication process development and packaging is complex and still relies on knowledge and experience of MEMS expert from each design stage. Current MEMS design and development process is slow because iterative structural analysis, layout and testing are necessary to reach complete optimal product.

In the past, many MEMS researchers and designers adapted a technology-driven approach to find out what they could do with technology; this involved repeating their design for different process technology runs, component geometries and materials to achieve an optimum MEMS product (Saloman, 2000). Later a hierarchically structured design approach which was borrowed from VLSI industry was adopted. In the design hierarchy schematic capture of a design technology was followed by behavioral simulation, layout generation, parasitic extraction and final verification. Computer Aided Design (CAD) tools enabled devices that had not been constructed to be simulated and prototyped computationally (Estibals et al., 2001). Wherever they are applicable and useful, software modeling tools rapidly gained acceptance by the design community. So MEMS product optimization and evaluation is now done using CAD tools. Without CAD tools, fabrication would remains in the domain of experts, and evolution of the design process would relie on empirical approaches. The design is selected using simulation then the time consuming fabrication process and package development delay the product release. But the final verification of the MEMS product always happens in the lab and CAD tools are used to avoid wasteful and slow experiments by carrying out less expensive computer work in order to get the fabrication right the first time (Maseeh et al., 1990).

Today CAD tools are useful for design verification, but are not often used in the early phases of design. Additionally they are generally useful for in-depth simulation of an individual device in a new process, rather than collection of devices forming an entire microsystem (Clark et al., 2002). The simulation of large MEMS product is often unreachable for designers using Finite Element Analysis (FEA) with less than a few gigabytes of memory, or too time consuming to be practical, taking days to complete (Swart et al., 1998), which transforms semi compliant components to rigid bodies. But hours may still be too time consuming for the user who wants to quickly explore the design possibilities. Alternatively, the simulation may need to be embedded in a design computation that may require thousands of iterations, such as those required for optimization and evolutionary synthesis (Clark et al., 2002).

Current commercial design tools can not deal with complex multi-domain architectures that will be necessary to create the next-generation of commercial MEMS products (Fedder et al., 1995). Some commercial tools implement full, self consistent, three-dimensional simulation of coupled electrostatic devices and can solve for the quasi-static or frequency domain behavior. But these design and evaluation tools are time consuming and computationally costly to simulate the small-amplitude general dynamic behavior of these coupled nonlinear models (Estibals et al., 2001). Fast multi-domain simulation tools are required to ease both process development and design optimization.

These numerical tools by themselves may not be practical for rapid iterative design since physical layout and the process must be changed for each iteration without necessarily knowing what to change to best to improve the device performance. Changing layout is basically varying the design parameters and is a time consuming process. Currently, a self-consistent electromechanical analysis of a simple device requires many person-hours to create the 3-D geometry and perform a numerical analysis. This manual design cycle in MEMS has not decreased significantly over the past few years since knowledge from previous development efforts cannot be easily reused by future developers (Fedder et al., 1995).

Reducing the cost would require the evolution of a methodology that would incorporate cost effectiveness as well as fast tools for optimization. A new methodology that would help the MEMS designer and manufacturer in deciding subsystems as well as MEMS product selection and ranking has been generated using Multiple Attribute Decision Making (MADM) and Fuzzy Multiple Attribute Decision Making (Fuzzy MADM) (Prince and Agrawal, 2009; Prince and Agrawal, 2010). This methodology would help in achieving expected performance and quality of the final product by choosing optimum design specifications, fabrication, package, materials etc. using the systems approach. A new optimal design method has also been reported with an example which reduces the final MEMS product design time and cost (Mamiya et al., 2004).

This chapter discusses a new design flow which supports the total evaluation of MEMS product prior to each product development stage (Design specification, fabrication, package etc.). This design method can clarify and simplify the relation between design parameters and the system characteristics using the MADM/Fuzzy MADM technique. The sensitivity of each design attribute or fabrication attribute or package attribute or material attribute for the system performance could show numerically how the design parameter or fabrication or package or the material parameter influences the system characteristics. The trade-offs between the parameters at any level of product development could be minimized by both modifying design concept and adjusting sensitivities. Therefore MEMS designers would be able to optimize the total product development based on the information from MADM array. This would make the evaluation of system validity possible at the concept design stage. This method at the beginning of development would lead the reduction of the total MEMS design time and cost. The proposed method would save time and cost in the development process because design optimization would be performed first, followed by verification using existing tools. Similarly fabrication process, package could also be optimized, followed by application of existing methods.

RF MEMS encompasses several distinct types of devices, including RF switches and relays, resonators, varactors and inductors. Applications of RF MEMS include all types of wireless communications, radar, satellites, military, radio, instrumentation and test equipment. Compared to conventional RF components, RF MEMS offer significant benefits, including lower power consumption, lower insertion loss, lower cost and smaller form factor (Mansour et al., 2003). RF MEMS have come to market more recently than other types of MEMS, but the RF MEMS market is now growing rapidly. An RF MEMS power sensor was designed for selecting the best design specification system and the proposed design flow has been explained. Optimized design results obtained have been presented and were verified using CAD tools. Sensitivity analysis was carried out by varying design attributes of the RF power sensor. The results clearly highlight the power of the methodology.

5.2 Traditional MEMS Product Design Methodology

The MEMS products that are successfully achieved the performance and cost targets have required, on an average between 4 to 10 years from concept to final volume production and market insertion. The time consuming factor in most cases has been the persistence in using a traditional MEMS product design and manufacturing approach (Da Silva et al., 2002). Figure 5.1 shows a traditional MEMS product design and manufacturing flow. It is difficult for the MEMS product designers to predict the total system performance and design required for the MEMS device structures at the beginning of the product development stage. Mostly MEMS product development starts from device level designs based on the concept and limitation, which are derived from system demands (Mamiya et al., 2004). Design concepts are implemented in a manual layout and then the performance is analyzed using numerical analysis tools. A large number of iterations are required to achieve an optimal design solution. These numerical analysis tools are time consuming and take large amounts of memory during simulations. Finding critical design attribute/parameter is also done in the same manner. Microelectronics design and fabrication is already a well developed method so the number of iteration required is less. Further development processes, fabrication, packaging and testing also involve many iterations. Because of this the total product development is labor-intensive, time consuming and cost-effective.

The total MEMS product development time of the system becomes extremely long when using the traditional design methodology. Figure 5.2 shows the traditional MEMS product development time chart. Since the final MEMS product is matured through several evolutions, most of the products in the market are established based on a combination of design concepts. A new development cannot begin without completing the former development stage.

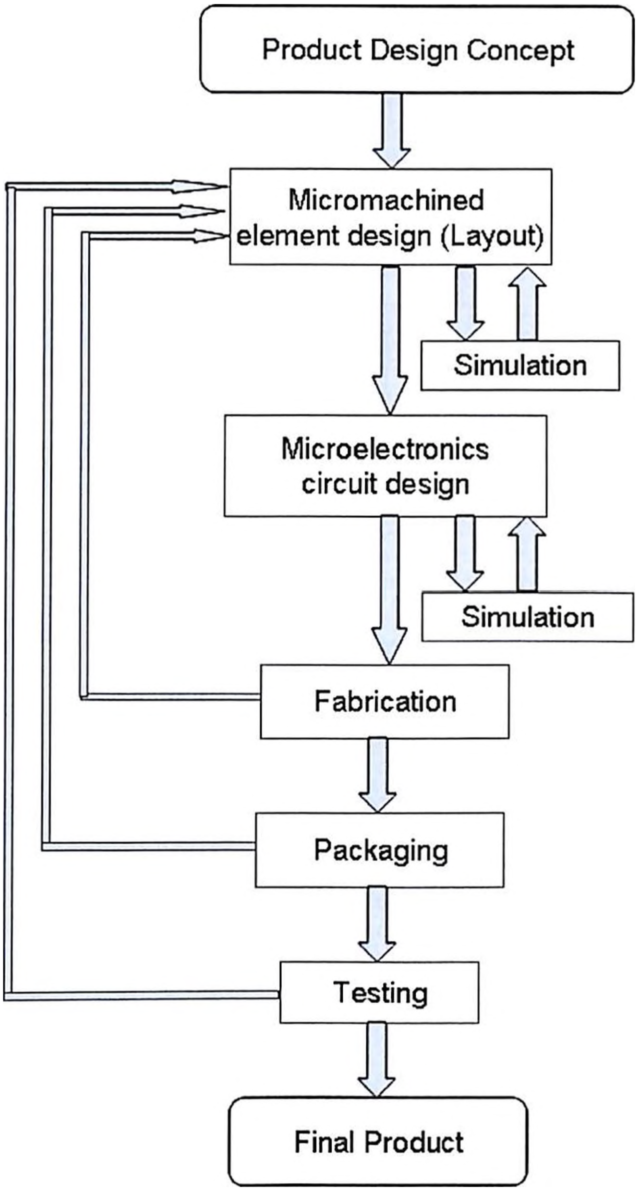


Figure 5.1: Traditional MEMS product design and manufacturing flow.

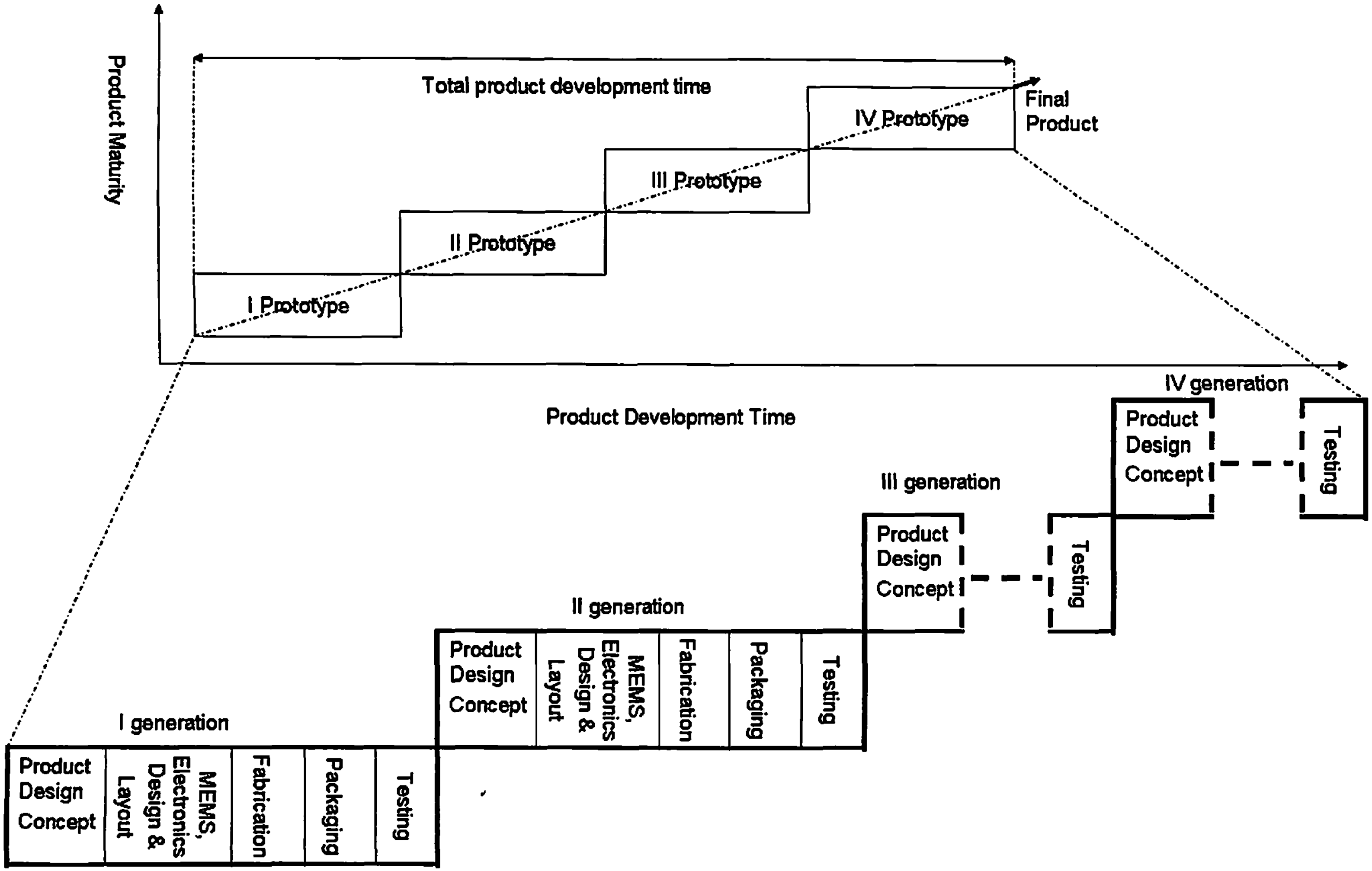


Figure 5.2: Traditional MEMS product development time chart.

There have been several references in literature to top down design approaches that reduce the product development time (Senturia, 1998; Fedder, 2000). These methods use models called 'macro models' or 'reduced order models' and can be used in place of computationally expensive full three dimensional or FEA tools (Estibals et al. 2001). But developing MEMS macro models is an art which requires a lot MEMS knowledge, experience and skills. Besides, even with macro models, an optimum solution can not be achieved without several iterations.

5.3 New MADM/Fuzzy MADM Based Methodology

Even for a simple structure it is very difficult to predict the performance, because MEMS is an inter-disciplinary area which includes electrical, mechanical, chemical, optical, RF and bio engineering. Therefore simplifying the MEMS product system and rough evaluation of the total performance are important at the conceptual deign stage itself. MADM and Fuzzy MADM are new design methodologies that enable all MEMS designers and manufactures to understand the relationship between parameters/attributes and performance of the final product in the conceptual stage and also in each development stage (design, fabrication, packaging, testing etc). This is done by sensitivity analysis i.e. by varying required attributes and determining the rank. A total evaluation can also be done which gives optimum solution or very nearly optimum solution depending on the weight matrix. If the weight matrix is well defined, then a very optimum solution can be obtained. If the obtained solution is nearly optimum then less number of iterations would be required during product development.

Figure 5.3 shows the MEMS product design flow diagram using MADM. Since MADM/Fuzzy MADM enables design evaluation at the conceptual design stage, wasteful iterative design analysis, verification and iterative prototyping processes are not needed. Note that only the iterative process is replaced by MADM. MADM algorithm runs in the computer using the existing database and takes less time. Figure 5.4 shows the MEMS product development time chart for the new method. When compared with the traditional MEMS development, the total time to reach the optimum product is reduced when using the new method. This is only because MADM concept design methodology shrinks iterative design, fabrication and package of the MEMS product system prototyping. Thus the next concept can be immediately created, immediately after the previous concept, on the basis of the MADM design information. Hence the total development time and cost will be drastically reduced.

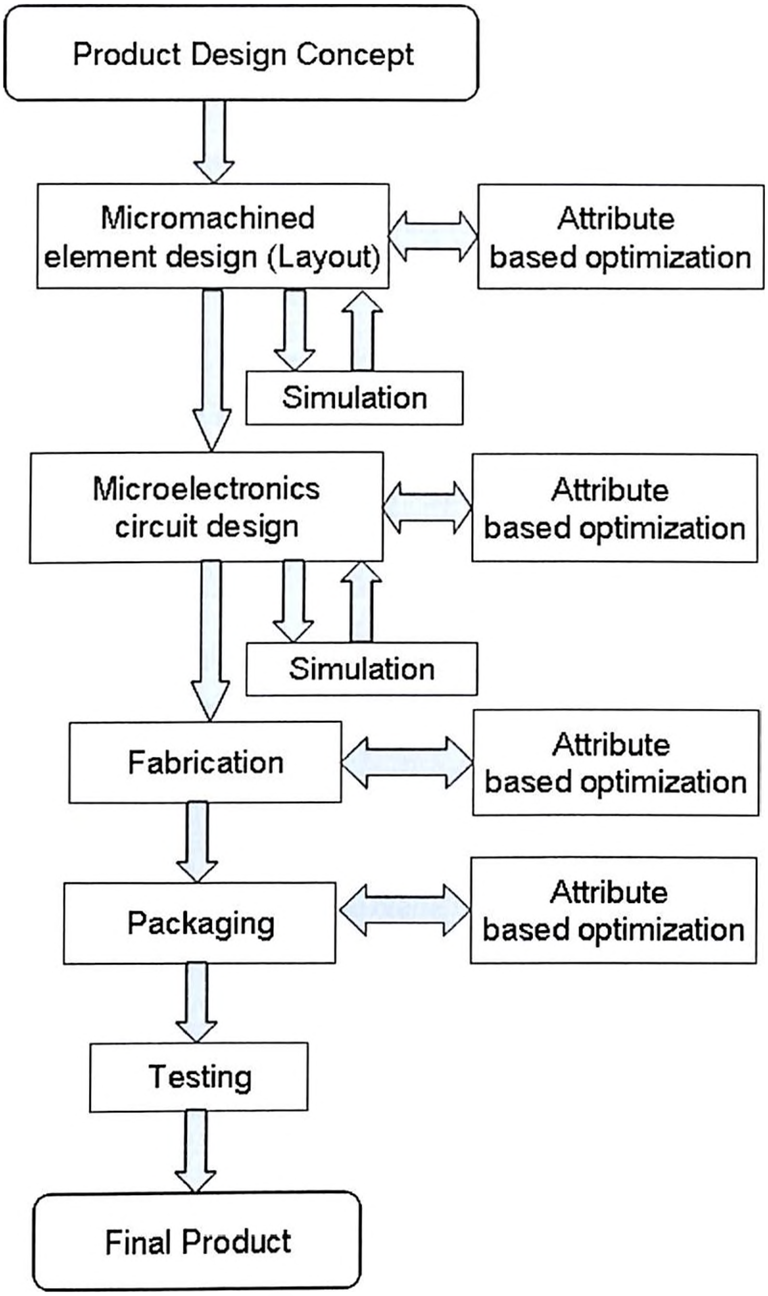


Figure 5.3: New MEMS product design and manufacturing flow using MADM.

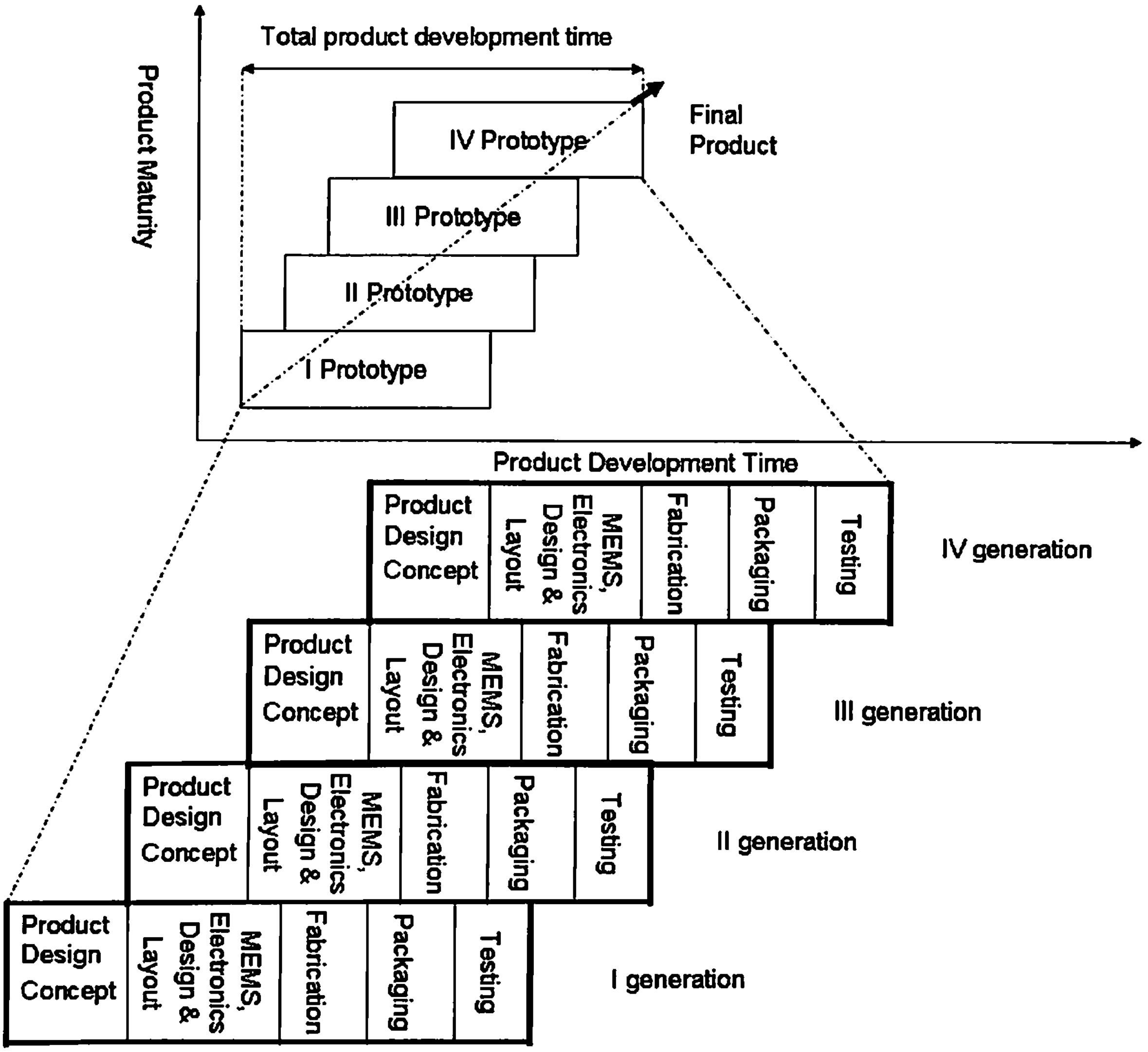


Figure 5.4: New MEMS product development time chart using MADM.

5.4 Design Example RF MEMS Power Sensor

In order to explain the proposed design methodology using MADM, this section considers the example of RF MEMS power sensor, which is used to measure the power of the RF signal flowing in a line. Figure 5.5 shows the schematic of the proposed RF MEMS power sensor looking from the conductor side. Figure 5.5 (a) is the 3D view, Figure 5.5 (b) is the top view and Figure 5.5 (c) is the cross section view. Similarly Figure 5.6 shows the schematic of the proposed RF MEMS power sensor looking from the bridge side. Figure 5.6 (a) is the 3D view, Figure 5.6 (b) is the top view and Figure 5.6 (c) is the cross section view.

