University of Alberta

An Integrated Framework to Reduce Time to Market for MEMS/NEMS Developments

by

Benjamin Tetsuhei Nakashima-Paniagua

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"Any fool can know. The point is to understand."

— Albert Einstein (1879-1955)

For my parents, Paty & Min.
Thank you for all your endless love and the education that you have given me; I could not have had better role models than you two in my life.

For my four reasons to exist
My wife Olga and my children, Tetsuhei, Keimi and Kenzi.
I love you with all my heart

ABSTRACT

Innovative products based on micro and nanotechnologies (MNT) have made rapid improvements in terms of functionality, cost and performance. Several developments based on these technologies have already benefited society greatly. However, many applications and devices based on these systems are still in the research phase, struggling to reach the commercial stage. The ultimate goal of our research work is to develop a new methodology that reduces the time to market for MNT based products.

The first research methodology used as part of our work is based on prescriptive research to investigate the current state of affairs of the *micro and nano electro-mechanical-systems* (MEMS/NEMS) industry to identify, synthesize, and tie together different perspectives regarding MEMS/NEMS development. By doing this, it was possible to identify the main bottlenecks in the process and define a more specific objective: To develop a new methodology that allows MEMS/NEMS designers to expedite the design and fabrication stages for devices based on those technologies.

The second research methodology used is based on descriptive research to propose an algorithmic methodology to assist some of the main problems for the MEMS/NEMS industry. A modular knowledge based system was conceived, where different managerial and technical tools are used. We developed a standardized language to define manufacturing steps required to fabricate and prototype MEMS devices based on an international standard: ISO 18629. We also developed a hierarchical structure based on object-oriented principles to define new taxonomic levels of abstraction for MEMS processes, providing a generic, but at the same time, comprehensive, and flexible structure. Another important part of our research work was the development of

mathematical models to evaluate potential alternatives for MEMS manufacturing process. Many of the manufacturing processes for MEMS are new variants of semiconductor processes or totally new processes. Because of this, there is very little statistical information which can be used to evaluate alternatives. We developed mathematical models using fuzzy inference systems to evaluate potential alternatives in an efficient way, effectively reducing the MEMS/NEMS development time and impacting positively the time to market for these developments.

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TABLE OF CONTENTS

List of Tables

LIST OF FIGURES

LIST OF ABBREVIATIONS

μm	*Micrometre*
ACAMP	*Alberta Centre for Advance MNT Products*
CLIF	*Common Logic Interchange Format*
DLP	*Digital light processor*
EBNF	*Extended Backus-Naur Form*
IC	*Integrated circuit*
ISO	*International Organization for Standardization*
KBM	*Knowledge-based management*
MAPS	*MNT Automated Process Selection*
MEMS	*Micro-electro-mechanical-systems*
MNT	*Micro and nanotechnologies*
MOS	*Metal-oxide-semiconductor*
NEMS	*Nano-electro-mechanical-systems*
NINT	*National Institute for Nanotechnology*
NIST	*National Institute of Standards and Technology*
nm	*Nanometre*
PSL	*Process Specification Language*
R&D	*Research and development*
RDF	*Resource Description Framework*
RGT	*Resonant gate transistor*
TTM	*Time-to-market*
XML	*eXtensive-Markup-Language*

CHAPTER 1.
INTRODUCTION

This thesis presents an analysis of the need for efficient managerial tools in order to address various challenges and opportunities for the *micro and nano-electro-mechanical-systems* (MEMS/NEMS) industry, and to expedite the development cycle and shorten the total time from idea-to-market for devices based on these technologies. Innovative products based on MEMS/NEMS have made rapid improvements in terms of functionality, cost and performance. However, many applications and devices based on these systems are still in the research phase, struggling to reach a commercial stage. A methodology to provide support to the MEMS/NEMS practitioners (i.e., researchers, designers, and entrepreneurs) is proposed and described. This methodology offers guidance during the early stages of MEMS/NEMS product development, provides means to manage research and development, and acts as a *virtual broker* in order to coordinate collaboration among various organizations. All of these means help to optimize the use of existing fabrication infrastructure and to assist with the decision making process while selecting potential alternatives for MEMS/NEMS manufacturing.

1.1. Objectives of this Thesis

As the title of the thesis suggests, the ultimate objective of this thesis, expressed in one sentence, would be: *To develop a new methodology that allows a reduced time-to-market* (TTM) *for micro and nanotechnologies* (MNT) *based products*. It is possible to break down this main objective into more specific objectives. These are:

1. To provide a formal analysis of the various obstacles that the MEMS designers are facing while trying to take their designs from an idea to a commercial stage,

2. To shed some light on the multiple opportunities to develop management tools (e.g., product development management, knowledge management, R&D management) for the MEMS/NEMS industry, and
3. To offer an initial practical solution to mitigate some of the identified challenges to improve the overall time-to-market for MEMS/NEMS.

In order to provide a relevant scientific contribution, we have designed a methodology, to ultimately be expressed as a software tool, which will be implemented as a knowledge-based system to help researchers, development groups, and lead users in academia as well as in industry. By utilizing this system, we aim to improve the time to market for MEMS/NEMS development by leveraging management methods and techniques that have been proven successful in other domains (e.g., [1]–[9]). In these domains, users can produce important innovations within the technological domains of manufacturers' expertise and manufactures can perceive innovations as more commercially attractive.

1.2. Scope of this Research

This research work is focused on assisting MEMS practitioners that already have a defined process flow to accelerate the prototyping and fabrication of micro/nano components and devices. The work in this thesis is *not* aimed to validate the quality of designs (i.e., will the structure of a device do what the designer wants it to do? Are those the optimal physical features for the application intended for the device?).

As it will be explained in more detail in the remaining chapters of this thesis, there are many ways to build micro and nanodevices. This work is concerned with the fabrication techniques for MEMS/NEMS that evolved from the semiconductor industry, which are known as *Top-Down* manufacturing. Other popular fabrication techniques that are outside the scope of this work are the *Bottom-Up* techniques (e.g., molecular self-assembly).

1.3. Thesis Structure

In order to design our novel philosophy to improve the overall time to market for MEMS, we utilized the "funnel approach" (i.e., decomposing the main problem into smaller and more specific entities as the research advances) [10], [11]. In the next paragraphs we briefly describe the content of each chapter.

CHAPTER 2 presents the basic mathematical definitions and concepts used by the algorithms and methods described in this work. In CHAPTER 3, we provide an overview of the micro and nanosystems with special interest on their manufacturing processes, as these are the focal points where our proposed methods are applied. A detailed analysis of the various challenges and opportunities for the MEMS industry is presented in CHAPTER 4.