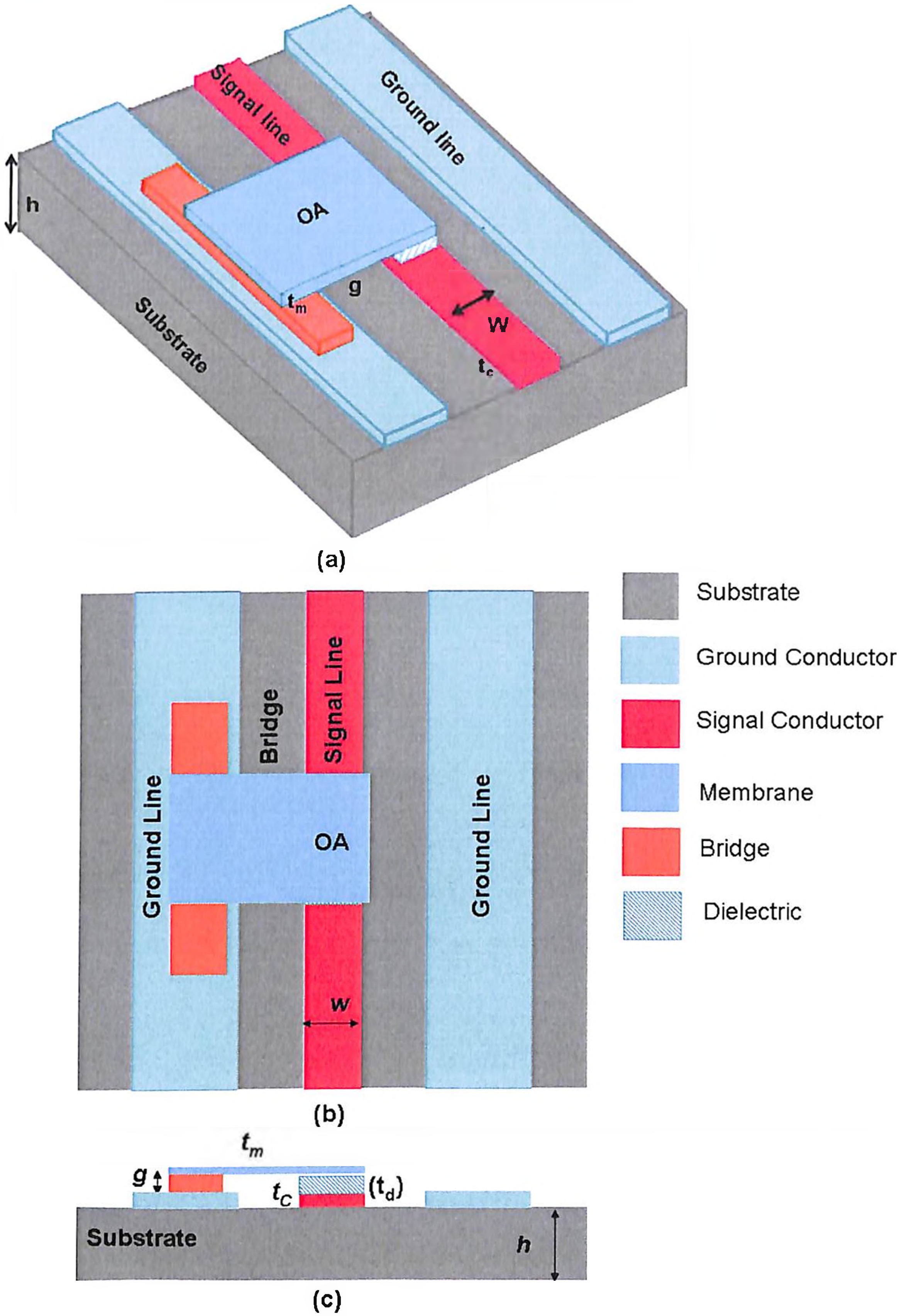


Figure 5.5: Schematic of the RF MEMS power sensor looking from the conductor side. **(a)** 3D view, **(b)** top view and **(c)** cross section view

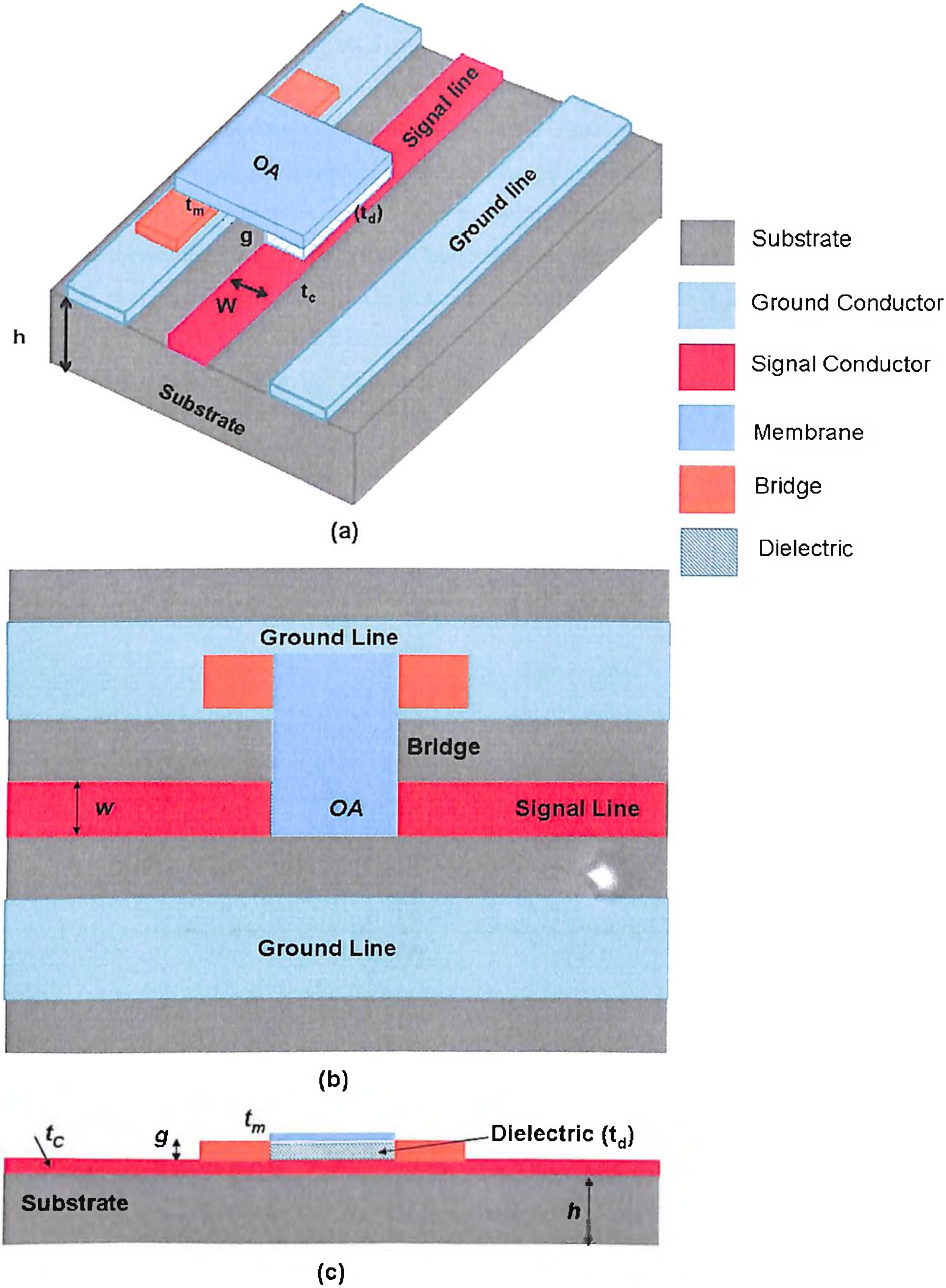


Figure 5.6: Schematic of the RF MEMS power sensor looking from the bridge side **(a)** 3D view, **(b)** top view and **(c)** cross section view

The basic structure of the sensor is a Coplanar Waveguide (CPW), where the RF signal is traveling through the central conductor and the rest is ground. The sensor consists of a clamped grounded membrane like a cantilever. This metal beam covers up some area of the conductor line of the CPW. This is called the overlap area and this arrangement creates a capacitance between the plate and the line. In order to avoid short circuit while sensing, a thin layer of dielectric is placed on the RF signal conductor. Sensing electrodes are placed below the movable membrane in order to detect its movement capacitively. The membrane can move in the z direction in proportion to the power of the RF signal flowing through the line. The functining of the MEMS RF power sensor is based on measuring the change in capacitance. The equivalent circuit model of the sensor is shown in Figure 5.7, where Z_L is the line impedance and Z_B is the bridge impedance. The movement of the membrane in proportion to the RF signal power is modeled as a variable capacitor.

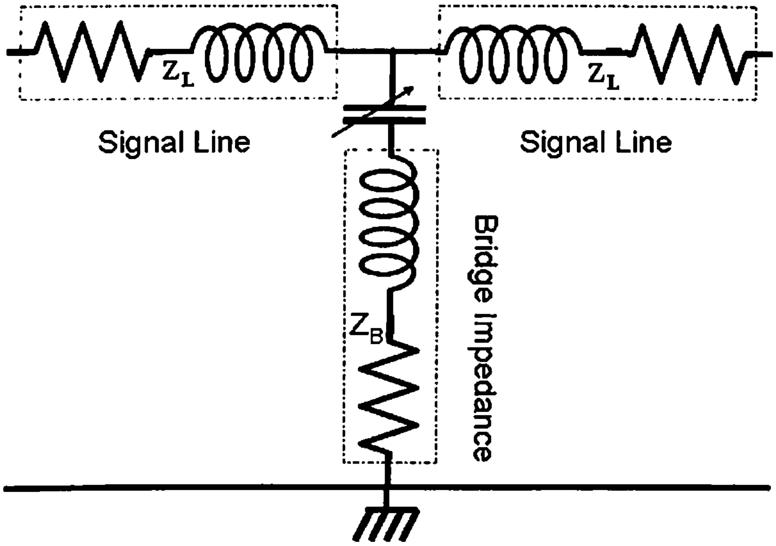


Figure 5.7: Equivalent circuit model of the MEMS power sensor

5.4.1 Operating principle

The basic principle of operation is based on the attractive force between the two electrodes. When potential is applied to the plates, the electrostatic force will pull the movable plate towards the fixed plate. This attractive force principle is used in many MEMS devices and the force experienced between the plates is given in equation (5.1) (Fernandez et al., 2004)

$$\bar{F} = \frac{q^2}{2\varepsilon A}\bar{x} = \frac{\varepsilon A}{2(d-x)^2}V^2\bar{x} \tag{5.1}$$

Where ε is the dielectric constant, d is the gap at time $t = 0$, x is the displacement of the movable plate, A is the area of the plate, V is the voltage between the plates and q is the charge on each plates. The capacitance C experienced by the structure is given as

$$C = \frac{q}{V} = \frac{\varepsilon A}{d-x} \tag{5.2}$$

For an applied ac voltage between the capacitor electrodes, the force is always attractive. The average force is important for frequencies much above the mechanical resonant frequency, and the voltage v in equation (5.2) becomes the rms value of the applied ac excitation. The rms voltage of the ac signal can be related to the displacement of the movable plate or the force needed to keep the plate in its initial position. This principle can be used for measuring the power on transmission lines at very high frequencies in the RF range (Seppa et al., 2001). In such proposed case any one electrode has to be replaced by an RF transmission line.

Thus the RF signal power $P = {v^2}/{Z}$, where Z is the impedance of the CPW and v is the rms voltage of the signal. Normally the thickness of the movable plate is very thin, the signal power and displacement are proportional to the square of the voltage level. So this sensor gives a linear relation between power and displacement (Fernandez et al., 2006).

5.4.2. Performance characteristic of RF power sensor

A few important performance characteristics of RF power sensors include: insertion loss, reflection loss, Voltage Standing Wave Ratio (VSWR), bandwidth, characteristic impedance etc. This analysis took into consideration the first three performance parameters.

Insertion Loss

Insertion loss is the loss of signal power resulting from the insertion of a device in an RF signal line. It is a very important characteristic for the RF power sensor to show how much loss the sensor is introducing. Usually expressed as a ratio in dB relative to the transmitted signal power, it can also be referred to as attenuation. It is denoted as S_{12}. If the input power is P_{in} and the out put power from the sensor is P_{out}, and then the insertion loss in dB is given by $10\log(P_{out}/P_{in})$. Insertion loss should be as low as possible.

Reflection Loss

Reflection loss is expressed in decibels (dB). It is caused due to impedance mismatch between two or more circuits. For a simple RF power sensor, there will be a mismatch where the connector is matched with the sensor. A high magnitude of return-loss in dB denotes better quality of the power sensor. It is denoted as S_{11} in dB. If the input power is P_{in} and the reflected power due to impendence mismatch from the sensor is P_r, then the insertion loss in dB is given by $10\log(P_r/P_{in})$.

VSWR (Voltage Standing Wave Ratio)

It is a measure of how efficiently radio-frequency power is transmitted from a power source, through the power sensor line, into a load. In an ideal system, 100% of the energy is transmitted. The signal's AC voltage will be the same from end to end since it runs through without interference, such ideal case VSWR is 1. In real systems, mismatched impedances cause some of the power to be reflected back towards the source (like an echo). Reflections cause destructive interference, leading to peaks and valleys in the voltage at various times and distances along the line. VSWR measures these voltage variances. It is the ratio of the highest voltage anywhere along the transmission line to the lowest. For a better RF device VSWR should be closer to unity.

5.5 Product Evaluation of RF MEMS Power Sensor

This section shows the evaluation of design subsystem specification of the MEMS RF power sensor using MADM and verification of the result using EDA CAD tools. The EDA tool used is IE3D from Zeland. The same technique can be applied to evaluate fabrication, package, etc. For design subsystem evaluation six attributes were considered: gap between the electrodes ($X_1 = g\,\mu m$), thickness of the dielectric ($X_2 = t_d\mu m$), thickness of the movable membrane ($X_3 = t_m\mu m$), thickness of the conductor ($X_4 = t_c\mu m$), overlapping area of the membrane over the RF line

($X_5 = OA\mu m^2$) and width of the conductor ($X_6 = w\mu m$). These design attributes are represented in Figure 5.5 and Figure 5.6. For simplicity all other attributes were assumed to be constant. Eight different combinations (8 alternatives named as PS1, PS2... PS8) of different attributes were taken for evaluation and the resulting D matrix was given by

$$D = \begin{array}{c} \\ PS1 \\ PS2 \\ PS3 \\ PS4 \\ PS5 \\ PS6 \\ PS7 \\ PS8 \end{array} \begin{array}{c} \begin{array}{cccccc} g & t_d & t_m & t_c & OA & w \end{array} \\ \begin{bmatrix} 5 & 0.15 & 0.2 & 3 & 12500 & 100 \\ 5 & 0.15 & 0.1 & 2 & 11250 & 90 \\ 3 & 0.2 & 0.1 & 2 & 12500 & 100 \\ 3 & 0.2 & 0.2 & 3 & 11250 & 90 \\ 3 & 0.2 & 0.1 & 2 & 11250 & 90 \\ 3 & 0.2 & 0.2 & 3 & 12500 & 100 \\ 5 & 0.15 & 0.1 & 2 & 12500 & 100 \\ 5 & 0.15 & 0.2 & 3 & 11250 & 90 \end{bmatrix} \end{array} \tag{5.3}$$

The relative importance matrix, weight matrix, which is resulting by MADM procedure, is given in equation (5.4) and (5.5) respectively (Prince and Agrawal, 2009). This matrix is decided by the expert team members already worked in this area using relative importance between the attributes (Prince and Agrawal, 2009). Even for the current iterative design tools, a knowledge base is required to perform iterative design optimization. Also the fabrication process flow is subject to expert's ingenuity and knowledge background (Crary, 1995).

$$A = \begin{bmatrix} 1 & 1 & 0.11 & 0.2 & 0.11 & 0.2 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 9 & 1 & 1 & 0.11 & 0.33 & 0.33 \\ 5 & 1 & 9 & 1 & 1 & 0.33 \\ 9 & 1 & 3 & 1 & 1 & 0.33 \\ 5 & 1 & 3 & 3 & 3 & 1 \end{bmatrix} \tag{5.4}$$

$$W = \begin{bmatrix} 0.04183893755586 \\ 0.13305218727535 \\ 0.10668783282807 \\ 0.2426157739504 \\ 0.17971252549008 \\ 0.29609274290024 \end{bmatrix} \tag{5.5}$$

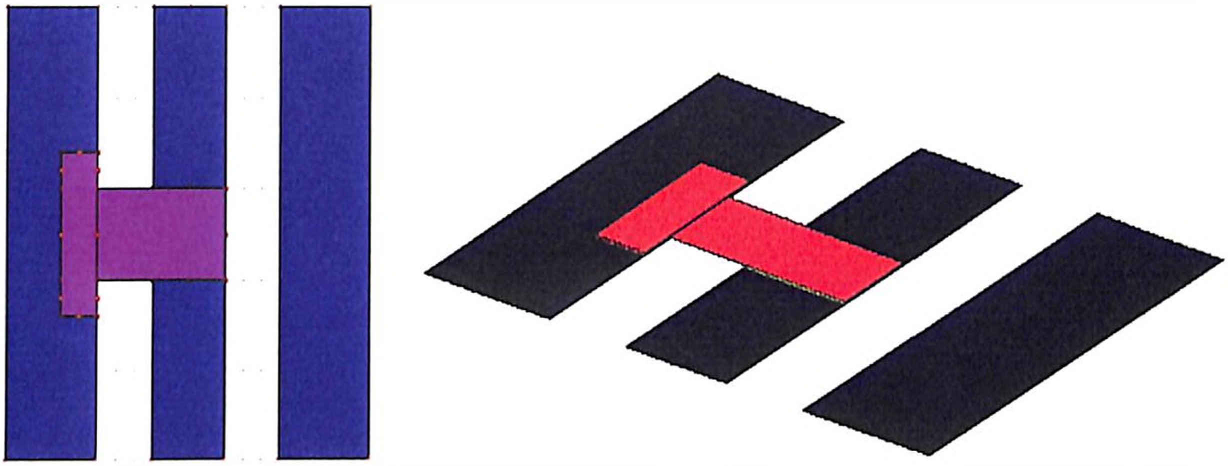
$$C^{+} = \begin{bmatrix} 0.76699730286862 \\ 0.13697570007498 \\ 0.30662448770572 \\ 0.74623538698154 \\ 0.23300269713138 \\ 0.86302429992502 \\ 0.25376461301846 \\ 0.69337551229428 \end{bmatrix} \tag{5.6}$$

The result of the MADM based evaluation and ranking from equation (5.6) indicated that PS6 was the best design candidate amongst the eight alternatives. The order was given by $PS6 > PS1 > PS4 > PS8 > PS3 > PS7 > PS5 > PS2$. The manufacturer could proceed for further analysis and manufacturing with PS6 design specifications. Similarly other stages of manufacturing could be evaluated within less time and less cost.

5.5.1 Verification

In order to verify the results of MADM based evaluation, simulation of each alternative was done. This section presents the simulated result to verify MADM based evaluation. The layout and 3D model of the RF sensor is shown in Figure 5.8 (a) and Figure 5.8(b).

The simulated results of S_{12}, S_{11} and $VSWR$ for eight different design alternatives are shown in Figure 5.9 (a), (b) and (c) respectively. The simulated result indicated that the evaluation and ranking by MADM was efficient. Further the performance characteristics S_{12}, S_{11} and $VSWR$ are tabulated at 1.5GHz along with their ranks in Table 5.1. Table 5.1 results show that the rank obtained by the proposed MADM method and the CAD tools are equal. Evaluation using time consuming tools can be replaced by the proposed method and further for verification the traditional techniques can be used.



(a) (b)

Figure 5.8: RF MEMS power sensor **(a)** Layout and **(b)** 3-D view.

Table 5.1: Comparative design evaluation result of the power sensor.

	Design parameters/attributes						Performance characteristics			Evaluation/Rank	
	g	t_d	t_m	t_c	OA	W	S_{12}	S_{11}	$VSWR$	MADM	Simulation
PS1	5	0.15	0.2	3	12500	100	-0.4273	-25.533	1.112	2	2
PS2	5	0.15	0.1	2	11250	90	-0.6957	-21.7965	1.177	8	8
PS3	3	0.2	0.1	2	12500	100	-0.6314	-22.898	1.154	5	5
PS4	3	0.2	0.2	3	11250	90	-0.4718	-24.8334	1.122	3	3
PS5	3	0.2	0.1	2	11250	90	-0.6957	-21.89	1.175	7	7
PS6	3	0.2	0.2	3	12500	100	-0.428	-25.956	1.106	1	1
PS7	5	0.15	0.1	2	12500	100	-0.6302	-22.635	1.159	6	6
PS8	5	0.15	0.2	3	11250	90	-0.472	-24.659	1.124	4	4

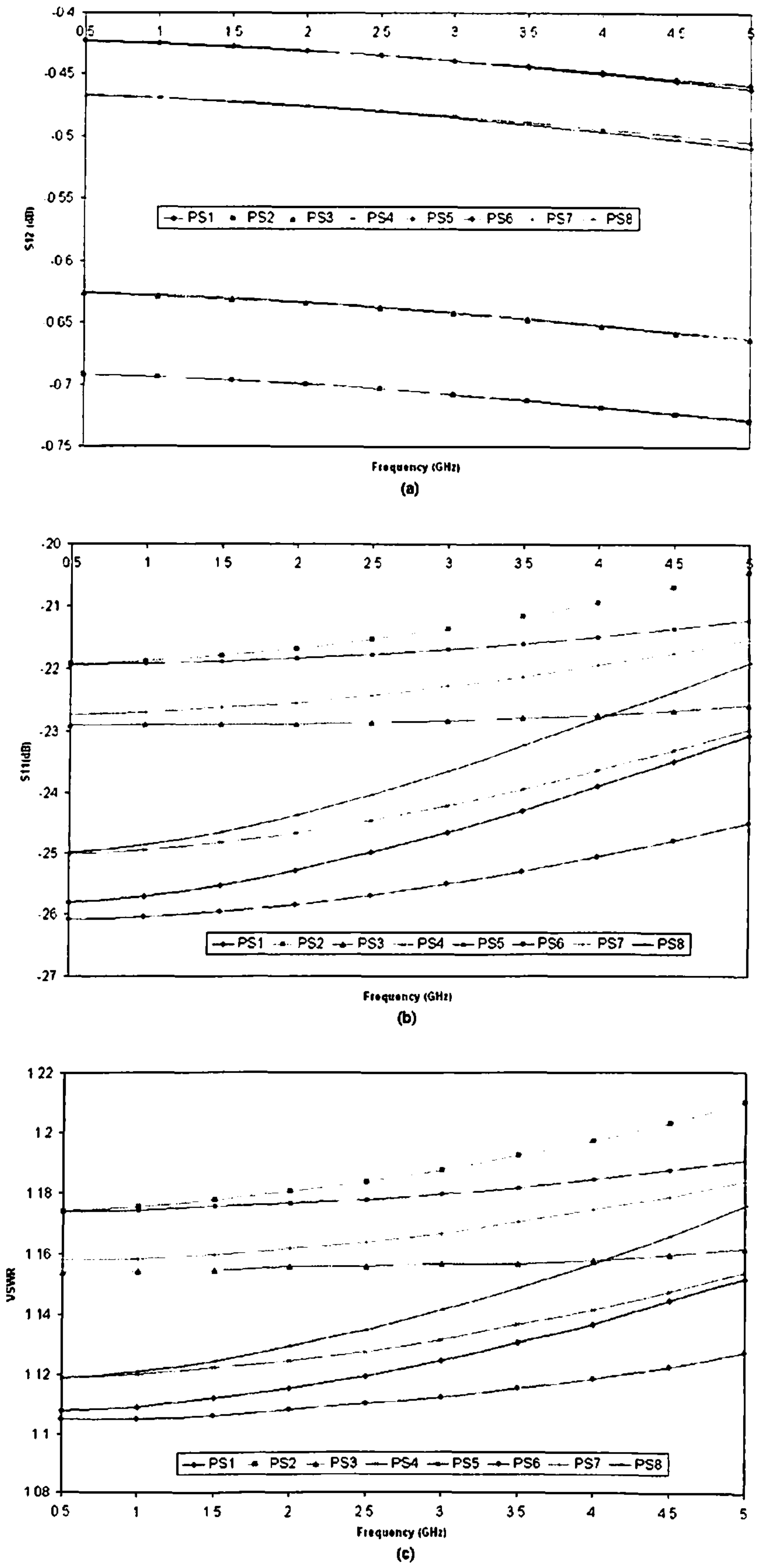


Figure 5.9: Simulation results for different designs of a MEMS power sensor **(a)** Insertion loss, **(b)** Reflection loss and **(c)** VSWR.

5.6 Sensitivity Analysis

Sensitivity analysis was carried out to determine the sensitivity or criticality of a few important attributes out of the large number of attributes considered. By optimizing these critical parameters it was possible to design and develop a better MEMS product with less cost and less time, from the initial stage. To carry out sensitivity analysis a number of experiments were designed in which each of these critical attributes were changed either alone or in different combinations, and their effects on C_i^+ were observed. This procedure helped in identifying a few critical attributes and their combinations which could be monitored to achieve success.

The MADM based evaluation and ranking algorithm developed was best suited for computer coding, it was easy to proceed mathematically or even by developing Matlab code. Matlab is very good in matrix operation for finding eigen values and weight vectors. Matlab coding was developed with the help of flow-chart in Figure 5.10 to generate Decision Matrix (D), Relative Important Matrix (A), Weighted Normalized Data Matrix (V) and weight vector for optimum selection of a MEMS product system. This code was useful in carrying out sensitivity analyses and is elaborated in Appendix A.

Sensitivity analysis involves finding performance variation with respect to the changes in the design attribute/attributes. The existing EDA tools help the designer to perform sensitivity analysis with respect to change in design attributes by sacrificing time, because changing the attribute may result in redrawing the entire layout and the simulation would require more memory and time. Sensitivity analysis helps the designer to find the critical attributes and parameters associated with the design subsystem which help the designer to perform further optimization. In order to carryout sensitivity analysis the power sensor $PS3$ has been considered. In this example only the thickness of the conductor t_c was varied, keeping other parameters constant. $S0, S1, S2 \text{and} S3$ were the alternatives with only variation in t_c. Sensitivity analysis using proposed MADM based methodology and simulation results are presented in Table 5.2. As t_c increases the rank improves, so the performance parameters S_{12}, S_{11} and $VSWR$ became better as shown in Figure 5.11 (a), (b) and (c) respectively.

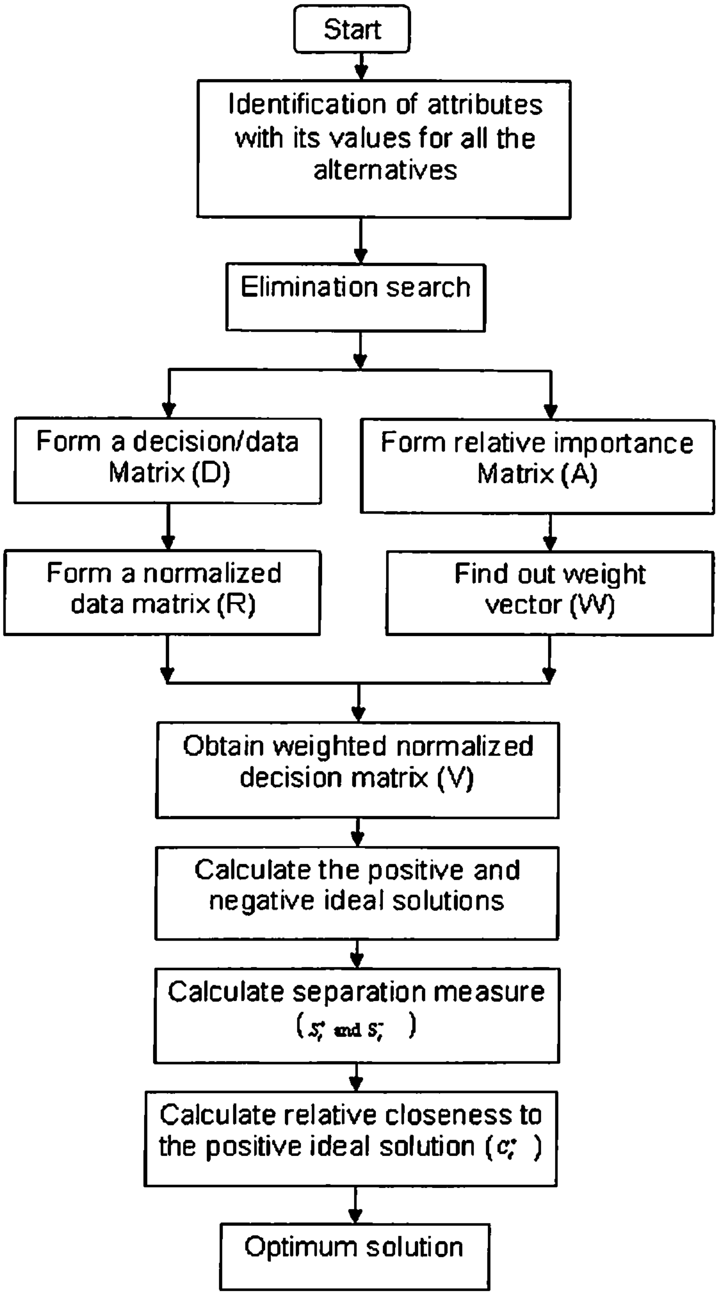


Figure 5.10: Flow chart for the TOPSIS (MADM) algorithm

Table 5.2: Comparative design evaluation results of the power sensor for different t_c.

	Design parameters/attributes						Performance characteristics			Evaluation/Rank	
	g	t_d	t_m	t_c	OA	W	S_{12}	S_{11}	$VSWR$	MADM	Simulation
S0	3	0.2	0.1	2	12500	100	-0.6314	-22.898	1.154	3	3
S1	3	0.2	0.1	3	12500	100	-0.4284	-25.964	1.106	2	2
S2	3	0.2	0.1	3.5	12500	100	-0.3695	-27.095	1.092	1	1
S3	3	0.2	0.1	1.5	12500	100	-0.83	-20.699	1.203	4	4

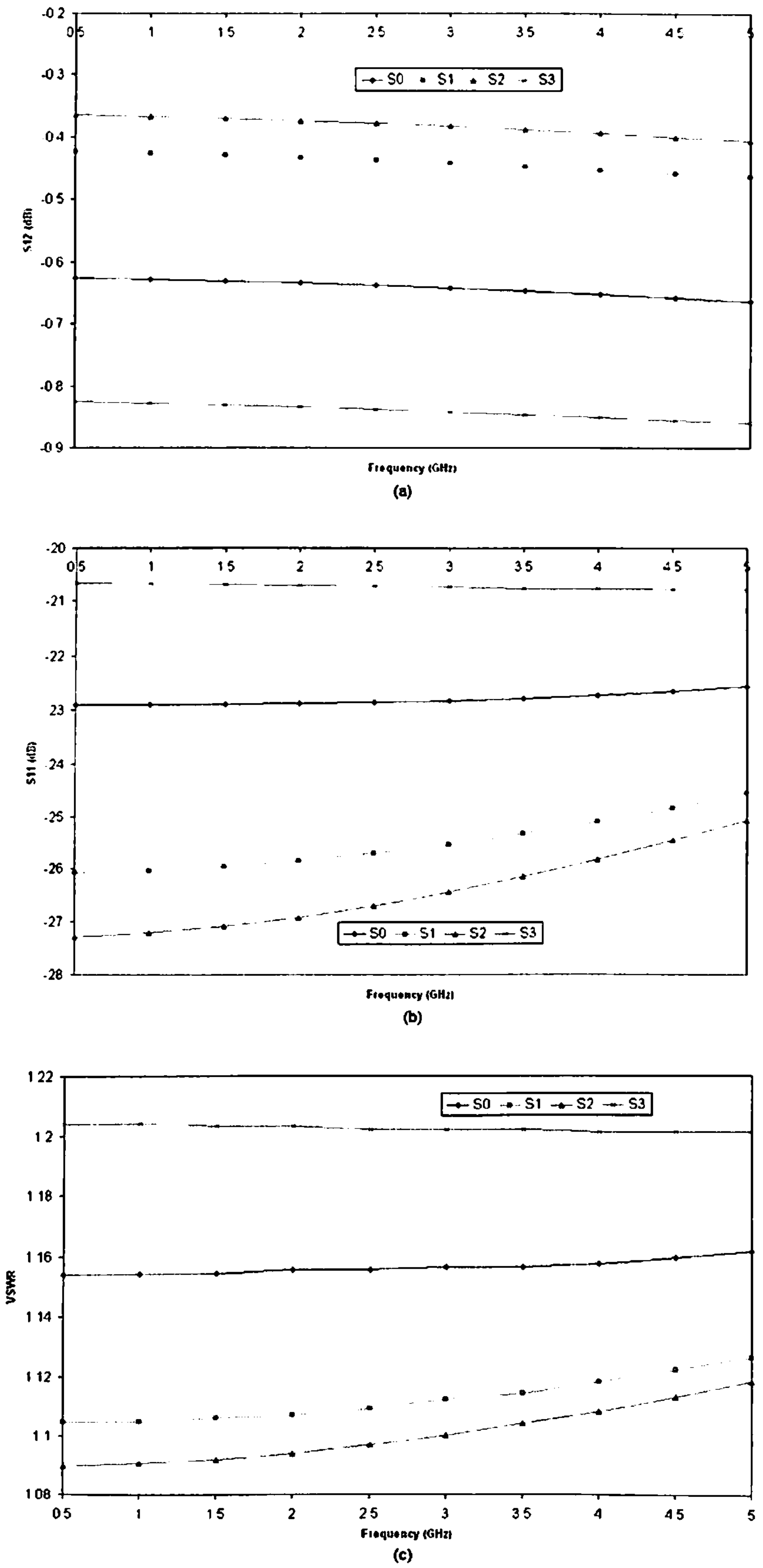


Figure 5.11: Simulation results of MEMS power sensor for different t_c **(a)** Insertion loss, **(b)** Reflection loss and **(c)** VSWR.

The example in this chapter illustrated only the design subsystem optimization and evaluation for the proposed design flow. The above example proved the efficiency of the proposed design methodology. In each stage such techniques can be applied to reduce the product development time and cost. The MEMS product designer and manufacturer will be benefited by the new proposed design methodology.

5.7 Conclusions

This chapter described a new design methodology for MEMS product development to reduce the time and cost involved in the traditional method. The proposed MADM based methodology would support the total product design evaluation and optimization at the conceptual stage itself.

- In this methodology the total performance of the MEMS product could be enhanced by modifying the parameters/attributes of the development process.
- New product development flow diagram and time chart have been presented in comparison with the traditional method.
- Since the proposed method is used at the beginning, time consuming iterating analysis and prototyping of product are circumvented.
- The proposed methodology uses MADM which can run in a computer with less time and require less memory. This also helps the designer to perform sensitivity analysis.
- The trade-offs between the product performance and the attributes or parameters can be enhanced by adjusting weights.

A RF power sensor was designed and its design parameters were varied to achieve an optimum solution. The proposed methodology was verified using traditional tools. It was clearly highlighted that the proposed methodology reduces product development time and cost. The RF power sensor with insertion loss 0.428 (dB), reflection loss 25.956 and VSWR of 1.106 was reported at 1.5GHz.

CHAPTER 6

CONCURRENT DESIGN OF MEMS PRODUCTS FOR X-ABILITIES

6.1 Introduction

Partly because of its infancy, and because it involves such a large number of disciplines, there is not yet a developed science of design for MEMS. Teams of interdisciplinary researchers are needed with a common interest in establishing the required science and engineering for MEMS design, which can be seen as consisting of design synthesis and process planning. The establishment of a set of methodologies for the design of MEMS that starts from a specification of desired function and leads to an optimized fabrication of a MEMS system is a very important goal.

Smaller markets for MEMS product that need custom design are often ignored due to the virtually non-recoverable cost of design. Since in-depth expertise in various engineering disciplines, product design and system integration is required for MEMS product development, MEMS continues to be dominated by high-volume markets (Mukherjee, 2003; Fedder, 1999).

Current MEMS product design analysis is carried out using tools which require large memory based systems that are too time consuming to be practical, taking days to complete (Swart et al., 1998). The present MEMS product development process is slow because iterative analysis, layout and testing are necessary to reach complete optimal product.

The non-ideal design methodology combined with the length of time and high costs associated with MEMS prototyping results in a very inefficient and ineffective scenario for commercial MEMS product development (Zha and Du, 2003).

CE is a concept of bringing together all the people who normally would be involved sequentially over the life cycle of MEMS product development (Bazu, 2004). The development time of MEMS products from concept to final volume production and market insertion takes on an average 4-10 years. According to Da Silva et al. (2002), if a powerful top-down methodology is introduced with concurrent engineering practice for the design of MEMS product the design and manufacture will be faster. In such case the design group's activities should not occur in isolation.

A MEMS designer requires a high level knowledge of fabrication, packaging, materials property as well as the environment in which it is going to function, in order to embody a successful design. Reducing the cost requires methodologies have cost effective and time-efficient tools for optimization. Despite concerted efforts and serious concern, methodologies that consider all design aspects together for developing a MEMS device or product using concurrent model for 'X'-abilities are few and far between. This Chapter mainly focuses on the MEMS product design process, which is a highly promising and widely acceptable manufacturing process for the MEMS products used in engineering applications. The work reported in this thesis focused on methodologies, which consider various design aspects along with critical parameters for designing the 'X'-abilities of the MEMS product at the conceptual stages of product development.

Concurrent methodology has been successfully applied in various fields of engineering. Concurrent product development has been carried out using MADM and Graph theory in various fields (Kiran and Agrawal, 2008; Prabhakaran et al., 2006c).

In this work, MEMS product design and development aspects called X-abilities were identified, concurrent models using MADM and graph and matrix approach were developed. The results of both the approaches were compared and it was established that the graph theory based approach could deal with the interaction among the aspects very well compared to the MADM approach. Using the design graph and taking into consideration the interdependence/interaction between various design aspects, a design index was derived. The design index was useful in establishing the interaction between the subsystems and also in deciding the overall design acceptability of the MEMS product or device requirements at the conceptual stage. The power sensor which was elaborated in Chapter 5 was considered for the detailed analysis here. In order to verify the concurrent methodologies, the power sensor was simulated and the results were compared.

6.2 Concurrent Engineering in MEMS Design for X-Abilities

Designing a MEMS product for design, functionality, manufacturability, testability, quality, reliability, scalability, microelectronics, materials, environment, packaging, fabrication/manufacturing, cost, low product development time, life cycle etc., has become crucial during the last few years in the MEMS industry. In order to develop the methodology, MEMS product development is considered as a system in total and different subsystems called X abilities (design aspects) were identified based on the product design flow. The design aspects identified are micromachined element design, microelectronic circuit design, fabrication, packaging, materials and environment. This study does not claim that the design aspects identified are fixed, the product designer and manufacturer has full freedom to choose design aspects. A few more identified design aspects include: quality, testability, maintainability, reliability, cost etc. The concurrent MEMS product development is presented in Figure 6.1, which illustrates that the experts from all subsystem should participate right from beginning in the product development. In the conceptual stage itself the product should be ranked and evaluated in order to avoid time consuming, trial and error process involved in the present product development method.

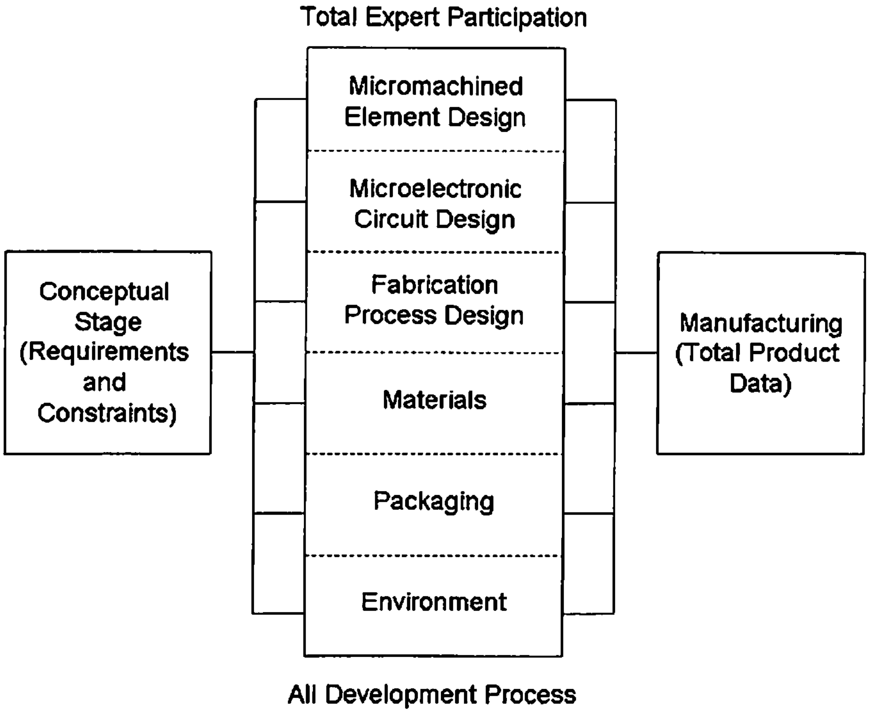


Figure 6.1: Concurrent MEMS product development flow diagram

Design for X-abilities (DFX) refers to considering simultaneously all product or application specific design goals (abilities) and constraints at the beginning of the design (Kiran and Agrawal, 2008). To suit application specific needs, products/services require many of the abilities with varying degree of relation/importance. For example, to develop an optimum MEMS product understanding of micromachined element design, microelectronics design, fabrication process, material properties, packaging design and environment in which the product is going to act are required.

6.2.1 Micromachined element design

The present practice in MEMS product development is for the designer to specify and send the mask set to the fabricator. It is not necessary that the design specification from the design experts will be adaptable or acceptable by the fabrication and packaging experts (Schropfer et al., 2004). The designer is necessarily involved in the details of the processing so that the mask set design will compensate for any and all divergences between the mask of a layer and the physical structure that is generated by that mask/process combination. A series of iterations enables the designer to bring the masks and the process in line to give the appropriate structures. Thus each mask is suitable only for the specific fabricator since adjustments for process idiosyncrasies may not be appropriate for the other vendors (Hilibrand and Chern, 1995). The design group's activities should not occur in isolation.

6.2.2 Microelectronics circuit design

Until recently, in MEMS device design, the corresponding integrated or discrete electronic circuits and packaging development was carried out by separate teams. As the complexity of MEMS increases, it is becoming increasingly important to design and optimize the coupling between the micromachined elements, the microelectronics circuits that control them and the constraints due to packaging. The fabrication sensitivities of the MEMS device, the microelectronics circuit or the packaging, impact the specifications of the other. This means that design trade-offs are necessary to produce a complete sensor system (Schropfer et al., 2004). Even though the microelectronics design and fabrication field is well developed, integration of microelectronics circuit and the micromachined element need to be fabricated in the same wafer. Thus involvement of microelectronic designer is very important from the product design stage itself.

6.2.3 Materials

Knowledge of materials and their properties is a prerequisite for design and fabrication experts. Since MEMS devices are essentially considered as mechanical, their design requires that a fabrication unit also accurately characterise all relevant material properties. It is known that in general the stress in a film layer varies across a wafer and that the larger the wafer diameter, the larger the magnitude of variation observed (Schropfer et al., 2004). The specific reason for such variation is due to critical material properties, such as Young's modulus, stress, fracture strength, electrical conductivity, dielectric permittivity, permeability, loss tangent, stiction, etc. There are many more material properties of interest available to the design group depending on the specific product application in mind. For example, RF applications require high frequency permittivity & loss that optical applications do not. However, it is practical for process groups to make available as much material property information within the design kit as possible to span quite a few different application areas (Da Silva et al., 2002).

6.2.4 Fabrication

Concurrently with the initiation of the design group's activity, the process group begins to create manufacturing specifications (Da Silva et al., 2002). This specification contains (i) Process requirements, (ii) compatibility with the packaging, (iii) availability of materials and etchent, (iv) stability under the required environment etc. If the industry has an established, well characterized fabrication flow, it is better to use the standard process as it is more cost effective. The design specifications of the product have to be analyzed carefully along with design group experts to acertain whether the product design itself might necessitate modifications to the existing fabrication process method, and in some cases, an entirely new process flow may be necessary (Schropfer et al., 2004).