In CHAPTER 5, we address the main problems identified in CHAPTER 4 by proposing a virtual broker methodology that improves various aspects of the commercialization process for MEMS/NEMS products. It is possible to achieve this improvement by managing knowledge generation and providing an efficient utilization of existing fabrication infrastructure. In order to properly design this methodology, we perform an extensive literature review of the evolution and progression of MEMS technology to understand the current state of the MEMS industry. We examine the industry as a whole, we review specific references on how MEMS/NEMS technology has been managed, and we analyse the main hurdles and opportunities in the commercialization path for products based on these technologies using several perspectives. During this analysis, we identify critical features required for a new MEMS product to become a successful commercial product. Finally, we present a system that uses a virtual broker methodology to manage knowledge and optimize the use of existing fabrication infrastructure to improve the MEMS/ NEMS development cycle.

While working on CHAPTER 5, which addresses the need of proper knowledge management for MEMS/NEMS development, we identified another more specific problem. One of the most critical challenges for MEMS/NEMS development is the lack of standardized terminology for process specification. CHAPTER 6 provides a foundation for formally describing the set of activities related to managing the manufacturing processes used by the MEMS community. First, we develop new taxonomic levels of abstraction for MEMS processes. We then use logic foundations provided in international standard ISO-18621-1 to develop a methodology that allows designers and product developers to remove ambiguities and misconceptions when interchanging information about MEMS manufacturing processes. We present a case study where we apply our methodology to generate eXtensive-Markup-Language (XML) code to capture the processes' structure and critical information.

Once a standardized formalism to represent process steps to form a process flows for MEMS/NEMS manufacturing is proposed, additional work is required to further improve the TTM for products based on these technologies. In CHAPTER 7 we present the development of a system to evaluate alternatives for manufacturing process steps for MEMS/NEMS. We explain in detail a formal process flow definition for MEMS fabrication. Then, we develop a fuzzy inference system which allows MEMS developers to capture users' preferences to rank the alternatives available to complete the process steps required to fabricate a device. It is important to note here that when we mention "users' preferences" we are referring to individual users as well as groups of stakeholders in charge of the development of a project, who provide the directives and dictate the priorities to be considered in the design of MEMS/NEMS systems. In the last part of this chapter, we evaluate alternatives for MEMS processes in two case studies: Case study #1 –impurity doping and case study #2 –lead zirconate titanate (PZT) patterning. Using an assortment of user preferences data to rate a variety of criteria for potential alternatives, our approach produces a clear preference for one specific alternative in each case. This exemplifies the usefulness of the system proposed and illustrates how effective this methodology is towards improving the fabrication process for MEMS.

Finally, we close with CHAPTER 8 presenting a summary of the work performed for this thesis, highlighting the main contributions of the research work performed and potential research lines of future work.

1.4. Research Methodology for this Work

1.4.1. Descriptive Research

When developing any new methodology or system, the requirement analysis phase is the most critical step in the development life cycle. To effectively design a useful system we needed to capture the real needs and critical points to improve upon. In order to identify, synthesize, and tie together different perspectives regarding MEMS/NEMS development, we used descriptive research to investigate the current state of affairs of the MEMS industry.

Descriptive research involves collecting data that describes events and then organizes, tabulates, depicts and describes the data [12]. This type of research can provide assistance to describe a phenomenon or specific characteristics of a population. It addresses the question of what are the characteristics of the population being examined [13]. By using this descriptive research a substantive or declarative knowledge is generated [14].

For this thesis, we generated declarative knowledge by interacting directly with MEMS/NEMS practitioners from various institutions. We used observational, interviews and informal surveys techniques to gather data and define specific behaviours.

We observed, interacted and learn from various universities, government organizations, research centres and MEMS foundries (e.g., the University of Alberta, University of Calgary, nanoAlberta, Alberta Innovates Technology Futures, the National Institute for Nanotechnology (NINT), the Alberta Centre for Advance MNT Products, Micralyne, Norcada). Within the industry and government organizations, we worked closely with entrepreneurs (some of them have created multiple successful MEMS companies) CEOs, CTOs, VPs of Business Development, VPs of Engineering and directors of research. In the academia, we interacted directly with more than twenty seven MEMS/NEMS developers and researchers from different institutes and different faculties and departments (e.g., Mechanical Engineering, Electrical Engineering, Chemical and Materials Engineering, Biomedical Engineering, Biological Sciences, Medicine). We examined and track the development of more than eighteen different projects. Unfortunately, specifics of these projects cannot be divulged as non-disclosure and confidentiality agreements were signed while working with some of these organizations. However, by doing this, it was possible to properly identify the current state and practices within the MEMS/NEMS industry directly from experts in the various areas of the development and commercialization processes. We were able to define the main obstacles that need to be improved in the process of commercializing MNT-based products, as well as detailed behaviour and specific traits of this process. For instance, we observed a specific correlation between how common a fabrication process is with the initial yield of that specific process; this relation is not linear. We were able to express the general behaviour of this relation by defining the Commonness Process Index (Figure 7-5). Another example of the work we did of distilling behaviour using descriptive research is shown in Figure 7-10, where the relation between the complexity of the process and the probability of success is mapped into four distinct regions. This graph was created as a result of aggregating comments from researchers with vast experience in microfabrication (e.g., 35 years, 18 years, 15 years).

1.4.2. Prescriptive Research

Research with prescriptive purpose is designed to develop and test methods for aiding people in conforming with desired normative principles [15]. We used the prescriptive research approach to propose an algorithmic methodology to assist some of the main problems that were previously identified for the MEMS/NEMS industry. A knowledge-based system was designed, which integrates various managerial and technical tools. We developed a standardized and formal language to define manufacturing steps required to manufacture MEMS/NEMS devices. We based this development on an international standard: ISO 18629 [16]–[19]. We developed a new taxonomic classification for MEMS manufacturing processes that presents a hierarchical structure based on object-oriented principles to provide generic, comprehensive, flexible structure, and to which new processes can be easily added in an organized fashion. By using prescriptive research, we also developed mathematical models to evaluate alternatives for MEMS/NEMS manufacturing process in an efficient way.

CHAPTER 2.
MATHEMATICAL CONCEPTS AND DEFINITIONS

The work in this thesis is supported by the use of various mathematical concepts and definitions from a few areas of study. In this chapter, we provide a concise overview of these concepts and definitions to ensure that the reader has the proper context and a suitable understanding of the mathematical constructions and formulae used in the research work on which this thesis was built upon.

2.1. Logic

2.1.1. Propositional Calculus

A *proposition* is the mental reflection of a fact, expressed as a sentence in a natural or artificial language [20]. Every proposition is considered to be either true (denoted by "T" or 1) or false (denoted by "F" or 0). The true and false values are referred as *truth values* of the proposition. Propositional logic is concern with identifying the truth of the *composition of propositions*, by investigating the truth value of the components and the operations applied. For instance, in propositional calculus, the propositions A and B are considered variables (i.e., *propositional variables*). A list of the propositional operations, their symbolic representation and their truth tables are shown in Table 2-1. It is possible to form *formulas* (i.e., compound expressions) using the operations in Table 2-1. These formulas are defined in an inductive way:

1. Propositional variables and the constants T, F are formulas
2. If A and B are formulas, then (A), $(A \wedge B)$, $(A \vee B)$, $(A \Rightarrow B)$, $(A \Leftrightarrow B)$ are also formulas

If two propositional formulas determine the same truth function, these are considered *logically equivalent* or *semantically equivalent*, i.e., $A = B$. This means that it is possible to check the logical equivalence of propositional formulas in terms of truth tables.