6.2.5 Packaging

Packaging of the MEMS products also needs to be considered in a systematic manner. In the microelectronics industry, package design is handled by a separate group, which gets involved in the design fairly late in the product development cycle. The MEMS chips need to communicate with the environment for sensing and actuation. Moreover the microelectronics circuits should be protected from potential environmental impact (Monk et al., 1996). It is vital for product success that packaging options available be assessed and preliminary development of the packaging specification be initiated simultaneously with MEMS product design (Da Silva et al., 2002).

6.2.6 Environment

Unlike IC die packaging, MEMS dice need to interface with the environment for sensing, interconnection, and/or actuation. So the environment is also a system which may affect the performance of the MEMS product. Mir et al. (2006) have discussed the importance of considering the effect of environment in system performance. They also emphasizes that the interaction with the environment can dramatically reduce the reliability, safety levels and performance of the MEMS system. Persson and Boustedt (2002) tabulated the impact of environmental factors on MEMS device, and discussed at length, the potential environmental impact on MEMS product performance. Some of the environmental impacts which affect the MEMS product performance are radiation, vacuum, thermal shock and vibration. Other possible considerations included atomic oxygen and plasmas (Shea, 2006).

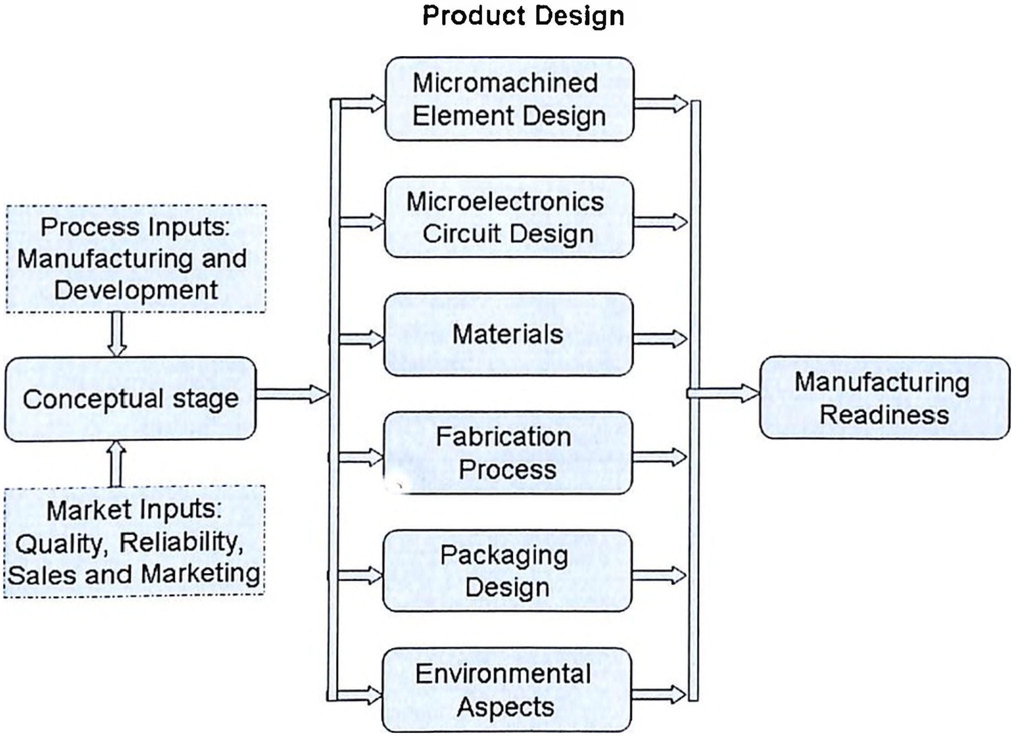


Figure 6.2: Concurrent MEMS product design and manufacturing flow

The design aspects (X-abilities)/ subsystems identified in the work are micromachined element design (DFX_1), microelectronics circuit design (DFX_2), materials (DFX_3), fabrication (DFX_4), packaging (DFX_5) and environment (DFX_6). The proposed concurrent MEMS product design, development and manufacturing model developed in this work is shown in Figure 6.2.

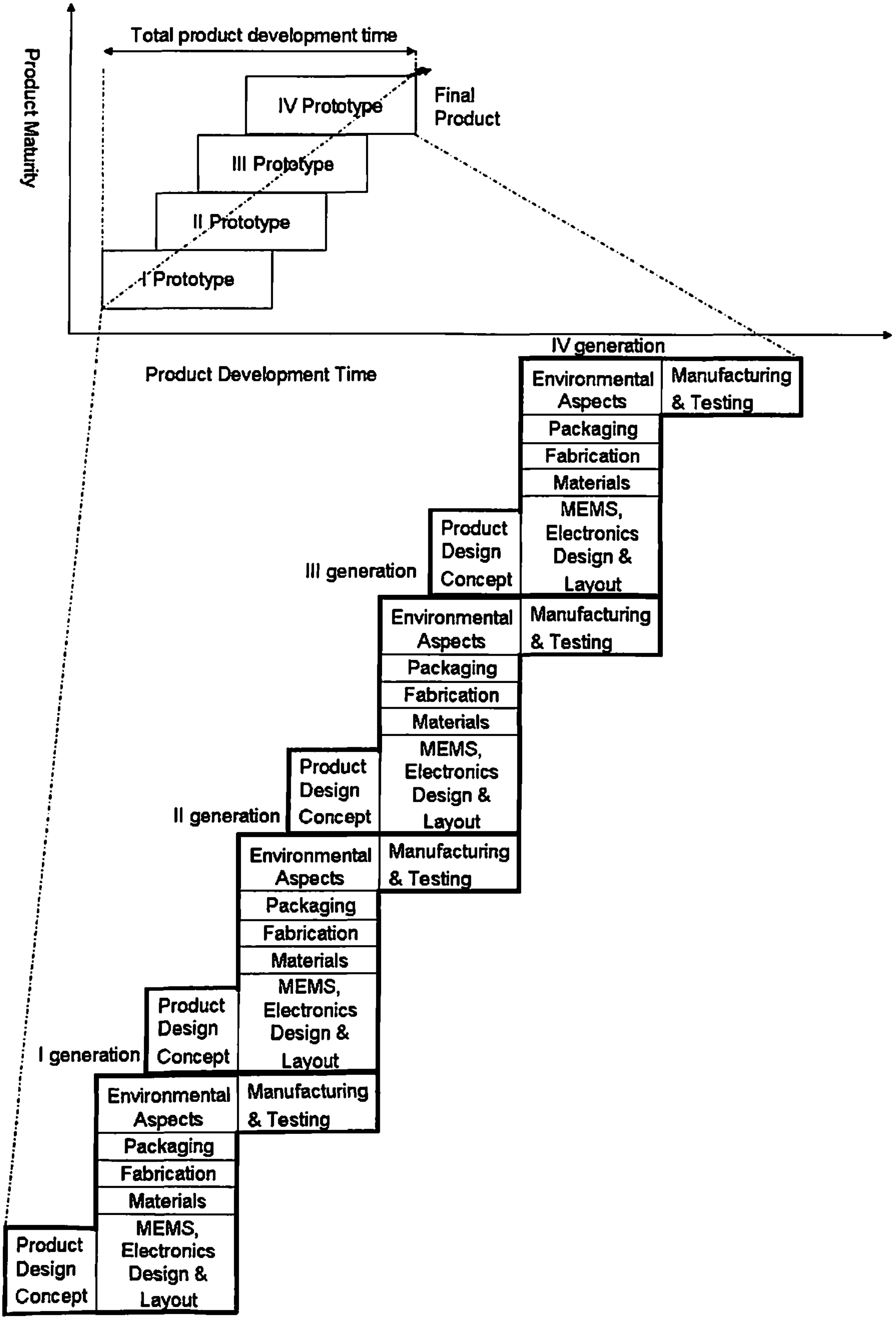


Figure 6.3: Concurrent MEMS product development time chart

Since experts from micromachined element design, microelectronics, fabrication, package, materials, environment etc. evaluate the product at the conceptual stage itself the product development time is considerably reduced. The product development time is illustrated in the form of time chart in Figure 6.3. The time span for the product maturity is much reduced compared to the traditional and the new serial manufacturing flow time charts shown in Chapter-5.

6.3 Methodology Developed

In a concurrent design cycle, all the six design aspects $DFX_i = 1,2,\ldots,6$ are considered in parallel. Usually no interaction of DFX_i and DFX_j are taken into account, while these interactions could be very significant in MEMS design and development. This work does not claim that only the above mentioned six systems should work in parallel. There is a need to develop a methodology based on a multidisciplinary approach, which can consider all the design parameters of various design aspects in a single stroke. One could apply MADM or graph theoretic systems approach for such analysis. Two models have been proposed: one employing the traditional MADM technique and the second using graph theory. The proposed models have taken into account the concurrent/parallel engineering methodology and also the interactions among various design aspects.

6.4 MADM Based Modeling for Concurrent MEMS

Multiple attributes are processed in MADM technique for ranking finite number of alternatives to arrive at a single choice for the best MEMS product. This work also employed TOPSIS, a MADM technique to select the best MEMS product. Figure 6.4 shows the flow of the proposed design methodology. The design of the MEMS product starts with specifying product objectives and requirements from the users. A team of experts from the micromachined element design, microelectronics circuit design, fabrication, materials, packaging and environment would identify pertinent attributes concurrently, at the conceptual stage. Attributes obtained from the team of experts from different area, would be used to find the best alternative MEMS product using TOPSIS.

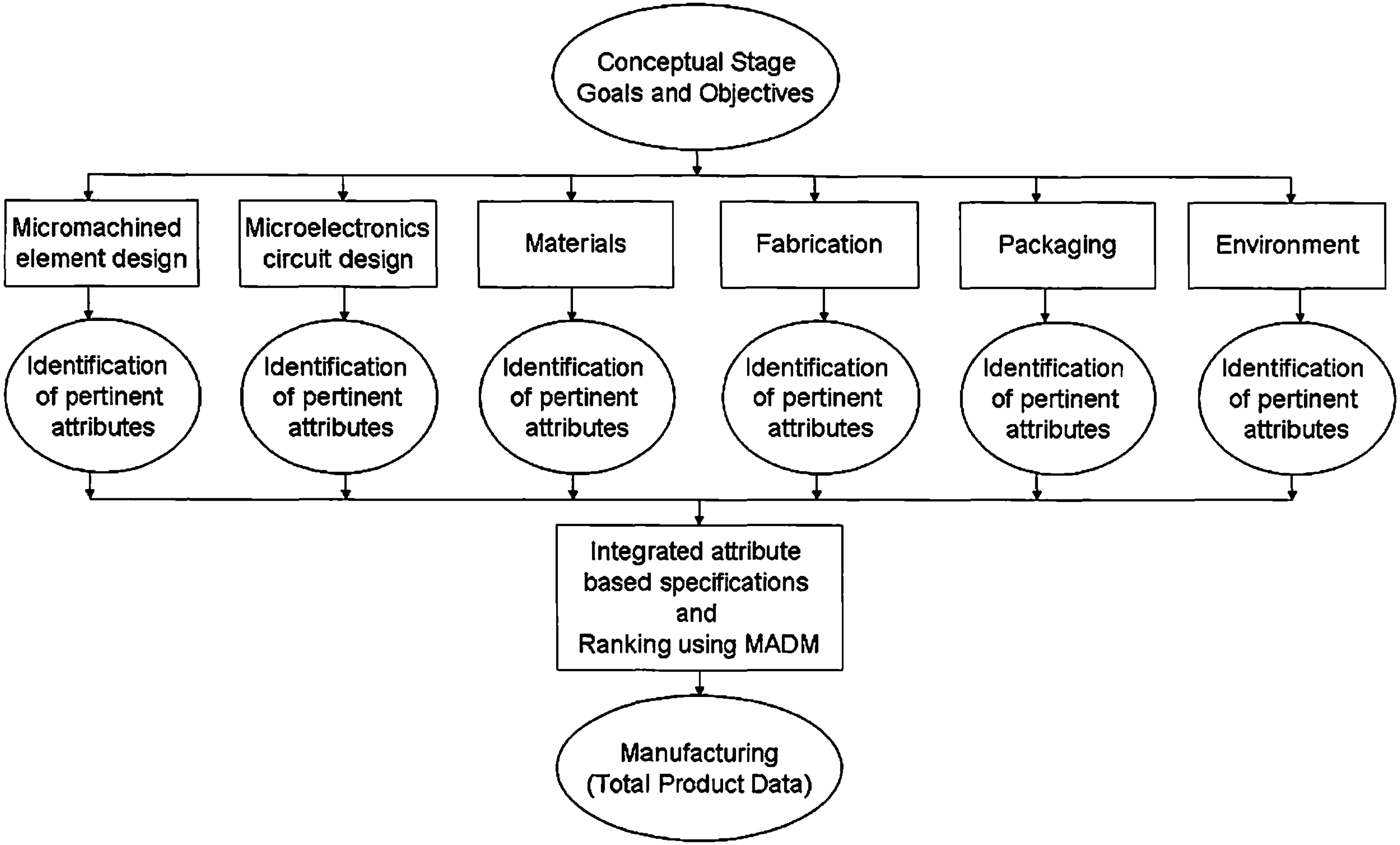


Figure 6.4: Product development flow for concurrent design of MEMS for x-abilities using MADM

6.5 MADM Based Concurrent Model Validation

This section describes the use of the RF MEMS power sensor designed and explained in Chapter-5 for validating the MADM based concurrent model. In this work only three subsystems (X-abilities) were considered to validate the proposed model. The analysis considered attributes from micromachined element design, materials and environment. From the micromachined element design six attributes were considered, say gap between the capacitive plates ($X_1 = g\mu m$), thickness of the dielectric ($X_2 = t_d\,\mu m$), thickness of the movable membrane ($X_3 = t_m\,\mu m$), thickness of the conductor ($X_4 = t_c\,\mu m$), overlapping area of the membrane with the signal line ($X_5 = OA\,\mu m^2$) and width of the conductor ($X_6 = w\,\mu m$). For the purpose of explanation of the methodology, all other attributes have been assumed to be constant. Material selection is very important in MEMS design. This study considered four different material combinations for the power sensor. The number of material attributes totally considered were six. Conductivity of the signal conductor ($X_7 = \sigma_c\,{}^{S}\!/_{cm}$), conductivity of the membrane ($X_8 = \sigma_m\,{}^{S}\!/_{cm}$), dielectric constant of the dielectric ($X_9 = \varepsilon_d$), loss tangent of dielectric ($X_{10} = LT_d$), dielectric constant of the substrate ($X_{11} = \varepsilon_s$), loss tangent of substrate ($X_{12} = LT_s$) were defined, and the rest of the attributes were assumed to be constant. The materials used with the above assumptions were for signal conductor Aluminium, Gold and Copper, for membrane materials Titanium, Silver and Aluminium, for dielectric N4Si3 and SiO2 and for substrate Silicon and Gallium arsenide.

The sensor was assumed to work in three different environments say distilled water, air and ethanol fuel. The attributes considered for environment are dielectric constant of the environment ($X_{13} = \varepsilon_e$), loss tangent of the environment ($X_{14} = LT_e$), permeability of the environment ($X_{15} = \mu_e$) and resistivity of the environment ($X_{16} = \rho_e\,\Omega.cm$).

The objective was to evaluate the product by considering attributes from all the sub-system/abilities in the conceptual stage rather than going for iterative design verification, process verification, material selection etc. A total of twelve alternatives ($MP1, MP2, \ldots, MP12$) were considered for the analysis with different design attributes, material combinations and environments. The result of the proposed methodology was as follows:

Twelve different combinations (The 12 alternatives were named as $MP1, MP2, ..., MP12$) of attributes representing eight different designs, four different materials and three different environments were taken for evaluation and the resulting D matrix is given in (6.1).

$$D = \begin{array}{r|cccccccccccccccc|}
 & g & t_d & t_m & t_c & OA & w & \sigma_c & \sigma_m & \varepsilon_d & LT_d & \varepsilon_t & LT_t & \varepsilon_e & LT_e & \mu_e & \rho_e \\
MP1 & 5 & 0.15 & 0.2 & 3 & 11250 & 90 & 378000 & 25000 & 7.9 & 0.0017 & 13.1 & 0.006 & 1.0005 & 0.004 & 1.0 & 1.25E16 \\
MP2 & 5 & 0.15 & 0.2 & 3 & 12500 & 100 & 378000 & 25000 & 3.9 & 0.0010 & 11.9 & 0.005 & 1.0005 & 0.004 & 1.0 & 1.25E16 \\
MP3 & 3 & 0.20 & 0.2 & 3 & 12500 & 100 & 378000 & 25000 & 3.9 & 0.0010 & 11.9 & 0.005 & 1.0005 & 0.004 & 1.0 & 1.25E16 \\
MP4 & 3 & 0.20 & 0.2 & 3 & 12500 & 100 & 596000 & 378000 & 7.9 & 0.0017 & 13.1 & 0.006 & 1.0005 & 0.004 & 1.0 & 1.25E16 \\
MP5 & 3 & 0.20 & 0.2 & 3 & 11250 & 90 & 378000 & 25000 & 7.9 & 0.0017 & 13.1 & 0.006 & 1.0005 & 0.004 & 1.0 & 1.25E16 \\
MP6 & 3 & 0.20 & 0.1 & 2 & 12500 & 100 & 596000 & 378000 & 7.9 & 0.0017 & 13.1 & 0.006 & 24.500 & 1.000 & 1.2 & 0.2000 \\
MP7 & 5 & 0.15 & 0.1 & 2 & 12500 & 100 & 596000 & 378000 & 7.9 & 0.0017 & 13.1 & 0.006 & 76.700 & 0.157 & 0.9 & 2.00E3 \\
MP8 & 3 & 0.20 & 0.1 & 2 & 12500 & 100 & 452000 & 630100 & 3.9 & 0.0010 & 11.9 & 0.005 & 24.500 & 1.000 & 1.2 & 0.2000 \\
MP9 & 5 & 0.15 & 0.1 & 2 & 12500 & 100 & 452000 & 630100 & 3.9 & 0.0010 & 11.9 & 0.005 & 76.700 & 0.157 & 0.9 & 2.00E3 \\
MP10 & 3 & 0.20 & 0.1 & 2 & 11250 & 90 & 596000 & 378000 & 7.9 & 0.0017 & 13.1 & 0.006 & 76.700 & 0.157 & 0.9 & 2.00E3 \\
MP11 & 3 & 0.20 & 0.1 & 2 & 11250 & 90 & 452000 & 630100 & 3.9 & 0.0010 & 11.9 & 0.005 & 76.700 & 0.157 & 0.9 & 2.00E3 \\
MP12 & 5 & 0.15 & 0.1 & 2 & 11250 & 90 & 378000 & 25000 & 7.9 & 0.0017 & 13.1 & 0.006 & 1.0005 & 0.004 & 1.0 & 1.25E16
\end{array} \tag{6.1}$$

The TOPSIS incorporates the team of experts' opinion in the form of relative importance matrix. Current iterative MEMS product development strategies also use expert opinion for the product development (Crary, 1995). A simple algorithm which yield the results by a bench mark coefficient C^+, a simple numerical index representing sixteen attributes was used. C^+ would vary between zero and one. The method ensured that alternatives with largest C^+ were closest to the hypothetical best solution. The results are presented in (6.2).

$$C^+ = \begin{array}{r|c|}
MP1 & 0.866374 \\
MP2 & 0.866553 \\
MP3 & 0.866553 \\
MP4 & 0.888222 \\
MP5 & 0.866374 \\
MP6 & 0.140403 \\
MP7 & 0.094404 \\
MP8 & 0.122133 \\
MP9 & 0.057597 \\
MP10 & 0.081265 \\
MP11 & 0.026289 \\
MP12 & 0.861710
\end{array} \tag{6.2}$$

The MEMS power sensor with the largest C^{*} would be the best choice. Alternative $MP4$ was the best choice as per the results obtained. The above twelve alternatives were simulated using RF MEMS EDA tools and the rank obtained was verified with the TOPSIS result. The simulated results were compared with the proposed MADM based concurrent methodology and the results are presented in Table 6.1. The simulated result also identified $MP4$ as the best alternative.

Table 6.1: Comparative product evaluation result of the power sensor

Sl.No	Alternative	VSWR	Evaluation	
			MADM	Simulation
1.	MP1	1.1433	5	5
2.	MP2	1.1314	3	3
3.	MP3	1.11911	2	2
4.	MP4	1.08002	1	1
5.	MP5	1.1384	4	4
6.	MP6	1.76847	7	7
7.	MP7	1.98163	9	9
8.	MP8	1.77673	8	8
9.	MP9	2.04604	11	11
10.	MP10	1.99828	10	10
11.	MP11	2.09558	12	12
12.	MP12	1.2051	6	6

Alternative $MP4$ had the following design attributes: $g = 3\mu m, t_d = 0.2\mu m,$ $t_m = 0.2\mu m, t_c = 3\mu m, OA = 12500\mu m^2$ and $w = 100\mu m$. The materials combinations for alternative $MP4$ as follows: Copper as the CPW conductors, Aluminium as the membrane conductor, SiO2 as the dielectric and GaAs as the substrate. The environment it could work effectively was Air or free space. Simulated $VSWR$ of the alternative $MP4$ is shown in Figure 6.5.

The simulated results of $VSWR$ at 2 GHz for the twelve alternative RF MEMS power sensor are tabulated along with their rank using MADM in Table 6.1. This table illustrates that the proposed methodology would be an effective method to evaluate the MEMS product at the conceptual stage. This would help the MEMS designer and manufacturer to bring the better quality product to the market in a cost effective and time efficient manner.

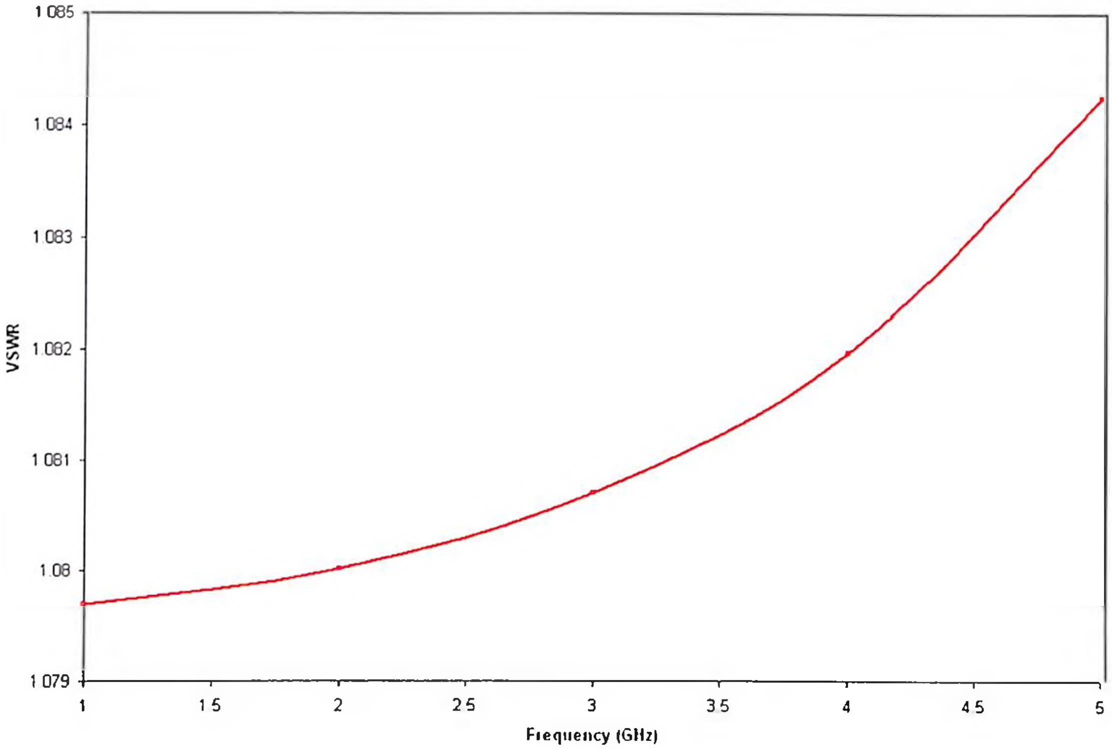


Figure 6.5: VSWR for the alternative $MP4$

6.6 Graph Theory and Matrix Based Modeling for Concurrent MEMS

By considering all the aspects in the concurrent way, a systems approach for developing a MEMS product system as $[M.I]$ of its design set $\{M\} = \{M_1, M_2, ..., M_n\}$ and interdependence/interaction set $\{I\} = \{I_1, I_2, ..., I_n\}$ where M_i represents the i^{th} design (and attributes associated with it) while I_j represents j^{th} connectivity/interaction between two corresponding design aspects of the MEMS device/product. A graph $G = f(V, E)$ consists of a set of objects $V = \{v_1, v_2, ..., v_n\}$ called vertices or nodes, and another set $E = \{e_1, e_2, ..., e_n\}$, of which the elements are called edges, such that each edge e_k is identified with a pair of vertices. The vertices v_i and v_j associated with edge e_k are called the end vertices of e_k. The most common representation of a graph is by means of a diagram, in which the vertices are represented by small points of circles, and each edge as a line segment joining its end vertices.

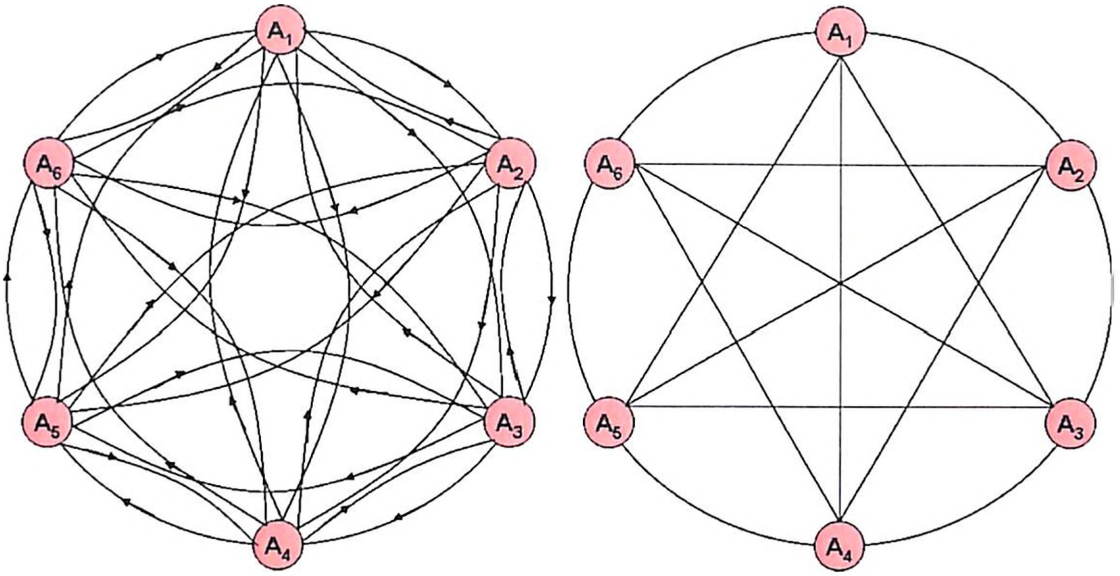
6.6.1 Directed graph or digraph

A directed graph or a digraph is a graph with directed edges. A concurrent MEMS *DFX* digraph models the *DFX* aspects and their interrelationship/interaction for a given MEMS device/product. The diagraph consists of nodes and edges. A node $\{A_i\}$ represents presence or measure of an i^{th} *DFX* aspect. The number of nodes considered is equal to the number of *DFX* aspects considered for a given MEMS device/product. The directed edge represents the relative importance/interdependency/interaction among the aspects. If node i has an interaction over another node j, then a directed edge or arrow is drawn from node i to node j (i.e., a_{ij}). If node j has an interaction over another node i, then a directed edge or arrow is drawn from node j to node i (i.e., a_{ji}).

To demonstrate MEMS *DFX* digraph, six design aspects were considered. Let these six 'X' abilities named as $DFX_1, DFX_2, DFX_3, DFX_4, DFX_5, \text{and}\, DFX_6$ form a graph shown in Figure 6.6(a). Let these be represented by six vertices $\{A_1, A_2, A_3, A_4, A_5, A_6\}$ i.e., Design for X (DFX$_i$) is represented by vertex A_i as shown below:

A_1 - DFMED (Design for micromachined element design) = DFX$_1$
A_2 - DFMCD (Design for microelectronics circuit design) = DFX$_2$
A_3 - DFM (Design for materials) = DFX$_3$
A_4 - DFF (Design for fabrication) = DFX$_4$
A_5 - DFP (Design for packaging) = DFX$_5$
A_6 - DFE (Design for environment) = DFX$_6$

The $a_{ij} \neq a_{ji}$ means that the influence of the i^{th} design aspect attributes on j^{th} design aspect attributes is not equal to the influence of the j^{th} design aspect attributes on i^{th} design aspect attributes. If the directional property is not significant, the design graph is represented by a unidirectional graph as shown in Figure 6.6 (b), in this case $a_{ij} = a_{ji}$.



(a) (b)

Figure 6.6: (a) Diagraph representation of design for six aspects of MEMS products; **(b)** Undirected graph representation of design for six aspects of MEMS products.

6.6.2 Matrix representation of the Digraph

A *DFX* digraph yields a graphical representation of the design aspects and their interactions for quick visual appraisal. As the number of nodes and their interrelations increases, the digraph becomes more complex. In such a case, the visual analysis of the digraph is expected to be difficult and complex. To overcome this constraint, the digraph is represented in a matrix form.

A matrix called the Concurrent MEMS Product Design Aspect Interaction Matrix (IM-CMPDA) is defined. This is represented by a binary matrix (a_{ij}) , where a_{ij} represents the interaction between attributes i and j such that

$a_{ij} = 1$, if the design aspect i is interdependent or connected to another design aspect j

$a_{ij} = 0$, otherwise

It is noted that $a_{ii} = 0$ for all i, since an attribute can not have relative importance over itself. The concurrent MEMS product design aspect interaction matrix (IM-CMPDA) corresponds to the digraph shown in Figure 6.6 is written as in (6.3)

$$P=\begin{array}{cccccc|c} 1 & 2 & 3 & 4 & 5 & 6 & vertex \\ \hline 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 & 1 & 2 \\ 1 & 1 & 0 & 1 & 1 & 1 & 3 \\ 1 & 1 & 1 & 0 & 1 & 1 & 4 \\ 1 & 1 & 1 & 1 & 0 & 1 & 5 \\ 1 & 1 & 1 & 1 & 1 & 0 & 6 \end{array} \qquad (6.3)$$

An identity matrix I, and A is a variable representing design aspect of the MEMS product, were considered. The characteristic matrix already used in mathematics (Jurkat and Ryser, 1966) was used to characterize the design aspects of a MEMS product system. The Concurrent MEMS Product Design Aspect Characteristic Interaction Matrix (CIM-CMPDA) Q, for the digraph is expressed in (6.4)

$$Q=[AI-P]=\begin{array}{cccccc|c} 1 & 2 & 3 & 4 & 5 & 6 & vertex \\ \hline A & -1 & -1 & -1 & -1 & -1 & 1 \\ -1 & A & -1 & -1 & -1 & -1 & 2 \\ -1 & -1 & A & -1 & -1 & -1 & 3 \\ -1 & -1 & -1 & A & -1 & -1 & 4 \\ -1 & -1 & -1 & -1 & A & -1 & 5 \\ -1 & -1 & -1 & -1 & -1 & A & 6 \end{array} \qquad (6.4)$$

The interconnections between various design aspects have been assigned values of 0 and 1 depending on whether it exists or not. This does not represent the real design solution which involves, varying the degree of dependency of the design aspects, as well as considering one design aspect over another design aspect. In order to consider this, another matrix, R, called the Concurrent MEMS Product Design Aspect Variable Characteristic Interaction Matrix (VCIM-CMPDA) was proposed. The VCIM matrix is expressed in (6.5)

$$R=\begin{array}{cccccc|c} 1 & 2 & 3 & 4 & 5 & 6 & vertex \\ \hline A_1 & -a_{12} & -a_{13} & -a_{14} & -a_{15} & -a_{16} & 1 \\ -a_{21} & A_2 & -a_{23} & -a_{24} & -a_{25} & -a_{26} & 2 \\ -a_{31} & -a_{32} & A_3 & -a_{34} & -a_{35} & -a_{36} & 3 \\ -a_{41} & -a_{42} & -a_{43} & A_4 & -a_{45} & -a_{46} & 4 \\ -a_{51} & -a_{52} & -a_{53} & -a_{54} & A_5 & -a_{56} & 5 \\ -a_{61} & -a_{62} & -a_{63} & -a_{64} & -a_{65} & A_6 & 6 \end{array} \qquad (6.5)$$

The concurrent MEMS product design variable characteristic function is the characteristic of the product alternative and a powerful tool for concurrent MEMS product design evaluation. However, a close look at the multinomial reveals that its various characteristic coefficients carry both positive and negative signs. The concurrent MEMS product design variable characteristic function may not be able to provide the total objective value, when the numerical values for A_i and a_{ij} are substituted in the multinomial, because some of the information is lost by subtraction and addition operations in the determinant function. Considering these factors, the Concurrent MEMS Product Design Aspect Variable Permanent Function (VPF-CMPDA) was defined. This function was derived from a new matrix called the Concurrent MEMS Product Design Aspect Variable Permanent Interaction Matrix (VPIM-CMPDA). The concurrent MEMS product design aspect variable permanent interaction matrix, S, for the design aspect attributes digraph is expressed in (6.6)

$$S=\begin{array}{cc} \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array} & vertex \\ \left[\begin{array}{cccccc} A_1 & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & A_2 & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & A_3 & a_{34} & a_{35} & a_{36} \\ a_{41} & a_{42} & a_{43} & A_4 & a_{45} & a_{46} \\ a_{51} & a_{52} & a_{53} & a_{54} & A_5 & a_{56} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & A_6 \end{array}\right] & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \end{array} \qquad (6.6)$$

This is the most general representation, which consists of six design aspects of the MEMS device/product.

The permanent of S may be called as the Concurrent MEMS Product Design Aspect Variable Permanent Function (VPF-CMPDA). This decides the overall design and the development of the MEMS product produced according to the six design aspects satisfying the requirements. The permanent function can be derived from the matrix S as in (6.7) (Rao, 2007).

$$
\begin{aligned}
per(S)=\prod_{i=1}^{6}A_i &+\sum_{i=1}^{5}\sum_{j=i+1}^{6}\sum_{k=1}^{3}\sum_{l=k+1}^{4}\sum_{m=l+1}^{5}\sum_{\substack{n=m+1\\k,l,m,n\neq pus}}^{6}(a_{ij}a_{ji})A_kA_lA_mA_n\\
&+\sum_{i=1}^{4}\sum_{j=i+1}^{5}\sum_{k=j+1}^{6}\sum_{l=1}^{4}\sum_{m=l+1}^{5}\sum_{\substack{n=m+1\\k,l,m,n\neq pus}}^{6}(a_{ij}a_{jk}a_{ki}+a_{ik}a_{kj}a_{ji})A_lA_mA_n\\
&+\Bigg[\sum_{i=1}^{3}\sum_{j=i+1}^{6}\sum_{k=i+1}^{5}\sum_{l=i+2}^{6}\sum_{m=1}^{5}\sum_{\substack{n=m+1\\k,l,m,n\neq pus}}^{6}(a_{ij}a_{ji})(a_{kl}a_{lk})A_mA_n\\
&+\sum_{i=1}^{3}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=j+1}^{6}\sum_{m=1}^{5}\sum_{\substack{n=m+1\\k,l,m,n\neq pus}}^{6}(a_{ij}a_{jk}a_{kl}a_{li}+a_{il}a_{lk}a_{kj}a_{ji})A_mA_n\Bigg]\\
&+\Bigg[\sum_{i=1}^{4}\sum_{j=i+1}^{5}\sum_{k=j+1}^{6}\sum_{l=1}^{5}\sum_{m=l+1}^{6}\sum_{\substack{n=1\\k,l,m,n\neq pus}}^{6}(a_{ij}a_{jk}a_{ki}+a_{ik}a_{kj}a_{ji})(a_{lm}a_{ml})A_n\\
&+\sum_{i=1}^{2}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=i+1}^{6}\sum_{m=j+1}^{6}\sum_{\substack{n=1\\k,l,m,n\neq pus}}^{6}(a_{ij}a_{jk}a_{kl}a_{lm}a_{mi}+a_{im}a_{ml}a_{lk}a_{kj}a_{ji})A_n\Bigg]\\
&+\Bigg[\sum_{i=1}^{3}\sum_{j=i+1}^{5}\sum_{k=j+1}^{6}\sum_{l=j+1}^{6}\sum_{m=1}^{5}\sum_{\substack{n=m+1\\k,l,m,n\neq pus}}^{6}(a_{ij}a_{jk}a_{kl}a_{li}+a_{il}a_{lk}a_{kj}a_{ji})(a_{mn}a_{nm})\\
&+\sum_{i=1}^{1}\sum_{j=i+1}^{5}\sum_{k=j+1}^{6}\sum_{l=1}^{4}\sum_{m=l+1}^{5}\sum_{\substack{n=m+1\\k,l,m,n\neq pus}}^{6}(a_{ij}a_{jk}a_{ki}+a_{ik}a_{kj}a_{ji})(a_{lm}a_{mn}a_{nl}+a_{ln}a_{nm}a_{ml})\\
&+\sum_{i=1}^{1}\sum_{j=i+1}^{6}\sum_{k=i+1}^{3}\sum_{l=i+2}^{6}\sum_{m=k+1}^{5}\sum_{\substack{n=k+2\\k,l,m,n\neq pus}}^{6}(a_{ij}a_{ji})(a_{kl}a_{lk})(a_{mn}a_{nm})\\
&+\sum_{i=1}^{1}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=i+1}^{6}\sum_{m=i+1}^{6}\sum_{\substack{n=j+1\\k,l,m,n\neq pus}}^{6}(a_{ij}a_{jk}a_{kl}a_{lm}a_{mn}a_{ni}+a_{in}a_{nm}a_{ml}a_{lk}a_{kj}a_{ji})\Bigg]
\end{aligned}
\tag{6.7}
$$

Where '*pus*' stands for '*previously used subscripts*'

Use of the permanent concept in concurrent MEMS design would help in representing the design aspect attributes under consideration. Application of the permanent concept would lead to a better appreciation of MEMS design aspects since no negative sign would appear in the equation, and hence no information will be lost.

Several researches have used the permanent function of a matrix, which does not contain any negative terms, and thus provides the complete information without any loss (Venkatasamy and Agrawal, 1996; Gandhi and Agrawal, 1992; Rao and Padmanabhan, 2006).

Permanent of matrix S i.e. $per(S)$ contain 6! (720) terms. Different terms in the permanent function were arranged in seven groups. Some of the groups might also have subgroups. The permanent function consists of the structural components e.g., unconnected vertices $A_i s$, dyads $a_{ij}a_{ji}$, loops $a_{ij}a_{jk}a_{ki}, a_{ij}a_{jk}a_{kl}a_{li}$, etc. and their different combinations. Different groups in the permanent function were arranged in the descending number of the unconnected vertices, while the last term does not contain any unconnected vertex. The permanent function has terms in different groups stated as follows:

i. The first group is a set of six unconnected vertices $A_i s$, which has only one term.

ii. The second group does not have any term, because a particular design aspect cannot interact or influence itself.

iii. The third group has dyads $a_{ij}a_{ji}$ and the remaining four unconnected vertices $A_i s$. e.g. $a_{12}a_{21}A_3A_4A_5A_6$.

iv. The fourth group consists of a loop with three-vertex $a_{ij}a_{jk}a_{ki}$ and the three remaining unconnected vertices $A_i s$. e.g. $a_{12}a_{23}a_{31}A_4A_5A_6$.

v. The fifth group has two subgroups. The first subgroup has a loop with four-vertex $a_{ij}a_{jk}a_{kl}a_{li}$ and two unconnected vertices, while the second subgroup has a set of two dyads $a_{ij}a_{ji}$ and $a_{kl}a_{lk}$ and two unconnected vertices. e.g. $e_{12}e_{23}e_{34}e_{41}A_5A_6$ and $(a_{12}a_{21})(a_{34}a_{43})A_5A_6$.

vi. The sixth group has two sub groups. The first subgroup has five-vertex loop $a_{ij}a_{jk}a_{kl}a_{lm}a_{mi}$ and one unconnected vertex, while the second subgroup has one dyad $a_{lm}a_{ml}$ one three-vertex loop $a_{ij}a_{jk}a_{ki}$, and an unconnected vertex A_i. e.g. $a_{12}a_{23}a_{34}a_{45}a_{51}A_6$ and $(a_{12}a_{23}a_{31})(a_{45}a_{54})A_6$.

vii. The seventh group has four sub groups. The first subgroup has six-vertex loops $a_{ij}a_{jk}a_{kl}a_{lm}a_{mn}a_{ni}$, the second sub group consists of three dyads $a_{ij}a_{ji}, a_{kl}a_{lk}$ and $a_{mn}a_{nm}$, the third subgroup has one dyad $a_{ij}a_{ji}$ and one four-vertex loop $a_{ij}a_{jk}a_{kl}a_{li}$, and the fourth subgroup has two three-vertex loops $a_{ij}a_{jk}a_{ki}$ and $a_{lm}a_{mn}a_{nl}$. e.g.

$a_{12}a_{23}a_{34}a_{45}a_{56}a_{61},$ $(a_{12}a_{21})(a_{34}a_{43})(a_{56}a_{65}),(a_{12}a_{21})(a_{34}a_{45}a_{56}a_{63}),(a_{12}a_{23}a_{31})(a_{45}a_{56}a_{64})$

The six design aspect considered may interact among each other in the above said ways and it is shown in Figure 6.7.

For '*n*' different designs of MEMS product, design index S_i for each aspect was obtained. As the design aspect attributes vary the index S would also change. The a_{ij} could be selected by the experts in such a way that the dependency could be understood and acceptable values for the design aspect attributes could be found. The proposed methodology was applicable up to component level. The proposed methodology was shown in the subsystem level, but each subsystem was evaluated from the sub-subsystems using the same permanent index. The method was extendable up to component level. Usually the evaluation is carried out from bottom to top i.e. from component level to system level.

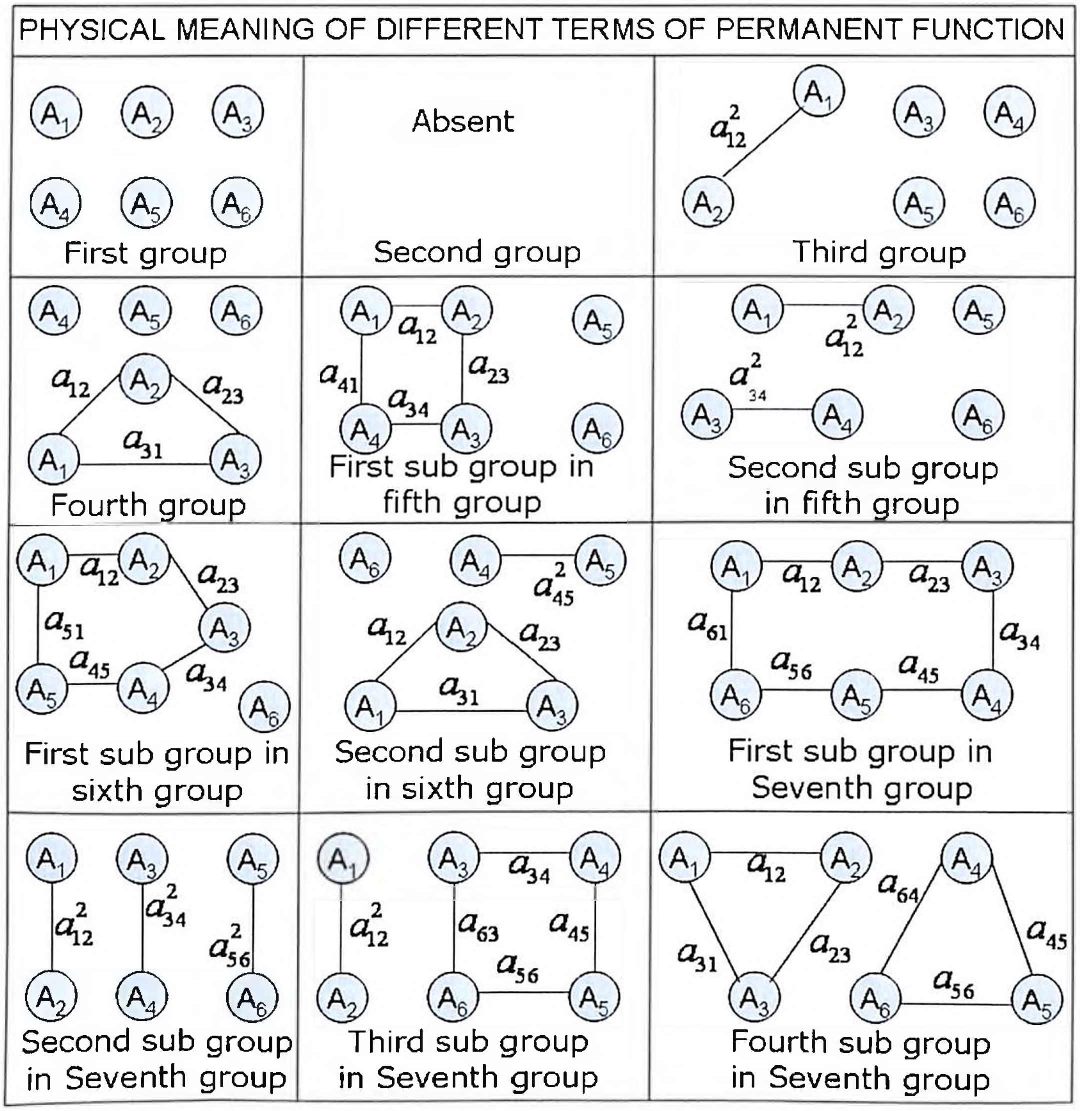


Figure 6.7: Graphical representation of the interaction of design aspects as per permanent function terms.