There are various *elementary laws of propositional calculus*. A list of these laws is presented in Table 2-2.

Table 2-1: Propositional Operations

Operation	Symbolic Representation	Truth Table
Negation: "NOT *A*"	$\neg A$ (Alternative notation: $\bar{A}$)	$\begin{array}{c\|c} A & A \\ \hline F & T \\ T & F \end{array}$
Conjunction "*A* AND *B*"	$A \wedge B$ (Alternative notation: AB)	$\begin{array}{c\|c\|c} A & B & A \wedge B \\ \hline F & F & F \\ F & T & F \\ T & F & F \\ T & T & T \end{array}$
Disjunction "*A* OR *B*"	$A \vee B$	$\begin{array}{c\|c\|c} A & B & A \vee B \\ \hline F & F & F \\ F & T & T \\ T & F & T \\ T & T & T \end{array}$
Implication "IF *A*, THEN *B*"	$A \Rightarrow B$	$\begin{array}{c\|c\|c} A & B & A \Rightarrow B \\ \hline F & F & T \\ F & T & T \\ T & F & F \\ T & T & T \end{array}$
Equivalence "*A* IF AND ONLY IF *B*"	$A \Leftrightarrow B$	$\begin{array}{c\|c\|c} A & B & A \Leftrightarrow B \\ \hline F & F & T \\ F & T & F \\ T & F & F \\ T & T & T \end{array}$

Table 2-2: Elementary Laws in Propositional Calculus

Name	Expressions
Associative Laws	$(A \wedge B) \wedge C = A \wedge (B \wedge C)$, $(A \vee B) \vee C = A \vee (B \vee C)$.
Commutative Laws	$A \wedge B = B \wedge A$, $A \vee B = B \vee A$.
Distributive Laws	$(A \vee B) \vee C = AC \vee BC$, $AB \vee C = (A \vee C)\ (B \vee C)$.
Absorption Laws	$A\ (A \vee B) = A$, $A \vee AB = A$.
Idempotence Laws	$AA = A$, $A \vee A = A$.
Excluded Middle	$A\,\overline{A} = \mathrm{F}$, $A \vee \overline{A} = \mathrm{T}$.
De Morgan Rules	$\overline{AB} = \overline{A} \vee \overline{B}$, $\overline{A \vee B} = \overline{A}\,\overline{B}$.
Laws for T and F	$A\mathrm{T} = A$, $A \vee \mathrm{F} = A$, $A\mathrm{F} = \mathrm{F}$, $A \vee \mathrm{T} = \mathrm{T}$, $\overline{\mathrm{T}} = \mathrm{F}$, $\overline{\mathrm{F}} = \mathrm{T}$.
Double Negation	$\overline{\overline{A}} = A$.

2.2. First-Order Logic

First-order logic (also known as *first-order predicate calculus* or *predicate logic*) provides a stronger expressive power than the one in the propositional calculus. This expressive power is used to describe the properties of most of the objects in mathematics and their relations between these objects. In propositional logic, each possible atomic fact requires a separate and unique propositional symbol. The predicate logic includes a richer ontology, which allows more flexible representation of the knowledge. An important element of the predicate logic (and the source of its name) is the use of predicates, which are the properties and relations of object of interest. We include the objects of interest in a group or set, i.e., *domain X of individuums (or universe)*. As an example, a domain could be defined as the set of the natural numbers (ℕ); an example of a property of individuums could be "n is a prime" (one-place predicate, also referred as unary predicate); an example of a relation between individuums could be "m is smaller than n" (two-places predicate, also referred as binary predicate). In general, an *n-place predicate* over the domain X of individuums is an assignment P: $X^n \rightarrow \{F,W\}$, assigns a truth value to every n-tuple of the individuums.

Another characteristic feature of predicate logic is the use of *quantifiers*. There are two quantifiers, the *universal quantifier* or *"for every" quantifier* represented by the symbol ∀, and the *existential quantifier* or *"for some" quantifier*, which is represented by the symbol ∃. The universal and existential quantifications are logically related to each other. Table 2-3 shows general identities for the quantifiers.

Table 2-3: General Identities for Quantifiers

General Identities
$\forall x \neg P \Leftrightarrow \neg\exists x\ P$
$\neg\forall x\ P \Leftrightarrow \exists x \neg P$
$\forall x\ P \Leftrightarrow \neg\exists x \neg P$
$\exists x\ P \Leftrightarrow \neg\forall x \neg P$
$\forall x\ (P(x) \wedge Q(x)) \Leftrightarrow \forall x\ P(x) \wedge \forall x\ Q(x)$
$\exists x\ (P(x) \vee Q(x)) \Leftrightarrow \exists x\ P(x) \wedge \exists x\ Q(x)$

The formulas in predicate calculus are defined in an inductive way:

1. If $x_1,\ldots, x_n$ are variables running over the domain of individuum variables and P is an n-place predicate symbol, then $P(x_1,\ldots, x_n)$ is a formula (*elementary formula*).

2. If A and B are formulas, then $(\neg A)$, $(A \wedge B)$, $(A \vee B)$, $(A \Rightarrow B)$, $(A \Leftrightarrow B)$, $(\forall x\ A)$ and $(\exists x\ A)$ are also formulas.

2.3. Classical Set Theory

It is possible to define a universe of discourse as a collection of objects (i.e., a *set*) sharing the same characteristics; they belong together for certain reasons [20]. The objects in this collection are called elements of the set. If we define this universe of discourse as X, the individual elements in the universe will be denoted as x.

Sets can be define by enumerating their elements or by defining a property possessed exactly by the elements of the set. For instance, a set S containing four different elements w, x, y and z, is denoted as: $S = \{w,x,y,z\}$. A set R of the odd natural numbers is defined and denoted by $R = \{x \mid x \text{ is an odd natural number}\}$. The symbol | means "such as". Hence the definition above reads as "R is a set of elements x such as x is an odd natural number".

In order to denote the membership of an element x, we can write "$x \in S$" to denote "x is an element of S" or "$x \notin S$" to denote "x is not an element of S". We can refer to all the elements in the set by using the universal qualifier $\forall$ ("for each"). $\forall x \in S$ reads as "for each element x having a membership in the set S". The existential qualifier, $\exists$, means "there is a". For example, the expression $\exists x \notin S$ reads as "there is an element x that is not an element of the set S".

Two sets A and B are considered to be *identical* if and only if they have exactly the same elements, i.e., $A = B \Leftrightarrow \forall x\ (x \in A \Leftrightarrow x \in B)$. If they do not have exactly the same elements they are not equal and are denoted by $A \neq B$.