6.7 Graph Theory and Matrix Based Concurrent Model Validation

This work considered only three subsystems (X-abilities) to validate the proposed model. The three aspects were design for micromachined element design ($DFMED$), design for materials (DFM) and design for environment (DFE) which were considered for the concurrent model validation in section 6.5 and was used further with the same set of values.

6.7.1. Design for micromachined element design ($DFMED$)

In order to obtain a better design from the conceptual stage itself, this study considered six micromachined element design parameters. They were as follows:

1. Gap between the membrane and the signal conductor ($X_1 = g\mu m$)
2. Thickness of the dielectric ($X_2 = t_d\mu m$)
3. Thickness of the movable membrane ($X_3 = t_m\mu m$)
4. Thickness of the signal conductor ($X_4 = t_c\mu m$)
5. Overlapping area of the membrane with the signal line ($X_5 = OA\mu m^2$)
6. Width of the conductors ($X_6 = w\mu m$)

The rest of the micromachined element design attributes were assumed to be constant to allow for simpler explanation.

This study considered all the six micromachined element design parameters together in the matrix form as given below:

$$D=\begin{array}{cccccc|c} 1 & 2 & 3 & 4 & 5 & 6 & vertex \\ \hline g & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & 1 \\ a_{21} & t_d & a_{23} & a_{24} & a_{25} & a_{26} & 2 \\ a_{31} & a_{32} & t_m & a_{34} & a_{35} & a_{36} & 3 \\ a_{41} & a_{42} & a_{43} & t_c & a_{45} & a_{46} & 4 \\ a_{51} & a_{52} & a_{53} & a_{54} & OA & a_{56} & 5 \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & w & 6 \end{array} \qquad (6.8)$$

The design for micromachined element design ($DFMED$) matrix could be obtained from matrix $[D]$ in a non-dimensional format by using the limits imposed by the designers. In Table 6.2, the design variables like g, t_d, t_m, t_c, OA and w that had been worked out for the eight alternatives ($D_1, D_2, ..., D_8$) are illustrated.

Table 6.2: Micromachined element design attributes for eight alternatives

	$X_1 = g\mu m$	$X_2 = t_d\mu m$	$X_3 = t_m\mu m$	$X_4 = t_c\mu m$	$X_5 = OA\mu m^2$	$X_6 = w\mu m$
D_1	5	0.15	0.2	3	12500	100
D_2	5	0.15	0.1	2	11250	90
D_3	3	0.2	0.1	2	12500	100
D_4	3	0.2	0.2	3	11250	90
D_5	3	0.2	0.1	2	11250	90
D_6	3	0.2	0.2	3	12500	100
D_7	5	0.15	0.1	2	12500	100
D_8	5	0.15	0.2	3	11250	90

A matrix called *DFMED* was defined, where in the diagonal elements were $\frac{g}{g_{\max}}, \frac{t_d}{t_{d\max}}, \frac{t_m}{t_{m\max}}, \frac{t_c}{t_{c\max}}, \frac{OA}{OA_{\max}}$ and $\frac{w}{w_{\max}}$. This study deliberately selected the non-dimensional format for the elements. The off-diagonal elements in *DFMED* were based on interaction and interdependency between attributes. Since few alternatives were to be ranked with more design parameters, the interaction was represented with two levels only (0 or 1). For example g and t_m were dependent so a_{13} and a_{31} could be given 1 and since t_d and w would not interact, a_{26} and a_{62} is 0. Similarly, using the expert's knowledge the interaction values could be assigned. It was not necessary that the interaction was always 1 or 0. If the interaction was very low it could be assigned to 0 provided fewer alternatives were to be ranked with more design parameters. If the number of alternatives were more and the design parameters were less, then greater levels of interaction should be used. Assigning interaction among the parameters is not a difficult job in MEMS design, because current MEMS product development also requires expert opinion to proceed in each stage.

The final *DFMED* for the eight alternatives could be derived as shown below:

$$DFMED_1 = \begin{bmatrix} \frac{5}{5} & 1 & 1 & 1 & 1 & 1 \\ 1 & \frac{0.15}{0.2} & 1 & 1 & 0 & 0 \\ 1 & 1 & \frac{0.2}{0.2} & 1 & 1 & 1 \\ 1 & 1 & 1 & \frac{3}{3} & 0 & 0 \\ 1 & 0 & 1 & 0 & \frac{12500}{12500} & 1 \\ 1 & 0 & 1 & 0 & 1 & \frac{100}{100} \end{bmatrix}$$

$$Per(DFMED_1) = 140$$

$$DFMED_2 = \begin{bmatrix} \frac{5}{5} & 1 & 1 & 1 & 1 & 1 \\ 1 & \frac{0.15}{0.2} & 1 & 1 & 0 & 0 \\ 1 & 1 & \frac{0.1}{0.2} & 1 & 1 & 1 \\ 1 & 1 & 1 & \frac{2}{3} & 0 & 0 \\ 1 & 0 & 1 & 0 & \frac{11250}{12500} & 1 \\ 1 & 0 & 1 & 0 & 1 & \frac{90}{100} \end{bmatrix}$$

$$Per(DFMED_2) = 110.962$$

$$DFMED_3 = \begin{bmatrix} \frac{3}{5} & 1 & 1 & 1 & 1 & 1 \\ 1 & \frac{0.2}{0.2} & 1 & 1 & 0 & 0 \\ 1 & 1 & \frac{0.1}{0.2} & 1 & 1 & 1 \\ 1 & 1 & 1 & \frac{2}{3} & 0 & 0 \\ 1 & 0 & 1 & 0 & \frac{12500}{12500} & 1 \\ 1 & 0 & 1 & 0 & 1 & \frac{100}{100} \end{bmatrix}$$

$$Per(DFMED_3) = 121.204$$

$$DFMED_4 = \begin{bmatrix} \frac{3}{5} & 1 & 1 & 1 & 1 & 1 \\ 1 & \frac{0.2}{0.2} & 1 & 1 & 0 & 0 \\ 1 & 1 & \frac{0.2}{0.2} & 1 & 1 & 1 \\ 1 & 1 & 1 & \frac{3}{3} & 0 & 0 \\ 1 & 0 & 1 & 0 & \frac{11250}{12500} & 1 \\ 1 & 0 & 1 & 0 & 1 & \frac{90}{100} \end{bmatrix}$$

$Per(DFMED_4) = 135.256$

$$DFMED_5 = \begin{bmatrix} \frac{3}{5} & 1 & 1 & 1 & 1 & 1 \\ 1 & \frac{0.2}{0.2} & 1 & 1 & 0 & 0 \\ 1 & 1 & \frac{0.1}{0.2} & 1 & 1 & 1 \\ 1 & 1 & 1 & \frac{2}{3} & 0 & 0 \\ 1 & 0 & 1 & 0 & \frac{11250}{12500} & 1 \\ 1 & 0 & 1 & 0 & 1 & \frac{90}{100} \end{bmatrix}$$

$Per(DFMED_5) = 113.898$

$$DFMED_6 = \begin{bmatrix} \frac{3}{5} & 1 & 1 & 1 & 1 & 1 \\ 1 & \frac{0.2}{0.2} & 1 & 1 & 0 & 0 \\ 1 & 1 & \frac{0.2}{0.2} & 1 & 1 & 1 \\ 1 & 1 & 1 & \frac{3}{3} & 0 & 0 \\ 1 & 0 & 1 & 0 & \frac{12500}{12500} & 1 \\ 1 & 0 & 1 & 0 & 1 & \frac{100}{100} \end{bmatrix}$$

$Per(DFMED_6) = 144$

$$DFMED_7 = \begin{bmatrix} \frac{5}{5} & 1 & 1 & 1 & 1 & 1 \\ 1 & \frac{0.15}{0.2} & 1 & 1 & 0 & 0 \\ 1 & 1 & \frac{0.1}{0.2} & 1 & 1 & 1 \\ 1 & 1 & 1 & \frac{2}{3} & 0 & 0 \\ 1 & 0 & 1 & 0 & \frac{12500}{12500} & 1 \\ 1 & 0 & 1 & 0 & 1 & \frac{100}{100} \end{bmatrix}$$

$$Per(DFMED_7) = 118.212$$

$$DFMED_8 = \begin{bmatrix} \frac{5}{5} & 1 & 1 & 1 & 1 & 1 \\ 1 & \frac{0.15}{0.2} & 1 & 1 & 0 & 0 \\ 1 & 1 & \frac{0.2}{0.2} & 1 & 1 & 1 \\ 1 & 1 & 1 & \frac{3}{3} & 0 & 0 \\ 1 & 0 & 1 & 0 & \frac{11250}{12500} & 1 \\ 1 & 0 & 1 & 0 & 1 & \frac{90}{100} \end{bmatrix}$$

$$Per(DFMED_8) = 131.325$$

From the above micromachined element design matrices the permanents were calculated using combinational mathematics; these values were referred to as *DFMED* indices. The higher the *DFMED* index, the more favorable the design for the application would be, in terms of micromachined element design considerations. The simulated results of S_{12}, S_{11} and *VSWR* for the eight alternatives obtained by keeping all other material and environment, etc. constant are shown in Figure 6.8 (a), (b) and (c). Further the performance characteristics S_{12}, S_{11} and *VSWR* are tabulated at 2 GHz along with their rank obtained using *DFMED* index and EDA simulation in Table 6.3. Table 6.3 results shows that the rank obtained using *DFMED* index and simulation are equal. The result showed that the alternative D_6 would be better for micromachined element design.

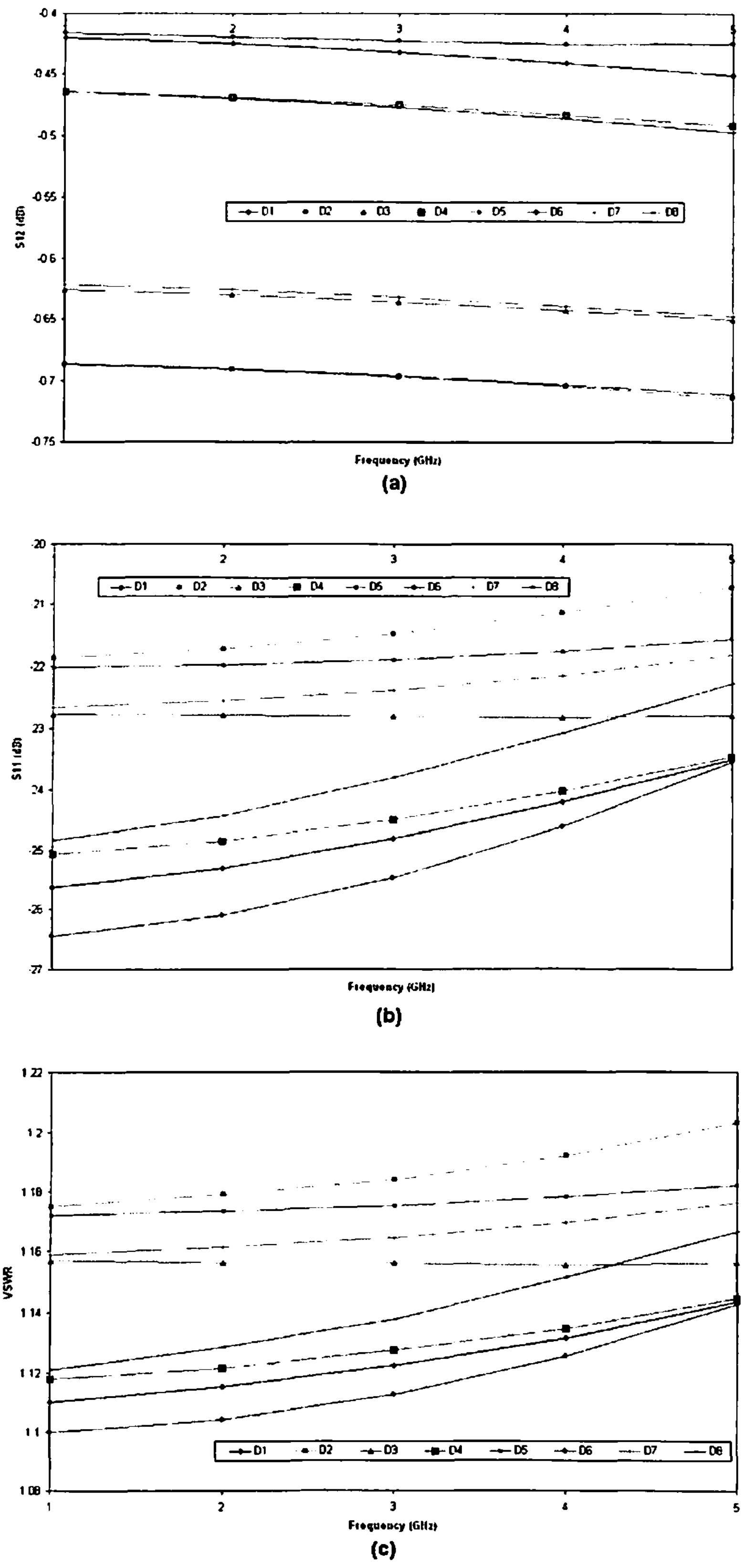


Figure 6.8: Simulated results for different micromachined element designs of a MEMS power sensor **(a)** Insertion loss, **(b)** Reflection loss and **(c)** VSWR

Table 6.3: Comparative micromachined element design evaluation of the power sensor

Alternative	**Performance characteristics**			**Evaluation/Rank**	
	S_{12}	S_{11}	*VSWR*	*DFMED* **index**	**Simulation**
D_1	-0.4252	-25.3248	1.11455	2	2
D_2	-0.69035	-21.7291	1.17853	8	8
D_3	-0.6298	-22.802	1.15616	5	5
D_4	-0.46872	-24.8581	1.12125	3	3
D_5	-0.68984	-21.9843	1.17291	7	7
D_6	-0.41992	-26.1122	1.1041	1	1
D_7	-0.62567	-22.5687	1.16076	6	6
D_8	-0.46947	-24.4411	1.1276	4	4

6.7.2 Design for materials (DFM)

Four different combinations of materials were considered for the analysis. $M1, M2, M3$ and $M4$ were the four different material alternatives. The materials used for CPW conductor, membrane, dielectric and substrate are tabulated in Table 6.4.

Table 6.4: Material combinations for the power sensor

	CPW	**Membrane**	**Dielectric**	**Substrate**
$M1$	Aluminium	Titanium	Silicon Dioxide (SiO2)	Silicon (Si)
$M2$	Gold	Silver	Silicon Dioxide (SiO2)	Silicon (Si)
$M3$	Aluminium	Titanium	Silicon Nitride (N4Si3)	Gallium Arsenide (GaAs)
$M4$	Copper	Aluminium	Silicon Nitride (N4Si3)	Gallium Arsenide (GaAs)

In order to get a better combination of materials at the conceptual stage, this study considered six material parameters as follows:

1. Conductivity of the CPW signal line ($X_7 = \sigma_c \, {}^{s}\!/_{cm}$)
2. Conductivity of the membrane ($X_8 = \sigma_m \, {}^{s}\!/_{cm}$)

3. Dielectric constant of the dielectric ($X_9 = \varepsilon_d$)
4. Loss tangent of dielectric ($X_{10} = LT_d$)
5. Dielectric constant of the substrate ($X_{11} = \varepsilon_s$)
6. Loss tangent of substrate ($X_{12} = LT_s$)

The rest of the material attributes were considered as constant to simplify the discussion. This study considered all the six materials parameters together in the matrix form as given below

$$M = \begin{array}{cccccc|l} 1 & 2 & 3 & 4 & 5 & 6 & vertex \\ \sigma_c & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & 1 \\ a_{21} & \sigma_m & a_{23} & a_{24} & a_{25} & a_{26} & 2 \\ a_{31} & a_{32} & \varepsilon_d & a_{34} & a_{35} & a_{36} & 3 \\ a_{41} & a_{42} & a_{43} & LT_d & a_{45} & a_{46} & 4 \\ a_{51} & a_{52} & a_{53} & a_{54} & \sigma_s & a_{56} & 5 \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & LT_s & 6 \end{array} \qquad (6.9)$$

Design for materials (DFM) matrix could be obtained from matrix $[M]$ in terms of a non-dimensional format by using the limits imposed by the designers. The materials attributes like $\sigma_c, \sigma_m, \varepsilon_d, LT_d, \varepsilon_s$ and LT_s have been worked out for the four alternatives (four material combinations M_1, M_2, M_3 and M_4) and are illustrated in Table 6.5.

Table 6.5: Materials attributes for four alternatives

	$X_7 = \sigma_c \, S/cm$	$X_8 = \sigma_m \, S/cm$	$X_9 = \varepsilon_d$	$X_{10} = LT_d$	$X_{11} = \varepsilon_s$	$X_{12} = LT_s$
$M1$	378000	25000	3.9	0.001	11.9	0.005
$M2$	452000	630100	3.9	0.001	11.9	0.005
$M3$	378000	25000	7.9	0.0017	13.1	0.006
$M4$	596000	378000	7.9	0.0017	13.1	0.006

A matrix called DFM was defined, wherein the diagonal elements and off diagonal elements were chosen as explained above. Since the material alternatives were only four and had six material attributes, the interaction can be defined using only two levels (0 or 1).

The final DFM for the four alternatives could be derives as shown below:

$$DFM_1 = \begin{bmatrix} \frac{378000}{596000} & 0 & 1 & 1 & 1 & 1 \\ 0 & \frac{25000}{630100} & 1 & 1 & 0 & 0 \\ 1 & 1 & \frac{3.9}{7.9} & 1 & 0 & 0 \\ 1 & 1 & 1 & \frac{0.001}{0.0017} & 0 & 0 \\ 1 & 0 & 0 & 0 & \frac{11.9}{13.1} & 1 \\ 1 & 0 & 0 & 0 & 1 & \frac{0.005}{0.006} \end{bmatrix}$$

$Per(DFM_1) = 22.4574$

$$DFM_2 = \begin{bmatrix} \frac{452000}{596000} & 0 & 1 & 1 & 1 & 1 \\ 0 & \frac{630100}{630100} & 1 & 1 & 0 & 0 \\ 1 & 1 & \frac{3.9}{7.9} & 1 & 0 & 0 \\ 1 & 1 & 1 & \frac{0.001}{0.0017} & 0 & 0 \\ 1 & 0 & 0 & 0 & \frac{11.9}{13.1} & 1 \\ 1 & 0 & 0 & 0 & 1 & \frac{0.005}{0.006} \end{bmatrix}$$

$Per(DFM_2) = 34.629$

$$DFM_3 = \begin{bmatrix} \frac{378000}{596000} & 0 & 1 & 1 & 1 & 1 \\ 0 & \frac{25000}{630100} & 1 & 1 & 0 & 0 \\ 1 & 1 & \frac{7.9}{7.9} & 1 & 0 & 0 \\ 1 & 1 & 1 & \frac{0.0017}{0.0017} & 0 & 0 \\ 1 & 0 & 0 & 0 & \frac{13.1}{13.1} & 1 \\ 1 & 0 & 0 & 0 & 1 & \frac{0.006}{0.006} \end{bmatrix}$$

$Per(DFM_3) = 29.809$

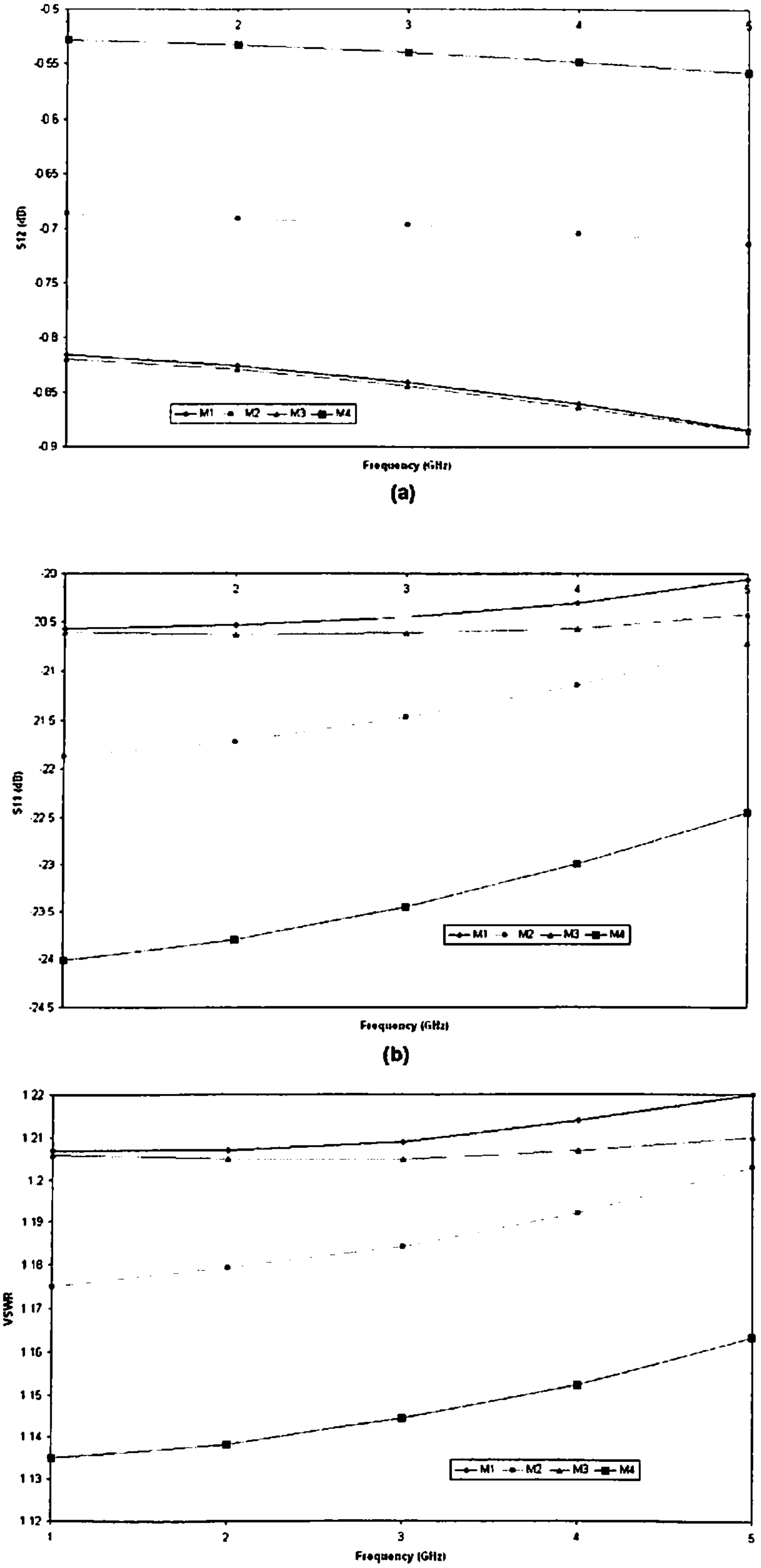
$$DFM_4 = \begin{bmatrix} \frac{596000}{596000} & 0 & 1 & 1 & 1 & 1 \\ 0 & \frac{378000}{630100} & 1 & 1 & 0 & 0 \\ 1 & 1 & \frac{7.9}{7.9} & 1 & 0 & 0 \\ 1 & 1 & 1 & \frac{0.0017}{0.0017} & 0 & 0 \\ 1 & 0 & 0 & 0 & \frac{13.1}{13.1} & 1 \\ 1 & 0 & 0 & 0 & 1 & \frac{0.006}{0.006} \end{bmatrix}$$

$$Per(DFM_4) = 43.998$$

From the above materials matrices, the permanents were derived using combinational mathematics; these values were called as DFM indices. The higher the DFM index more favorable would be the material combination for the application. The simulated results of S_{12}, S_{11} and $VSWR$ for the four materials alternatives by keeping all other micromachined element design and environment, etc. constant are shown in Figure 6.9 (a), (b) and (c). Further, the performance characteristics S_{12}, S_{11} and $VSWR$ are tabulated at 2 GHz along with their rank obtained by DFM index and simulation in Table 6.6. The results tabulated in Table 6.9 show that the rank obtained using DFM index and simulation are equal. This indicated that the material combination M_4 would be better for the power sensor design.