If A and B are sets and $\forall x\ (x \in A \Rightarrow x \in B)$ holds, which means that all the elements in A also belong to B, A is considered to be a *subset* of B. This is denoted by $A \subseteq B$. If there are further elements in B such that they are not in A, A is a *proper subset* of B and this is denoted by $A \subset B$.

Another important set to define is the *empty set* (also known as *null set* or *void set*), which is a set with no elements. This is represented by the symbol $\emptyset$. Conversely, the *whole set*, is the containing all the elements in the universe.

2.3.1. Common Operations on Classical Sets

Let A and B be two sets on the universe X. The common operations are for these two sets are defined in Table 2-4.

Table 2-4: Common Operations on Classical Sets

Set-theoretic terms for classical operations	
Union	$A \cup B = \{x \mid x \in A \text{ or } x \in B\}$
Intersection	$A \cap B = \{x \mid x \in A \text{ and } x \in B\}$
Complement	$\overline{A} = \{x \mid x \notin A \text{ and } x \in X\}$
Difference	$A - B = \{x \mid x \in A \text{ and } x \notin B\}$

2.4. Fuzzy Logic

Fuzzy logic is a method to formalize the human capacity of imprecise reasoning, or approximate reasoning [21]. Fuzzy logic provides an inference structure that enables the human reasoning capabilities to be applied to artificial knowledge-based systems and mathematical strength to the emulation of certain perceptual and linguistic attributes associated with human cognition [22].

In fuzzy logic we use *fuzzy sets*, which are the basic mathematical tools of multi-valued logic [20]. As explained in the previous sections of this chapter, in propositional logic the classical notion of (crisp) set is two-valued. Let X be a the universe, then for every $A \subseteq X$ there exist a function f_A: $X \rightarrow \{0,1\}$, such that it says for every whether this element x belongs to the set A or not: $f_A(x) = 1 \Leftrightarrow x \in A$ and $f_A(x) = 0 \Leftrightarrow x \notin A$.

2.4.1. Membership Functions

In fuzzy sets we consider the membership of an element of the set as a statement, the truth value of which is defined by a value from the interval [0,1] instead of {0,1}. This is expressed as: μ_A: $X \rightarrow [0,1]$. To every element $x \in X$ we assign a number $\mu_A(x)$ from the interval [0,1]. The mapping of μ_A is known as *membership function*. The value obtained by evaluating the function $\mu_A(x)$ at the point x is called the *grade of membership*. In fuzzy sets it is possible to assign linguistic values to quantities (e.g., "acceptable", "excellent", "small", "big", etc.). By the membership function of the $\mu_A(x)$ of a linguistic variable, the membership degree of a crisp value can be in the fuzzy set represented by $\mu_A(x)$. The membership functions can be of many forms, the formulae to define them and the graphical representation of them are presented in the figures below.

$$\mu_{\mathrm{A}}(x) = \begin{cases} 0, & x \le a \\ \dfrac{x-a}{m-a}, & a < x \le m \\ \dfrac{b-x}{b-m}, & m < x < b \\ 0, & x \ge b \end{cases}$$

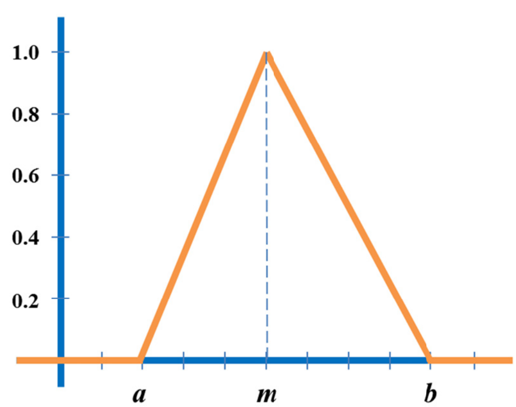


Figure 2-1: Triangular Membership Function

$$\mu_{\mathrm{A}}(x) = \begin{cases} 0, & (x < a) \ or \ (x > d) \\ \dfrac{x-a}{b-a}, & a \leq x \leq b \\ 1, & b \leq x \leq c \\ \dfrac{d-x}{d-c}, & c \leq x \leq d \end{cases}$$

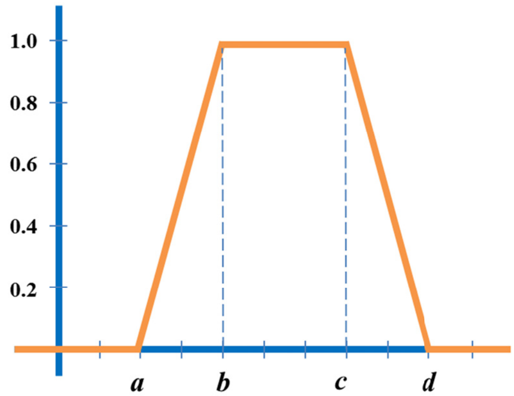


Figure 2-2: Trapezoidal Membership Function

R-Functions: $a = b = -\infty$

$$\mu_{\mathrm{A}}(x) = \begin{cases} 0, & x > d \\ \dfrac{d-x}{d-c}, & c \leq x \leq d \\ 1, & x < c \end{cases}$$

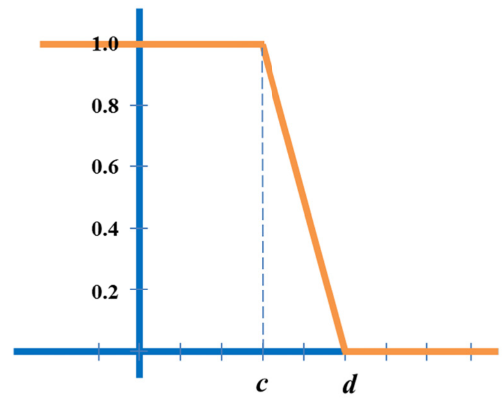


Figure 2-3: Trapezoidal R-Function

L-Functions: $c = d = +\infty$

$$\mu_{\mathrm{A}}(x) = \begin{cases} 0, & x < a \\ \dfrac{x-a}{b-a}, & a \leq x \leq b \\ 1, & x > b \end{cases}$$

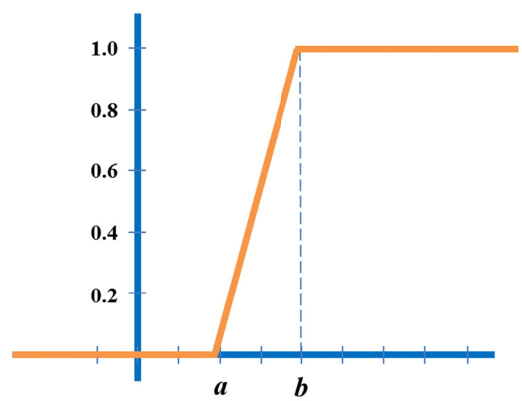


Figure 2-4: Trapezoidal L-Function

$$\mu_A(x) = e^{\frac{-(x-c)^2}{2\sigma^2}}$$

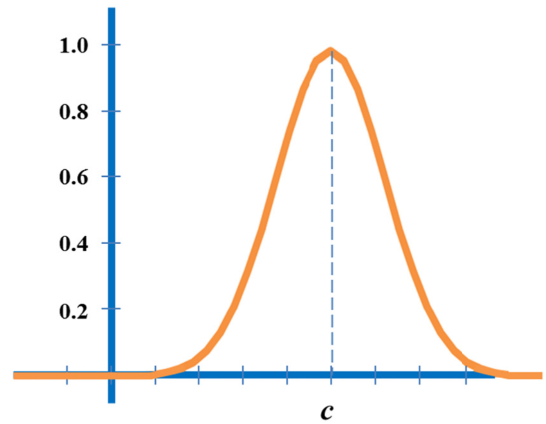


Figure 2-5: Gaussian Membership Function

2.4.2. Fuzzy Inference Systems

Fuzzy systems are knowledge-based or rule-based systems. The main constituent for this knowledge-based system is the so-called *fuzzy IF-THEN rules*. It is important to note here that despite the fact that the term *fuzzy* is defined in the English language as “difficult to perceive; imprecisely defined; confused or vague”, the word “fuzzy” in the term *fuzzy system* should be treated as a technical adjective. Even though the phenomena that the fuzzy systems theory characterizes may be fuzzy the theory itself is precise [22].

2.5. Summary of Definition and Symbols

Various definitions and symbols are used in this thesis and we have found that some of these definitions (and symbols to a lesser degree) may have different meanings depending on the context that they are used. We provide partial lists for these definitions and symbols as a quick reference for the reader.

Table 2-5: Partial List of Definitions

Definitions presented to remove possible semantic ambiguities.	
Axiom	"A well-formed formula in a formal language that provides constraints on the interpretation of symbols in the lexicon of a language" [23].
Lexicon	"A set of symbols and terms" [23].
Ontology	"A lexicon of specialized terminology along with some specification of the meaning of terms in the lexicon" [16]
Proposition	"It is the mental reflection of a fact, expressed as a sentence in a natural or artificial language" [20].
Tautology	In propositional calculus a formula is said to be tautology if the value of its truth function is identically the value T [20].
Universe of discourse	"The universe of all available information on a given problem" [21].

Table 2-6: Partial List of Symbols

Symbols	
$\neg$	*Not*
$\wedge$	*Logic AND*
$\vee$	*Logic OR*
$\Rightarrow$	*Implication*
$\Leftrightarrow$	*Equivalence*
$\cap$	*Intersection*
$\cup$	*Union*
$\prec$	*Precedes*
$\succ$	*Succeeds*
$\supset$	*Superset of*
$\subset$	*Subset of*
$\mid$	*Such as*
$\forall$	*For all*
$\exists$	*Exist*
$\in$	*Element of*
$\emptyset$	*Empty set*
$\mu_A(x)$	*Membership function*
$\tilde{x}$	*Fuzzy number*

CHAPTER 3.
MICRO AND NANOSYSTEMS

In this chapter we present an introduction and a general overview of miniaturized systems, including definitions and terminology used in this thesis which allows the reader to understand the basics concepts in the field of micro and nanotechnologies (MNT). After this, we provide details of the evolution of microsystems to illustrate where the technology is coming from. The following sections present the most widespread manufacturing practices to prototype and build systems based on these technologies.

3.1. Overview

The micro (μ) and nano (n) prefixes refer to a small fraction of the unit. It is possible to use these prefixes to refer to objects of miniscule size; for instance, one micrometre (μm) equals to 1×10^{-6} metres, and one nanometre equals to 1×10^{-9} metres. To put this into perspective of the macro world that we live in, the width of a human hair is about 100μm, and the diameter of a hydrogen atom is about 0.1nm.

During a presentation by Richard P. Feynman [24], he mentioned his vision about manipulating and controlling things at a small scale. This talk is consider by many as one of the first significant attempts to bring to the attention of the research community the importance and the great potential of developing technologies to allow us to develop tools to comprehend and operate things on a small scale.

Micro and nanotechnologies (MNT) are miniaturization technologies which are current leaders in the industrial revolution that is driving the new economy. MNT have the potential to generate a plethora of new systems and products by leveraging skills from across many domains [25]. While working with MNT many disciplines converge, (e.g., Chemistry, Electronics, Materials Engineering, Mechanical Engineering, Biology, etc.) and systems are created by understanding and controlling matter in the micro and nano realms. These systems can provide new solutions for ancient problems benefiting society in many different areas.

Over the last fifteen years, MNT have been gradually transferred from emergent to emerged technologies and, presently, it is possible to see several products based on these technologies being mass produced and available in the commercial world. Few examples of products with embedded microcomponents and microsystems that are part of our everyday life are: mobile telephones, tablets, video game controllers, laptop computers, digital cameras, automobile control systems, ink-jet printers, and a good number of medical diagnostic systems. However, many other products are still struggling to reach commercial success as many of the new developments depend on an advanced understanding of the fabrication processes and materials and, in many occasions, this understanding should be at molecular level.

3.2. MEMS/NEMS

MNT tend to be disruptive technologies that can provide new solutions for ancient problems. A subcategory of MNT is the *micro-electro-mechanical-systems* (MEMS), sometimes also referred to as *microsystems* or *micro-machined devices*. MEMS are defined as devices with dimensions on the order of micrometres that convert between electrical and some other form of energy. MEMS rely principally on their three-dimensional mechanical structure for their operation [26]. This same definition is extended to *nano-electro-mechanical-systems* (NEMS) when the physical features (e.g., dimensions of gaps or line width, step height, etc.) of a device are smaller than 100 nanometres [27].

A number of commercial applications of systems based on MEMS/NEMS technologies are already being mass produced. However, many major potential applications are still under development [25]. Despite the fact that more widespread dissemination of MEMS/NEMS devices could significantly improve quality of life, the emergence of commercial products based on these technologies has been relatively slow [28], [29]. These systems evolved from a very well-known industry: the semiconductor industry. However, there are substantial differences between the semiconductor industry and the MEMS industry. Eijkel et al. [30] mention that the lack of a true unit cell for MNT limits the learning curve experienced in the semiconductor industry. For instance, in the semiconductor industry the unit cell is the transistor. The main problem here is to find ways to reduce the size of it in order to increase the density of transistors per silicon die. In MNT, there are many different applications, which do not share a unique component (i.e., unit cell) or specific objective as a common focus for technology development. At the same time, there are plenty of management, planning, and manufacturing tools that have been successfully used in the semiconductor industry but they are often not effective when dealing with disruptive technologies like MEMS. Some devices based on these technologies can take more than 20 years to reach a mass production stage [31]. Some authors attribute high idea-to-market times to the complexity of the manufacturing process [32]–[35]. In order to improve this idea-to-market time, it is important to clearly understand the current status of the MEMS industry, identify the areas of opportunity, and make optimal use of resources (i.e., computer technology, processes, knowledge, human capital, etc.).