Table 6.6: Comparative material combination evaluation of the power sensor

Alternative	**Performance characteristics**			**Evaluation/Rank**	
	S_{12}	S_{11}	$VSWR$	DFM **index**	**Simulation**
$M1$	-0.82551	-20.5394	1.20745	4	4
$M2$	-0.69035	-21.7291	1.17853	2	2
$M3$	-0.82907	-20.6294	1.2051	3	3
$M4$	-0.5332	-23.8003	1.13804	1	1



(a)

(b)

(c)

Figure 6.9: Simulated results for different material combination of a MEMS power sensor **(a)** Insertion loss, **(b)** Reflection loss and **(c)** VSWR

6.7.3 Design for environment (DFE)

At the conceptual stage, based on the environment where the sensor is going to act, its design, material, fabrication and packaging need to be carried out. This study considers three different environments for the analysis say distilled water, air and ethanol fuel. $E1, E2$ and $E3$ are the three different environment alternatives

In order to identify the best environment in which the power sensor can work effectively at the conceptual stage itself, four environmental parameters were considered are as follows:

1. Dielectric constant of the environment ($X_{13} = \varepsilon_e$)
2. Loss tangent of environment ($X_{14} = LT_e$)
3. Permeability of the environment ($X_{15} = \mu_e$)
4. Resistivity of the environment ($X_{16} = \rho_e \, \Omega.cm$)

The rest of the environmental attributes were considered to be constant to simplify the discussion. This study considered all the four environmental parameters together in the matrix form as given below:

$$E = \begin{array}{c} \begin{array}{cccc} 1 & 2 & 3 & 4 \end{array} \quad vertex \\ \left[\begin{array}{cccc} \varepsilon_e & a_{12} & a_{13} & a_{14} \\ a_{21} & LT_e & a_{23} & a_{24} \\ a_{31} & a_{32} & \mu_e & a_{34} \\ a_{41} & a_{42} & a_{43} & \rho_e \end{array}\right] \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array} \end{array} \tag{6.10}$$

The design for environment (DFE) matrix could be obtained from matrix $[E]$ in a non-dimensional format by using the limits imposed by the designers. The environments attributes like $\varepsilon_e, LT_e, \mu_e$ and ρ_e have been worked out for the three alternatives (distilled water, air and ethanol E_1, E_2 and E_3) and are shown in Table 6.7.

Table 6.7: Environmental attributes for three alternatives

	$X_{13} = \varepsilon_e$	$X_{14} = LT_e$	$X_{15} = \mu_e$	$X_{16} = \rho_e \, \Omega.cm$
$E1$	76.7	0.157	0.999992	2.00e3
$E2$	1.0005	0.004	1	1.25e16
$E3$	24.5	1	1.2	0.2

A matrix called DFE was defined, where in the diagonal elements and off diagonal elements were chosen as explained above. Since less environmental attributes were considered, the interaction could be defied in three levels (0, 0.5 and 1).

The final DFE for the three alternatives could be derives as shown below:

$$DFE_1 = \begin{bmatrix} \frac{76.7}{76.7} & 1 & 0 & 0 \\ 1 & \frac{0.157}{1} & 0 & 0.5 \\ 0 & 0 & \frac{0.999992}{1.2} & 1 \\ 0 & 0.5 & 1 & \frac{2000}{1.25e16} \end{bmatrix}$$

$$Per(DFE_1) = 1.36533$$

$$DFE_2 = \begin{bmatrix} \frac{1.0005}{76.7} & 1 & 0 & 0 \\ 1 & \frac{0.004}{1} & 0 & 0.5 \\ 0 & 0 & \frac{1}{1.2} & 1 \\ 0 & 0.5 & 1 & \frac{1.25e16}{1.25e16} \end{bmatrix}$$

$$Per(DFE_2) = 1.83615$$

$$DFE_3 = \begin{bmatrix} \frac{24.5}{76.7} & 1 & 0 & 0 \\ 1 & \frac{1}{1} & 0 & 0.5 \\ 0 & 0 & \frac{1.2}{1.2} & 1 \\ 0 & 0.5 & 1 & \frac{0.2}{1.25e16} \end{bmatrix}$$

$$Per(DFE_3) = 1.39928$$

From the above environment matrices, permanents were derived using combinational mathematics; these values were referred to as DFE indices. The higher the DFE index, the more favorable would be the environment for the product. The simulated results of S_{12}, S_{11} and $VSWR$ for the three environment alternatives while keeping all other micromachined element design and materials, etc. constant are shown in Figure 6.10 (a), (b) and (c).

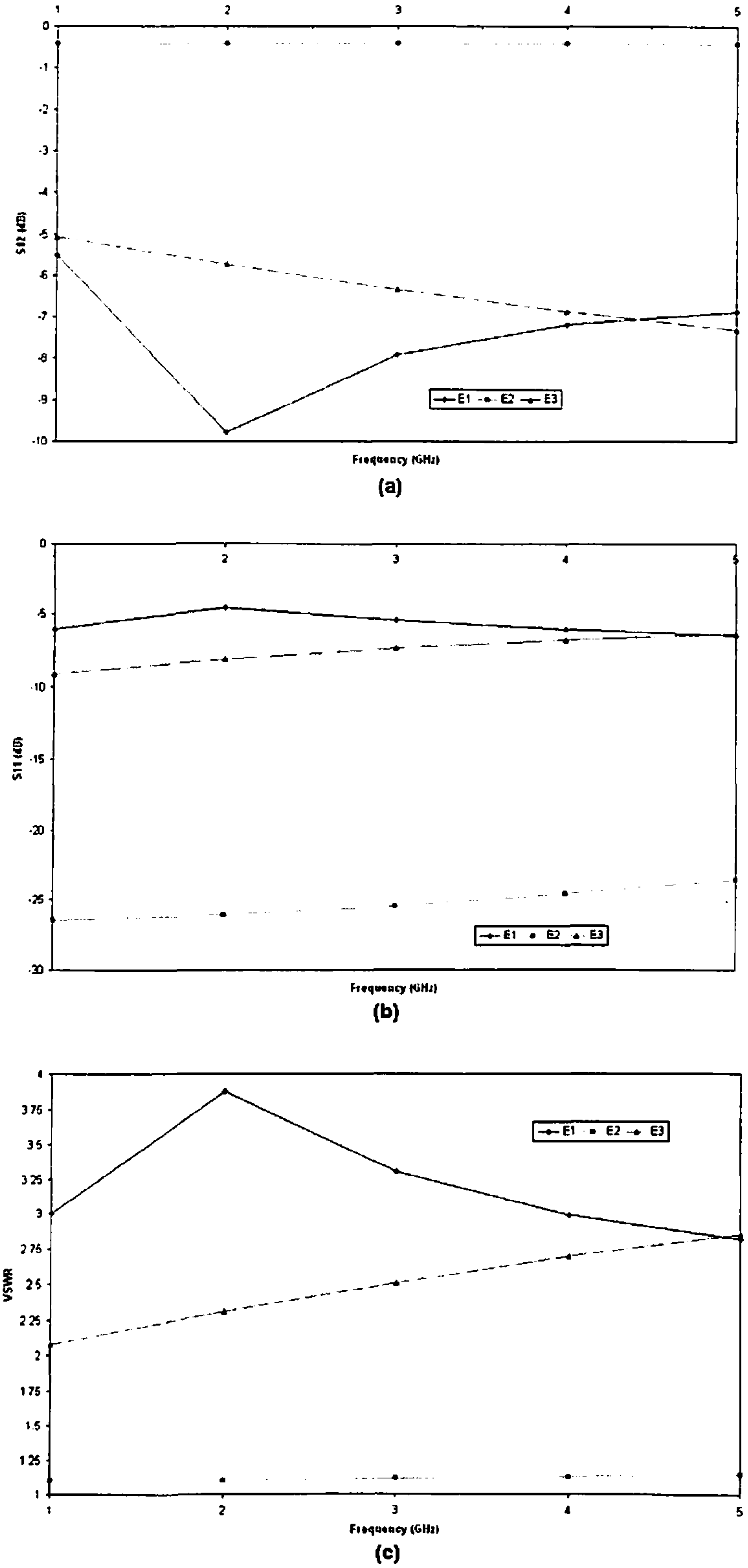


Figure 6.10: Simulated results of the MEMS power sensor at different environments **(a)** Insertion loss, **(b)** Reflection loss and **(c)** VSWR

Further the performance characteristics S_{12}, S_{11} and $VSWR$ are tabulated at 2 GHz along with their rank using DFE index and simulation in Table 6.8. Table 6.8 results indicate that the rank obtained using DFE index and simulation are equal. The result implied that the sensor could work effectively in air or free space (E_2).

Table 6.8: Comparative evaluation of the power sensor at different environments

Alternative	Performance characteristics			Evaluation/Rank	
	S_{12}	S_{11}	$VSWR$	DFE index	Simulation
$E1$	-9.77747	-4.58626	3.87539	3	3
$E2$	-0.41992	-26.1122	1.1041	1	1
$E3$	-5.72712	-8.09364	2.29945	2	2

6.7.4 Design for X (DFX)

To study the DFX algorithm, the three product development aspects of MEMS power sensor were considered (micromachined element deign, materials and environment). Design for micromachined element design $DFMED$ index, Design for materials DFM index, and Design for Environment DFE index were simultaneously put together in the DFX matrix for twelve alternatives, i.e. twelve alternatives (systems/products) were considered with the combination of three subsystems (micromachined element deign, materials and environment). $MP1, MP2, ..., MP12$ were the twelve different MEMS power sensor alternatives and the respective micromachined element design, material and environment combinations are indicated in Table 6.9. For example alternative $MP1$ had micromachined element design as D_8, material used was the M_3 combination and the environment in which it worked was assumed to be E_2 i.e. air.

This study considered all the three abilities/subsystem together in the matrix form as given below

$$X = \begin{array}{cccc} 1 & 2 & 3 & \text{vertex} \\ \left[\begin{matrix} DFMED & a_{12} & a_{13} \\ a_{21} & DFM & a_{32} \\ a_{31} & a_{32} & DFE \end{matrix}\right] & & & \begin{matrix} 1 \\ 2 \\ 3 \end{matrix} \end{array} \tag{6.11}$$

Table 6.9: MEMS power sensor alternatives and the subsystem combinations

Alternative	Subsystem combination
*MP*1	D8M3E2
*MP*2	D1M1E2
*MP*3	D6M1E2
*MP*4	D6M4E2
*MP*5	D4M3E2
*MP*6	D3M4E4
*MP*7	D7M4E1
*MP*8	D3M2E4
*MP*9	D7M2E1
*MP*10	D5M4E1
*MP*11	D5M2E1
*MP*12	D2M3E2

Design for X (DFX) matrix could be obtained from matrix $[X]$ in a non-dimensional format by using the limits imposed by the designers. A matrix called DFX was defined, where in the diagonal elements and off diagonal elements were chosen based on the interdependencies/interaction between subsystems. Since only three subsystems and twelve alternatives were to be ranked, the interactions could be defined in multiple levels (0.2, 1.5 and 2).

The final DFX for the twelve alternatives could be derives as shown below:

$$DFX_1 = \begin{bmatrix} \frac{131.325}{144} & 1.5 & 0.2 \\ 1.5 & \frac{29.809}{43.998} & 2 \\ 0.2 & 2 & \frac{1.836}{1.836} \end{bmatrix}$$

$$Per(DFX_1) = 7.74$$

$$DFX_2 = \begin{bmatrix} \frac{140}{144} & 1.5 & 0.2 \\ 1.5 & \frac{22.457}{43.998} & 2 \\ 0.2 & 2 & \frac{1.836}{1.836} \end{bmatrix}$$

$$Per(DFX_2) = 7.86$$

$$DFX_3 = \begin{bmatrix} \frac{144}{144} & 1.5 & 0.2 \\ 1.5 & \frac{22.457}{43.998} & 2 \\ 0.2 & 2 & \frac{1.836}{1.836} \end{bmatrix}$$

$$Per(DFX_3) = 7.98$$

$$DFX_4 = \begin{bmatrix} \frac{144}{144} & 1.5 & 0.2 \\ 1.5 & \frac{43.998}{43.998} & 2 \\ 0.2 & 2 & \frac{1.836}{1.836} \end{bmatrix}$$

$$Per(DFX_4) = 8.49$$

$$DFX_5 = \begin{bmatrix} \frac{135.256}{144} & 1.5 & 0.2 \\ 1.5 & \frac{29.809}{43.998} & 2 \\ 0.2 & 2 & \frac{1.836}{1.836} \end{bmatrix}$$

$$Per(DFX_5) = 7.86$$

$$DFX_6 = \begin{bmatrix} \frac{121.204}{144} & 1.5 & 0.2 \\ 1.5 & \frac{43.998}{43.998} & 2 \\ 0.2 & 2 & \frac{1.399}{1.836} \end{bmatrix}$$

$$Per(DFX_6) = 6.96$$

$$DFX_7 = \begin{bmatrix} \frac{118.213}{144} & 1.5 & 0.2 \\ 1.5 & \frac{43.998}{43.998} & 2 \\ 0.2 & 2 & \frac{1.365}{1.836} \end{bmatrix}$$

$$Per(DFX_7) = 6.81$$

$$DFX_8 = \begin{bmatrix} \frac{121.204}{144} & 1.5 & 0.2 \\ 1.5 & \frac{34.629}{43.998} & 2 \\ 0.2 & 2 & \frac{1.399}{1.836} \end{bmatrix}$$

$$Per(DFX_8) = 6.82$$

$$DFX_9 = \begin{bmatrix} \frac{118.212}{144} & 1.5 & 0.2 \\ 1.5 & \frac{34.629}{43.998} & 2 \\ 0.2 & 2 & \frac{1.365}{1.836} \end{bmatrix}$$

$$Per(DFX_9) = 6.67$$

$$DFX_{10} = \begin{bmatrix} \frac{113.898}{144} & 1.5 & 0.2 \\ 1.5 & \frac{43.998}{43.998} & 2 \\ 0.2 & 2 & \frac{1.365}{1.836} \end{bmatrix}$$

$$Per(DFX_{10}) = 6.67$$

$$DFX_{11} = \begin{bmatrix} \frac{113.898}{144} & 1.5 & 0.2 \\ 1.5 & \frac{34.629}{43.998} & 2 \\ 0.2 & 2 & \frac{1.365}{1.836} \end{bmatrix}$$

$$Per(DFX_{11}) = 6.53$$

$$DFX_{12} = \begin{bmatrix} \frac{110.962}{144} & 1.5 & 0.2 \\ 1.5 & \frac{29.809}{43.998} & 2 \\ 0.2 & 2 & \frac{1.836}{1.836} \end{bmatrix}$$

$$Per(DFX_{12}) = 7.08$$

From the above *DFX* matrices and *DFX* indices, it is clear that the higher the *DFX* index, more favorable would be the power sensor. The simulated results of *VSWR* for the twelve alternative RF MEMS power sensors is shown in Figure 6.11. Also *VSWR* for the twelve products are tabulated at 2 GHz along with their rank using *DFX* index, MADM and simulation in Table 6.10. The results from concurrent modeling using MADM, concurrent modeling using graph and matrix approach and the simulation were the same.

From the above analysis, the alternative *MP*4 was found to be the best among all possible alternatives that were considered. The product development could be carried out with these specifications. The above discussion considered only three abilities/subsystems, whereas the designer/manufacturer could consider all abilities/subsystem at the conceptual stage itself. This would reduce the MEMS product development time considerably. The algorithm proposed herein was very simple and it took less time and memory to run in a computer. Once the evaluation was done the product could be verified and manufactured using the normal development flow. If the interactions were defined more clearly, then fewer iterations would be required to obtain the finished product.

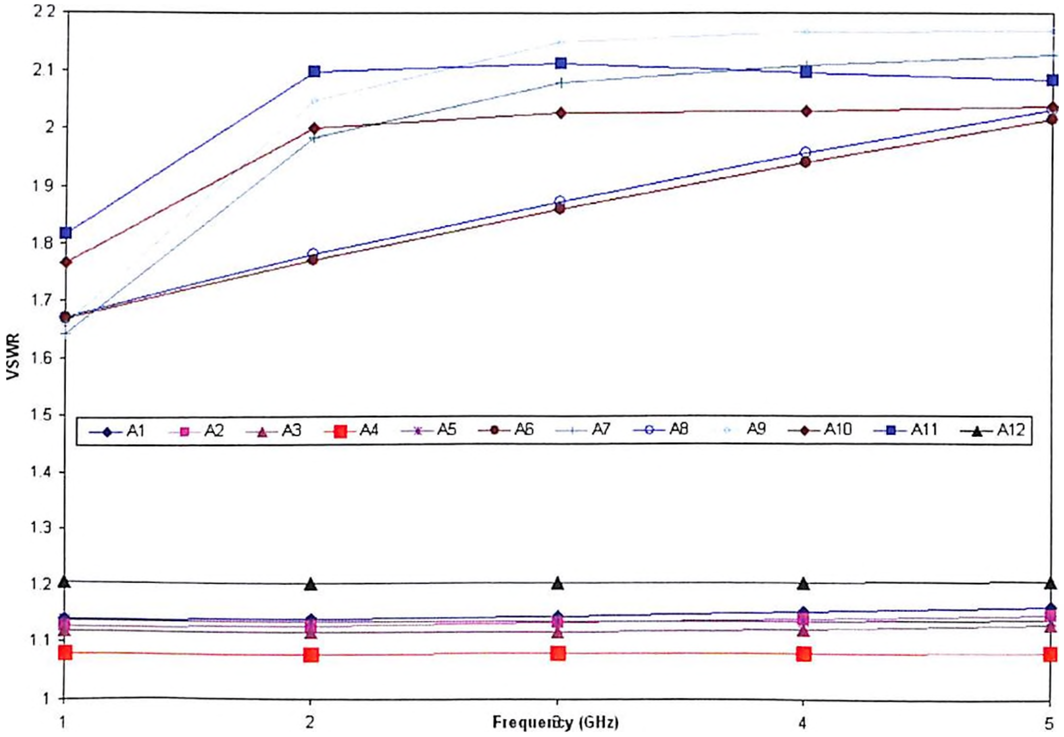


Figure 6.11: Simulated VSWR of the MEMS power sensor for X-abilities

Table 6.10: Comparative evaluation results of the MEMS power sensor

Alternative	*VSWR*	Evaluation/Rank		
		DFX index	MADM	Simulation
*MP*1	1.1433	5	5	5
*MP*2	1.1314	3	3	3
*MP*3	1.11911	2	2	2
*MP*4	1.08002	1	1	1
*MP*5	1.1384	4	4	4
*MP*6	1.76847	7	7	7
*MP*7	1.98163	9	9	9
*MP*8	1.77673	8	8	8
*MP*9	2.04604	11	11	11
*MP*10	1.99828	10	10	10
*MP*11	2.09558	12	12	12
*MP*12	1.2051	6	6	6

6.8 Conclusions

This chapter described the need for concurrent engineering in MEMS device and product development. Two concurrent modelling, design and analysis methodologies that were developed are described herein.

- A new methodology was proposed that combines all the design aspects together to generate a useful product. This methodology would be helpful for R&D experts to accept the design at the conceptual stage itself by considering all the parameters simultaneously.
- Concurrent product design and development was represented using a flow diagram and the product development time was depicted using a time chart.
- Designing a MEMS device by keeping various aspects of product design/development like micromachined element design, microelectronics circuit design, fabrication, packaging, materials, environment, cost, testability, reliability, maintainability, quality etc., were considered in an integrated manner.
- A concurrent model was developed using MADM which considered the attributes related to all the design aspects for evaluation.