3.2.1. Early Development of MEMS

The basic principles that allowed MEMS to start as promising technologies are not new. In 1954, Bell Laboratories published a great discovery which stimulated the development of the silicon sensors: The piezoresistance effect in semiconductor materials, specifically, in silicon and germanium [36]. Shortly after, in the late 1950's, Dr. Anthony D. Kurtz started Kulite Semiconductor Products Inc. and commercialized some of the first pressure sensors micro machined on silicon [37].

During the mid-1960s and the 1970s, a lot of researchers explored different applications for microstructures. The earliest device based on micromechanics that used actuating and sensing technologies on a microstructure, was a *resonant gate transistor* (RGT) operating as an analog filter (Figure 3-1). The RGT was developed in the 1960s at the research laboratories of Westinghouse Electric Corp., in Pittsburgh [38], [39]. The microstructure was a metal beam electrode, clamped in one end over an insulating oxide, parallel and suspended over a silicon surface. Underneath the end of the suspended electrode there is an input force plate. By applying voltages to that input plate, electrostatic forces were generated causing the electrode to vibrate (i.e., actuation technology). This vibration is only appreciable at the mechanical resonance frequency of the beam. Underneath the middle of the beam, a Metal-Oxide-Semiconductor (MOS) type detector was placed and used to detect the vibration of the device (i.e., sensing technology).

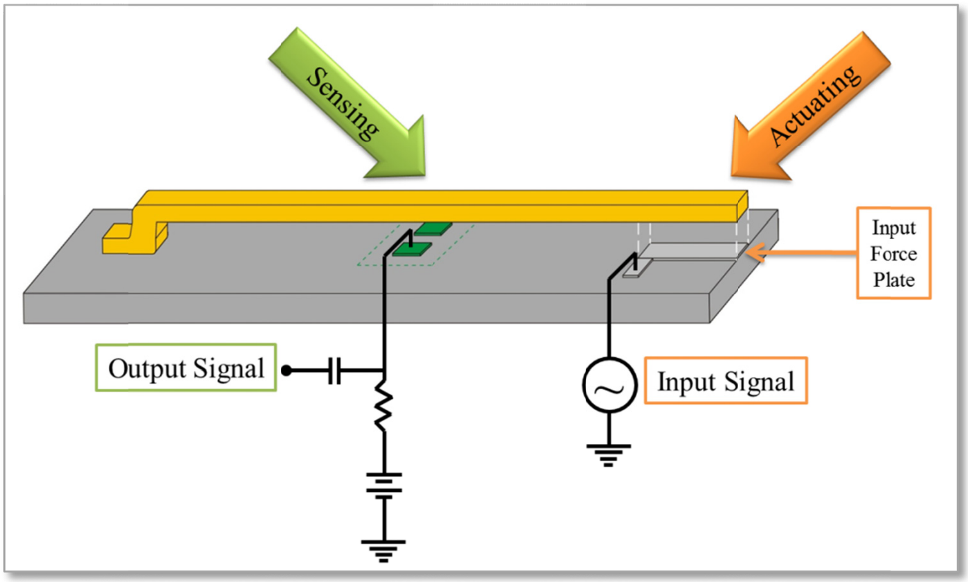


Figure 3-1: Resonant Gate Transistor.

This device never reached the commercial stage due to various challenges. Some were technical challenges and some other challenges were related to the overall technology development happening in the electronics industry at that time. These challenges will be discussed in more detail in the following sections of this thesis. The Westinghouse group continued doing more research on microstructures and proposed different applications like accelerometers, different vibrational sensors, tuning devices in integrated circuits, among others [40]. One of the applications developed at Westinghouse was an arrangement of electrostatic, silicon based, micro-actuators called mirrors arrays. Those micro mirrors were proposed to be used as light valves and projection systems [41], [42]. Closely related with these works another interesting micromechanical device was developed by the IBM Research Laboratory in California [43]. This device was a light modulator array fabricated in single-crystal silicon. Eventually, research in this area would provide bases for the Digital Light Processors (DLPs), an important MEMS commercial product developed by Texas Instruments [44].

Almost three decades after Smith's [36] publication another paper is published were several mechanical properties of silicon are reviewed [45]; in this publication micromechanical processing techniques and applications for microstructures are discussed. At that point in time, early 1980s, few companies were manufacturing silicon-based pressure transducers using complex and exotic technologies for specialized applications and process-control applications. Petersen's publication [45] is an important compendium and analysis of trends in the engineering literature that helped to disseminate important knowledge that was being exploited only by a few companies. By making this knowledge more accessible to public domain several new ideas for potential systems and applications using these techniques emerged. More companies started focusing not only on sensors, but also on silicon microstructures and actuators. At the same time important investments from governments around the world started funding research on this technology.

In the first few years of MEMS development, a lot of interest was focused on miniaturized pressure sensors [46]–[51], which eventually would become the most successful commercial applications for MEMS. The main reasons for this were: the fact the basic mechanical structures required for pressure sensors are relatively simple and easy to fabricate, and the several advantages of using silicon as base material for such devices. Development in MEMS as work-producing actuators happened at a slower pace. At that time, the main challenge for MEMS-based actuators was the lack of appropriate applications and the challenges of reliably coupling microactuators to the macroscopic world [52]. It was not until late 1980s when the micro-actuators field started to see remarkable progress [53]. In 1987 there was an extremely important event for the MEMS community: *The 4th International Conference of Solid-State Actuators and Sensors*. From this event, many publications of break through methods and applications emerged [54]–

[60]. Right after this event, an important patent publication appeared [61] protecting different micro-structures and their fabrication methods. Another event that captured the attention of different MEMS researchers around the world was when a micro-motor was proven to work successfully [62]. Shortly after this publication, another patent was published [63] where the description of these motors and their fabrication process is discussed.

Detailed information about the impact of silicon MEMS during the first 30 years of development can be found in the overview chapter of the book by Lindroos et al. [64]. An extensive review for high volume applications for MEMS sensors and microstructures is presented by Bryzek et al. [31]. In this same work, an analysis of the time required to take a working prototype for some MEMS devices is presented. Table 3-1 illustrates how long it took for various MEMS devices to go from the prototype stage to massive production volumes.

Table 3-1: Prototype to Mass production times [31]

MEMS based device	Working Prototype	Production of 1M units	Incubation Time
Pressure Sensor	1961	1984	23 yrs
Acceleration Sensor	1970 (*piezoresistive*) 1977 (*capacitive*)	1995 1995	25 yrs 18 yrs
Ink Jet Printers	1977	1996	19 yrs
Digital Light Processors	1979	2001	22 yrs

An additional important reference that should be examined whenever a review of the MEMS industry is done is the work by Walsh et al. [28]. This work presents an international roadmap for microsystems, MEMS, micromachining and Top-Down nanotechnologies; its main objective was to provide direction and assistance for different industries (e.g., industrial, automotive, information technologies, defense and life sciences among others) about the commercial development of products and systems based on micro/nano structures and devices. One more reference that complements the MEMS roadmap mentioned above is the *International Technology Roadmap for Semiconductors* [65]. This work assesses semiconductor industry's future technology needs and requirements for the next fifteen years (i.e., 2010-2025). This was done with the intention to drive present-day strategies for research and development among manufacturer's research facilities, universities, and national labs. By closely examining these roadmaps it is possible to have a clear understanding of these fields and identify trends for MEMS/NEMS.