- A Concurrent method using graph & matrix approach was developed, which considered all the design aspects in a unified systems approach without losing any useful information. The model had the capability to consider the interdependence of one design aspect over the other using the available parameters. Since the model was derived from the matrix algebra, it was easy to store in a computer and also very easy to develop software coding for it.

The RF MEMS based power sensor which was designed in Chapter 5 was used to explain the proposed methodologies. Using simulation results, the methodology was validated, a power sensor with VSWR of 1.08002 was reported.

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 Summary of the Thesis

Presented in this thesis is a comprehensive study directed towards developing an effective concurrent design and development model for MEMS products. Work towards this thesis was initiated by carrying out a preliminary literature survey. The outcome of the survey led to the definition of the main hypothesis underlying this thesis study, which is as follows: **MEMS is an interdisciplinary area, MEMS products involve a high degree of uncertainty in fabrication, and the development of MEMS products is a typically slow process because iterative structural analysis, layout and testing are necessary to achieve complete structures.** To test this general hypothesis and to develop a model (which could be realized using computer based algorithms) for the MEMS product development, the following objectives were proposed and accomplished:

Objective 1: *To analyze the MEMS product development process thoroughly by considering a MEMS product as a system in-toto, to identify subsystems as well as sub-subsystems up to component level as well as interactions among them which influence the overall performance of a MEMS product.*

Objective 2: *To characterize a better component level of the MEMS product system, collect the attributes pertaining to each subsystem of the MEMS product and also develop a simpler method to manage and manipulate the attributes by using a computer algorithm.*

Objective 3: *To develop methodologies which can rank/compare/select the better MEMS product using the attributes under fuzzy or crisp situations, from component level to system level [i.e. bottom to top approach]. To develop computer algorithms which use the coded and stored attributes to select better MEMS product system.*

Objective 4: *To develop an improved MEMS product development method which can reduce the product development time by reducing the number of iterations involved in traditional MEMS product development and to evolve a method to reduce the number of iterations involved in the time consuming EDA tool simulation.*

Objective 5: *To develop a concurrent product development methodology for MEMS product design which can evaluate the product at the conceptual stage itself by considering inputs from all the stages of product development in an integrated manner.*

A literature review was then conducted to confirm the statement in objective 1. In the work described in Chapter-3, MEMS is considered as a system *in toto* and its subsystems as well as sub-subsystems up to component level were identified. A hierarchical tree structure of the MEMS product system was developed. Using graph and matrix approach, an integrated systems model for the complete structure of the MEMS product system in terms of its constituents and interactions between constituents was developed.

In Chapter-4 the details of an in-depth literature study which was conducted to identify the pertinent attributes which belong to each MEMS product subsystem have been elaborated. A *n* digit alpha numeric coding scheme was developed to handle the large number of attributes which allow the designer to store, retrieve and compare the attributes using a computer. A conceptual model was developed which emphasized on the methods of collecting and handling the fuzzy and crisp attributes. Attributes-based evaluation methods MADM and Fuzzy MADM were enlisted for ranking and evaluation purposes. Graphical methods like Line graph and Spider diagram were used for verifying the results.

The work described in chapter-5 involved the development of a MEMS design and development flow and highlights its advantages as compared with the traditional MEMS product development method using time charts.

The study leading to the identification of different aspects of MEMS product development called X-abilities is discussed in chapter-6. Concurrent methodologies using MADM and Graph & matrix approaches were developed. Time charts were used to compare the advantages of the concurrent methodologies.

All the objectives were verified using illustrative examples. The structural model was verified using motion sensors as an example. MADM and Fuzzy MADM ranking methodologies were illustrated using the micromirror for optical scanning applications. An RF MEMS power sensor was developed; it was simulated for various design aspect conditions. The RF MEMS power sensor was used as an example to illustrate the methodologies developed in Chapter-5 and Chapter-6.

7.2 Principal Conclusions of the Thesis

- The MEMS product development process is of a highly uncertain nature owing to its premature, non-standard, and expensive micro-fabrication processes. The time involved in MEMS product development is very high because it is an interdisciplinary field requiring experts from all branches of engineering, science, economics, etc. Structural modeling involves a thorough understanding of the MEMS product using systems approach. At the beginning of the MEMS product development, the structure of the MEMS product can be defined to understand the product completely in all respects of engineering, science, cost, quality etc. Structural models can be used to analyze the failure of the existing products or to improve the quality of existing products.
- A coding scheme would be helpful in characterizing a MEMS product in terms of its attributes. Each MEMS product has a code, which is unique in nature. The ranking methodologies are useful to select a better product from the available set of products or to predict the better product using the information available from designers and manufacturers.
- Existing computer aided methods and tools are insufficient to support MEMS product development because these methods and tools require trial and several iterations to achieve the satisfactory product. Besides, a single iteration often takes several hours-days. The MEMS product can be evaluated using a simple algorithm developed at the conceptual stage and, subsequently, the traditional flow could be helpful.
- There is a great demand for a concurrent product development model in the MEMS industry. The concurrent models developed herein would be helpful in achieving the goals of the industry (quality, development time, cost etc.) in a limited time.

7.3 Contributions of the Thesis

The main contributions of this thesis are described below:

Characterization of the MEMS Product Using Systems Approach:

MEMS is a miniaturized complex system. Currently the designers and manufacturers of MEMS Products need to understand, model and control these physically minute, super-massive arrays of miniaturised electronic and mechanical devices. In order to understand the MEMS product in detail, a structural model and the structural identification of the MEMS product would be sufficient.

Development of a Methodology for Coding, Evaluation and Ranking:

Understanding of MEMS product system is a knowledge base which has attributes as the bottom level components. The attributes coding scheme is useful in handling these attributes and characterizing the MEMS product. Since attributes are responsible for the characteristics of the MEMS product, attributes-based selection methods can effectively be used to characterize the MEMS products. Further, these methodologies can be handled by computers, and hence, the knowledge base of a designer and manufacturer can be managed effectively using computers.

Advancement of the MEMS Product Development Process:

A new MEMS product design and development methodology which employed an attributes-based evaluation method to reduce the product development time was evolved. This is a serial development method. It yielded a road map that helped to arrive at the concurrent models. Two Concurrent MEMS product development models were proposed. The results of both the models were compared and they were found to be identical. Between the two proposed models, the graph and matrix based approach was found to be more effective because it could effectively handle the interactions between the systems from the bottom level to the top level (i.e. from the attribute level to the system level).

Development of RF MEMS Power Sensor:

RF MEMS power sensor is an interesting MEMS product from the RF application domain. In this study a capacitive, cantilever based RF MEMS power sensor with VSWR of 1.08002 was designed. This was simulated using various design parameters,

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7.4 Limitations and Future Work

This thesis study has a few limitations that warrant further research.

Firstly, the work needs to be extended to verify the proposed methodologies with fabricated product results. A number of fabrications need to be carried out to test various micro-machined element designs, materials, environment variations and packagings. Further the early phase of conceptual design should be expanded to accommodate other possible design aspects like cost, reliability, life-cycle, testability, etc.

Secondly, the idea of tapping an expert's knowledge base using technology needs to be further explored; specifically the relationship or interaction of the attributes or subsystems with the existing knowledge base tools needs to be clearly understood. A weighted aggregation method needs to be evolved to enhance the effectiveness of the selection process. However, a serious drawback of such a process is that a clear-cut method to aggregate the set of mono-criterion preferences to the global preference considering commensurability (measurability by the same standard or scale of values) and normalization is currently unavailable. In other words, the most important and difficult issue in MADM/Fuzzy MADM and GDM is the allocation of the scaling constants or weights fixing the relative power of each criterion and each decision-maker in the group.

It is generally assumed that these weights are allocated directly by a facilitator or supra decision-maker, determined informally upon consensus or agreement between decision-makers allowing interpersonal comparisons. However, the issue of how to systematically determine the weights should be studied carefully taking into consideration the characteristics of engineering design. Suggestions for achieving this are as follows:

- The grounds (e.g. certain quantitative values and their scales supported by engineering analyses and past design knowledge) on which the design participants represent their preferences should be clearly established.

- Experimental results of similar cases, past experience of a company, or other exclusive engineering know-how could be used as the primary basis for the design participants to determine logically consistent weight values using a transformation procedure. The allocation of weights upon agreement or consensus through negotiation or in an informal way appears to be difficult. To ensure that the weights are acceptable to all design participants, they should be established through transparent procedures based on tangible criteria that reflect the relevance of each design participant to the design concept selection problem.
- The work needs to be extended to tap the expert opinion data available, for development of a family of MEMS products. The basic operation of all members of a family of devices may be assumed to be essentially the same in principle. For example the RF power sensor and the RF MEMS switch have almost same principle of operation and performance characteristics. The expert opinion of the MEMS product can be reused for the other with minor changes.
- Contributions from a various companies could lead to the development of a MEMS product knowledge base which would serve as a source of relevant attributes and enable the designer to ascertain the interactions and interrelations between attributes. A web based prototype knowledge base advisory system for MEMS product design and development could be developed based on the client-knowledge server architecture and framework, to help the designer to find good design concepts, process variables, materials, packaging options, etc. This knowledge base can be updated online by experts, designers, researchers, students and manufactures for their specific product/process/material/package. This knowledge base will be one of the resources for estimation of aggregate weight and interaction levels.
- A large amount of the future work should be dedicated to the enhancement of design, process, material, package databases and knowledge base and the further development of the MEMS product system.

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APPENDIX A

MATLAB CODING FOR TOPSIS IMPLEMENTATION

The following MATLAB code was developed using the flowchart shown in Figure 5.10. This algorithm is capable of considering $n \times n$ matrix for the optimum selection of candidate and would also be useful to perform sensitivity analysis. The D and A matrices were inputted from a Microsoft excel file with the file name ‘topsis.xls’.

```
clc
clear all
format long
%Asking user to input the decision Matrix
fprintf('Enter the size of Database Matrix D \n')
drows=input('Number of rows of D = ');
dcolumns=input('Number of columns of D = ');
fprintf('Enter values of Database Matrix D \n')
d=xlsread('topsis',-1);

%---------------------------------------------------------------------
fprintf('--------------------------------------------------\n')
fprintf('Decision Matrix D is')
d
fprintf('-----------------------------------------------------\n')
%-----------------------------------------------------------

%Asking user to input the Relative Importance matrix A
size_of_a=dcolumns;
fprintf('Enter the values of Relative importance matrix A  \n')
a=xlsread('topsis',-1);
fprintf('Enter the values of Relative importance matrix A  \n')

%----------------------------------------------
fprintf('-----------------------------------------------------\n')
```

```
fprintf('Relative Importance Matrix A is')
a
fprintf('-------------------------------------------------------\n')
%----------------------------------------------------


[evec eval]=eig(a);       %calculating eigen vectors of Relative importance matrix
%disp(evec)
%disp(eval)
lamda_max=max(max(eval));           %calculating maximum value of eigen value
lamda_max
pp=lamda_max.*eye(size_of_a);
equation_matrix=minus(a,pp);
%'Therefore the equation matrix (A-(Lamda_max)I) is'
b=zeros(size_of_a,1);      % Solving the equation [A-(Lamda_max)I]W=0
x=null(equation_matrix);   %Gives orthogonal solution
xsum=sum(x);    %calculating weight matrix
w=x./xsum;
%------------------------------------------------------
fprintf('----------------------------------------\n')
fprintf('The weighted matrix W is')
w
fprintf('------------------------------------------------------------\n')
%------------------------------------------------------
%Calculating Normalized data Matrix r
dsquare=d.*d;
sumds=sum(dsquare);
for i=1:drows
   for j=1:dcolumns
      r(i,j)= d(i,j)/sqrt(sumds(1,j));
   end
end
%---------------------------------------------------------
fprintf('---------------------------------------------------\n')
fprintf('The Value of Normalized Data Matrix R is')
```

```
r
fprintf('----------------------------------------------------------------\n')
%----------------------------------------------------------------
%calculating Normalized decision matrix
wtranspose=w';
for i=1:dcolumns
   for j=1:drows
      p(j,i)= wtranspose(1,i).*r(j,i);
   end
end
%------------------------------------------------------------
fprintf('----------------------------------------------------------\n')
fprintf('The value of Normalized Decision Matrix P is\n')
p
fprintf('------------------------------------------------------------\n')
%---------------------------------------------------------------
pstar=max(p);
%---------------------------------------------------------------
fprintf('-------------------------------------------------\n')
fprintf('Positive ideal solution P* is')
pstar
fprintf('------------------------------------------------   -----\n')
%-----------------------------------------------------------------
pminus=min(p);
%----------------------------------------------------
fprintf('--------------------------------------------')
fprintf('Negative ideal solution P- is')
pminus
%--------------------------------------------------------------
fprintf('-------------------------------------------')

%Calculation of separation matrices
for i=1:drows
   for j=1:dcolumns
```

```
        smatrix(i,j)=p(i,j)-pstar(1,j);
    end
end
smatrixt=smatrix';
smatrixtsquare=smatrixt.*smatrixt;
sumsmatrixt=sum(smatrixtsquare);
for i=1:drows
      sstar(i,1)=sqrt(sumsmatrixt(1,i));
end
%-------------------------------
fprintf('------------------------------------------')
fprintf('Separation Matrix S* is')
sstar
%------------------------------------
fprintf('----------------------------------------')
for i=1:drows
    for j=1:dcolumns
        smatrix2(i,j)=p(i,j)-pminus(1,j);
    end
end
smatrixt2=smatrix2';
smatrixtsquare2=smatrixt2.*smatrixt2;
sumsmatrixt2=sum(smatrixtsquare2);
for i=1:drows
      sminus(i,1)=sqrt(sumsmatrixt2(1,i));
end
%---------------------------------------------
fprintf('---------------------------------------------')
fprintf('Separation Matrix S- is')
sminus
%-------------------------------------------------
fprintf('-------------------------------------------------')
for i=1:drows
    cstar(i,1)=sminus(i,1)/(sstar(i,1)+sminus(i,1));
```

```
end
%-----------------------------------------------------------------------
fprintf('------------------------------------------------------------')
fprintf('Relative closeness to actual matrix C values are (Given in a single column) is')
cstar
fprintf('------------------------------------------------------------------')
%-------------------------------------------------------------------
```

APPENDIX B

MATLAB CODING FOR PERMANENT INDEX CALCULATION

The following MATLAB code was used to illustrate the proposed methodologies in Chapter 6. This code is capable of considering 6×6 matrix for calculating permanent index.

```
function [ perma ] = perm( a )
%DET1 Summary of this function goes here
%   Detailed explanation goes here
fprintf('Enter the size of Matrix A for which PERM is to be calculated \n')
arows=input('Number of rows of A = ');
acolumns=input('Number of columns of A = ');
fprintf('Enter values of Matrix A \n')
a=zeros(arows,acolumns);

for i=1:arows
      for j=1:acolumns
         fprintf('Enter the values of A matrix ------- ROW : %d COLUMN : %d',i,j)
         a(i,j)= (input('  = '));
      end
end
%--------------------------------------------------------------------------
fprintf('---------------------------------------------------\n')
fprintf('The perm of Matrix A is')
s = size(a);

if( s(1) ~= s(2))
   error('the entered matrix is not square');

elseif (s(1) >= 7)
      error('computation limit.. maximum matrix size 6 by 6)
```

```
else

      switch (s(1))
         case(1)
            perma = a;
         case(2)
            perma = ( a(1,1) * a(2,2) + a(1,2) * a(2,1) );
         case(3)
            perma = Three (a);
         case(4)
            perma = Four (a);
         case(5)
            perma = Five (a);
         case(6)
            perma = Six (a);
         otherwise
            perma = 0;
      end
end

function [ f ] = Four( a )
%the function computes the permanent function of a 4 by 4 matrix

s1 = [ a(2,2) a(2,3) a(2,4)
      a(3,2) a(3,3) a(3,4)
      a(4,2) a(4,3) a(4,4)];

s2 = [a(1,2) a(1,3) a(1,4)
     a(3,2) a(3,3) a(3,4)
     a(4,2) a(4,3) a(4,4)];

s3 = [a(1,2) a(1,3) a(1,4)
     a(2,2) a(2,3) a(2,4)
     a(4,2) a(4,3) a(4,4)];
```

```
s4 = [a(1,2) a(1,3) a(1,4)
    a(2,2) a(2,3) a(2,4)
    a(3,2) a(3,3) a(3,4)];


f = a(1,1)* Three(s1) + a(2,1)* Three(s2) + a(3,1)* Three(s3) + a(4,1)* Three(s4);

function [ f ] = Three( a )
%This function calculates the permanent function of a 3 by 3
%matrix by direct expansion.

f = a(1,1)* (a(2,2)*a(3,3)+ a(2,3)*a(3,2)) + ...
   a(1,2)* (a(2,1)*a(3,3)+ a(3,1)*a(2,3)) + ...
   a(1,3)* (a(2,1)*a(3,2)+ a(2,2)*a(3,1));

function [ f ] = Five( a )
%the function computes the permanent function of a 5 by 5 matrix
s1 = [a(2,2) a(2,3) a(2,4) a(2,5)
    a(3,2) a(3,3) a(3,4) a(3,5)
    a(4,2) a(4,3) a(4,4) a(4,5)
    a(5,2) a(5,3) a(5,4) a(5,5)];

s2 = [a(1,2) a(1,3) a(1,4) a(1,5)
    a(3,2) a(3,3) a(3,4) a(3,5)
    a(4,2) a(4,3) a(4,4) a(4,5)
    a(5,2) a(5,3) a(5,4) a(5,5)];

s3 = [a(1,2) a(1,3) a(1,4) a(1,5)
    a(2,2) a(2,3) a(2,4) a(2,5)
    a(4,2) a(4,3) a(4,4) a(4,5)
    a(5,2) a(5,3) a(5,4) a(5,5)];

s4 = [a(1,2) a(1,3) a(1,4) a(1,5)
```

```
     a(2,2) a(2,3) a(2,4) a(2,5)
     a(3,2) a(3,3) a(3,4) a(3,5)
     a(5,2) a(5,3) a(5,4) a(5,5)];

s5 = [a(1,2) a(1,3) a(1,4) a(1,5)
     a(2,2) a(2,3) a(2,4) a(2,5)
     a(3,2) a(3,3) a(3,4) a(3,5)
     a(4,2) a(4,3) a(4,4) a(4,5)];

f = a(1,1)* Four(s1) + a(2,1)* Four(s2) + a(3,1)* Four(s3) + a(4,1)* Four(s4) +
a(5,1)* Four(s5) ;

function [f] = Six(a)

%the function computes the permanent function of a 6 by 6 matrix
s1 = [a(2,2) a(2,3) a(2,4) a(2,5) a(2,6)
     a(3,2) a(3,3) a(3,4) a(3,5) a(3,6)
     a(4,2) a(4,3) a(4,4) a(4,5) a(4,6)
     a(5,2) a(5,3) a(5,4) a(5,5) a(5,6)
     a(6,2) a(6,3) a(6,4) a(6,5) a(6,6)];

s2 = [a(1,2) a(1,3) a(1,4) a(1,5) a(1,6)
     a(3,2) a(3,3) a(3,4) a(3,5) a(3,6)
     a(4,2) a(4,3) a(4,4) a(4,5) a(4,6)
     a(5,2) a(5,3) a(5,4) a(5,5) a(5,6)
     a(6,2) a(6,3) a(6,4) a(6,5) a(6,6)];

s3 = [a(1,2) a(1,3) a(1,4) a(1,5) a(1,6)
     a(2,2) a(2,3) a(2,4) a(2,5) a(2,6)
     a(4,2) a(4,3) a(4,4) a(4,5) a(4,6)
     a(5,2) a(5,3) a(5,4) a(5,5) a(5,6)
     a(6,2) a(6,3) a(6,4) a(6,5) a(6,6)];
```

```
s4 = [a(1,2) a(1,3) a(1,4) a(1,5) a(1,6)
    a(2,2) a(2,3) a(2,4) a(2,5) a(2,6)
    a(3,2) a(3,3) a(3,4) a(3,5) a(3,6)
    a(5,2) a(5,3) a(5,4) a(5,5) a(5,6)
    a(6,2) a(6,3) a(6,4) a(6,5) a(6,6)];

s5 = [a(1,2) a(1,3) a(1,4) a(1,5) a(1,6)
    a(2,2) a(2,3) a(2,4) a(2,5) a(2,6)
    a(3,2) a(3,3) a(3,4) a(3,5) a(3,6)
    a(4,2) a(4,3) a(4,4) a(4,5) a(4,6)
    a(6,2) a(6,3) a(6,4) a(6,5) a(6,6)];

s6 = [a(1,2) a(1,3) a(1,4) a(1,5) a(1,6)
    a(2,2) a(2,3) a(2,4) a(2,5) a(2,6)
    a(3,2) a(3,3) a(3,4) a(3,5) a(3,6)
    a(4,2) a(4,3) a(4,4) a(4,5) a(4,6)
    a(5,2) a(5,3) a(5,4) a(5,5) a(5,6)];

f = a(1,1)* Five(s1) + a(2,1)* Five(s2) + a(3,1)* Five(s3) + a(4,1)* Five(s4) + a(5,1)*
Five(s5) + a(6,1)* Five(s6) ;
```

LIST OF PUBLICATIONS

1. Prince, A.A. and Agrawal, V.P. (2009) 'Structural modelling and integrative analysis of microelectromechanical systems product using graph theoretic approach', *Journal of Microsystem Technologies*, vol. 15 (7), pp. 1083-1096.

2. Prince, A.A. and Agrawal, V.P. (2009) 'Coding, evaluation, comparison, ranking and optimum selection of Micro-Electro-Mechanical System (MEMS) products', *International Journal of Mechatronics and Manufacturing Systems*, vol. 2 (1/2), pp.97–119.

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5. Prince, A.A., Jose, I. and Agrawal, V.P. (2010) 'A new microelectromechanical systems (MEMS) product optimal design and analysis using MADM', *IEEE/ASME Journal of Microelectromechanical Systems. (Under review)*.

6. Prince, A.A., Jose, I. and Agrawal, V.P. (2010) 'Concurrent design of microelectromechanical systems products for x-abilities using MADM approach', *Journal of Micro/Nano Mechatronics. (Under review)*.

7. Prince, A.A., Jose, I. and Agrawal, V.P. (2010) 'Concurrent design, modeling and analysis of microelectromechanical systems products - Design for 'X' abilities', *Journal of Microsystem Technologies. (Under review)*.

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