3.2.2. MEMS/NEMS Manufacturing Processes

Many manufacturing processes that can be used to produce miniaturized sensors for numerous variables (e.g., pressure, mass flow, velocity, temperature) and small actuators using various physical forces (e.g., electrostatic, thermal, magnetic) have been developed in recent years. There are many excellent sources for microfabrication technologies (e.g., [66]–[75]) where details of the underlying physics and parameters of the fabrication process that are presented in this section are discussed. The reader is encouraged to review these references if more technical details are required.

The manufacturing processes for MEMS/NEMS of interest for this thesis are those defined as *Top-Down* processes. This fabrication approach selectively etches, patterns, deposits material and/or modifies a bulk material (i.e., substrate), using various processes from the solid-state semiconductors and microelectronics (e.g., photolithographic patterning, impurity doping, epitaxial growth). For NEMS, there is another fabrication approach, which has been of interest in the last several years to the research community, the *Bottom-Up* processes (e.g., self-assembly structures, atomic and molecular building blocks). This approach has been left out of the scope of this thesis as we consider that there is still a need to develop more tools to provide an active manipulation to control matter and to define unit processes for the *Bottom-Up* approach and also we consider this fabrication method to be less mature than the *Top-Down* methodology. From this point on, for the sake of brevity, when we refer to manufacturing techniques or processes we will be referring to the *Top-Down* processes only.

Various materials can be used to fabricate MEMS/NEMS devices. We can arguably affirm that silicon and its compounds (e.g., polysilicon, silicon nitride) are still the most popular material used due all the characteristics mentioned previously is Section 3.2.1. The intrinsic semiconductor properties of silicon can be modified by adding impurity atoms of a different element. This will change the electrons and holes concentrations of the internal structure of the silicon. By doing this, the electrical and mechanical properties can be adjusted for specific purposes [72]. Two terms are used to define doped semiconductor materials: *n-type* (i.e., larger electron than hole concentration) and *p-type* (i.e., larger hole than electron concentrations).

The process flow to complete MEMS devices is a combination of processes from the semiconductor industry (sometimes referred as integrated circuit (IC) industry) and specialised micromachining operations to create mechanical structures on silicon. Most of these micromachining operations can be separated in the basic technologies listed below.

3.2.2.1. Bulk Micromachining

In order to shape the silicon to a specific structures, bulk micromachining selectively remove parts of a substrate (e.g., silicon), typically using aqueous etchants (also referred as wet etchants) in conjunction with masks and different forms of etch stops. The main two types of wet etchants are isotropic, which provide and equal etch rate in all directions, and anisotropic etchants, which etch the substrate at different rates along the different crystallographic planes (Figure 3-2).

Additionally, a degree of selectivity can be added to the wet etching process by doping the substrate with impurities that will reduce significantly the etch rate. For instance, silicon can be heavily doped with boron to create what is known as p+ etch stop, providing more control to achieve the desired final structure.

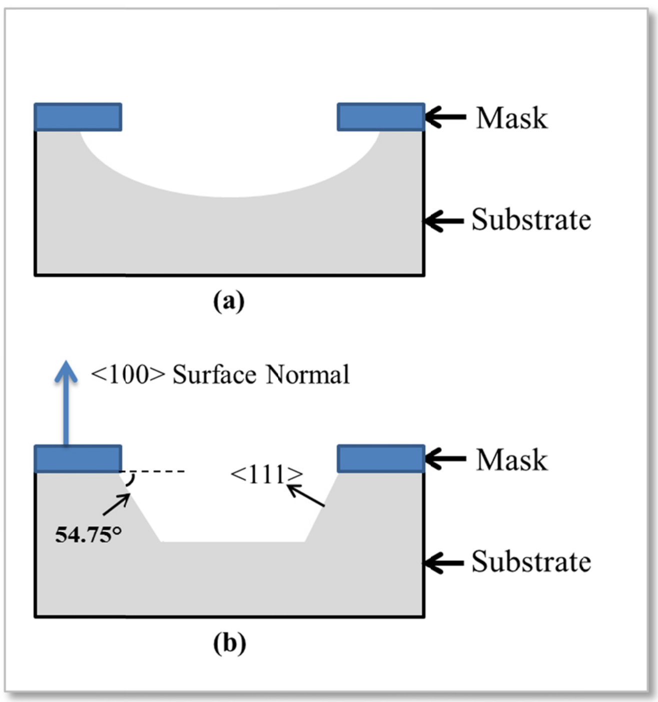


Figure 3-2: Isotropic (a) and anisotropic (b) wet etching

Another process to remove bulk material is the dry etching process. In this process, gas ions and etchant species are generated by applying a high electric field in a chamber filled with gaseous chemicals. The electric field breaks down the molecules of the gas and the etchants generated react and etch away the target material. Dry etching will generally achieve higher etch rates, better selectivity and anisotropy than wet etching.

As mentioned by [73], some of the performance parameters used to define what type of etching technique is the most appropriate for specific applications are: etch rate, etching selectivity, anisotropy, uniformity, surface quality, reproducibility, residue, microloading effects, device damage, particle control, post-etch corrosion, and profile control. A summary of etching methods and their parameters is presented in [68] (Table 3-2).

Table 3-2: Partial list of etching processes [59]

Subtractive Technique	Applications	Typical Etch Rate	Remark
Wet Chemical Etching (isotropic and anisotropic)	Isotropic: Si spheres, domes, grooves	Isotropic: Si polishing at 50 µm/min with stirring (room temperature, acid)	Isotropic: Little control, simple
	Anisotropic: Si angled mesas, nozzles, diaphragms, cantilevers, bridges	Anisotropic: etching at 1 µm/min on a (100) plane (90°C, alkaline)	Anisotropic: With etch-stop more control, simple
Electrochemical Etching	Etches p-Si and stops at n-Si (in n-p junction), etched n-Si of highest doping (in n/n+)	p-Si etching 1.25-1.75 µm/min. on a (100) plane, 105-115°C (alkaline)	Complex, requires electrodes
Wet Photoetching	Etches p-types layers in p-n junctions	Etches p-Si up to 5 µm/min (acid)	No electrodes required
Photoelectrochemical Etching	Etches n-Si in p-n junctions, production of porous Si	Typical Si etch rate: 5 µm/min (acid)	Complex, requires electrodes and light
Dry Chemical Etching	Resist stripping, isotropic features	Typical Si etch rate: 0.1 mm/min (but with more recent methods up 6 mm/min)	Resolution better than 0.1 mm, loading effects
Physical/Chemical Etching	Very precise pattern transfer	Typical Si etch rate: 0.1 to 1 µm/min (but with more recent methods up 6 µm/min)	Most important of dry etching techniques
Physical Dry Etching, Sputter Etching, and Ion Milling	Si surface cleaning, unselective thin film removal	Typical Si etch rate: 300 Å/min	Unselective and slow, plasma damage

Silicon bulk micromachining is one of the most widely used technologies to generate MEMS structures as the equipment required is simple and the processes are straightforward. However, there are some disadvantages. Many of the chemicals used as etchants are not compatible with IC fabrication equipment. Due this fact, a process flow should be well designed to normally perform all the bulk micromachining before all the IC processes that will provide the interface with the electronics to use the MEMS device. Another problem with bulk micromachining is that, in comparison with other technologies, it consumes an excessive amount of wafer surface making it less efficient and in some way more costly. Despite these limitations, we believe that bulk micromachining will continue to be the most widely used micromachining approach for the next several years.

3.2.2.2. Surface Micromachining

The fabrication processes under surface micromachining are those that create structures or devices on top of the surface of the substrate material (i.e., wafer) without ever penetrating the substrate material. In order to build these structures on the surface, a sacrificial layer is deposited and patterned to temporary support a thin-film material layer that will eventually be released to form a final structure. This final structure is anchored in the substrate by etching openings in the sacrificial layers before the thin-film materials are deposited. Figure 3-3 illustrates a generic surface micromachining process to fabricate a polysilicon cantilever structure. One of the major problems that has been significantly improved for surface micromachining is the stiction phenomena, which was one of the main reasons for poor yields for this type of micromachined structures.

The main advantage of the surface micromachining is the excellent compatibility with conventional IC processing, as the processes for this technique are based on standard IC thin-film deposition and patterning technologies. This allows an easy integration with electronic components on MEMS devices. The most important disadvantage that has been perceived for surface micromachining is the lack of flexibility for the shapes and forms of the achievable final structures. This limitation is due the fact that the processes in this micromachining technology evolved from two-dimensional planar technologies.

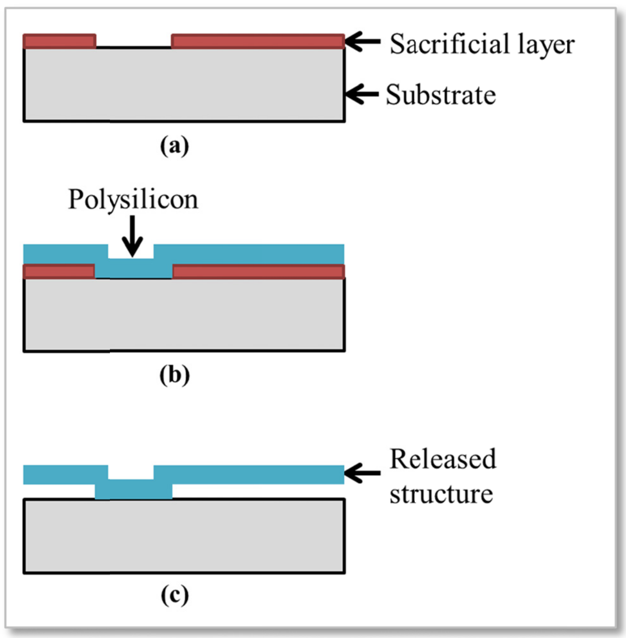


Figure 3-3: Surface micromachining

3.2.2.3. Wafer Bonding

For many MEMS devices require having structures with features sizes greater that those attainable with thin-film techniques. In order to fabricate structural layers from tens to hundreds of microns it is possible to use wafer bonding processes. These processes can be compared to welding processes, where material layers are fused together without the use of any adhesive substance. The three common types of wafer bonding are [76]:

- **Direct bonds.** Wafers are directly contacted without any intermediate layers or assistance of high pressures. This method relies on attraction forces that occur when surfaces are really smooth and flat. It relies on plastic deformation of the material to bring the atoms in close contact. For microstructures, in order to promote attraction and a proper bonding, a pre-bonding treatment of the surface (e.g., hydration, oxygen plasma exposure) is required. The bond is usually assisted by a modest pressure and a thermal-cycle to increase the strength of the bond.

- **Anodic bonds.** This type of bonding method is normally performed silicon and a sodium-baring glass. The wafers are aligned and contacted, and then a high voltage, between 200–1000V, is applied in the interface of silicon-glass under temperatures in the range of 300–450°C. This combination of voltage and temperature promotes the migration of sodium ions away from the bonded interface, leaving behind fixed charges in the glass, creating a high electric field with image charges on the silicon. An extremely strong chemical bond occurs, which fuses the wafers together.
- **Intermediate-Layer bonds.** These bonds are the ones using an intermediate layer to promote the union of two wafers. This category includes eutectic bonds (i.e., using gold thin-films), polymer, solders (i.e., using thin-film deposited solders or preforms), low melting temperature glasses (including glass frits) or thermo-compression bonds. These types of bonds are widely used in the die-level packaging of integrated circuits.

An additional reference [77], provides a general overview of the existing wafer bonding techniques as well as some of newer plasma enhance bonding methods to reduce the bonding temperature below 200°C.

3.2.2.4. Micromolding

For MEMS fabrications, an alternative to generate high-aspect-ratio structures on the surface of the substrate is the micromolding technique. The structures that can be generated by using this set of processes can have small lateral features (i.e., 1 or 2 μm), comparatively large vertical features (i.e., 10 to 500 μm).

An important micromolding process for micromachining is the LIGA process (from the name in German, **Li**thographie, **G**alvanoformung, **A**bformung) which is performed by the following steps sequence: A polymeric material (also referred as resist), poly-methyl methacrylate (PMMA), is exposed to a synchrotron radiation through a mask, which changes its dissolution rate in a liquid solvent (developer). Those irradiated regions are dissolved using the developer creating a high-aspect-ratio relief structure of PMMA. A complementary metallic structure is then obtained by an electroforming process, which uses the PMMA structure as a template, where metal is deposited onto the electrically conductive substrate in the gaps between the resist structures. The metallic structure can be either the final structure or can be used as a micro-mould-insert for moulding process.

The moulding process can be used for multiple reproductions. In the last several years, the micromolding process has been optimized. It has been demonstrated by many experiments that productions yields of close to 100% can be obtained in the micromolding process [78].

3.2.2.5. Low Temperature Cofired Ceramics

The Low Temperature Cofired Ceramics (LTCC) is a well-established technology for low volume high performance applications (e.g., military, space), as well as for high volume low cost (e.g., automotive industry, wireless communications). LTCC has been used for many years to produce multilayer substrate for packaging integrated circuits. More recently, LTCC have been utilized to fabricate sensors and actuators using three dimensional integrated microstrucutres [69], [79].

The materials for LTCC process are based on crystallisable glass or a mixture of glass and ceramics (e.g., alumina, silica or cordierite). The starting materials are produced by a tape casting method resulting in what is called *green ceramic tape*. Various properties of this tape can be modified by using materials with different electrical and physical properties (e.g., piezoelectric, ferroelectric) in order to make a network of conductive paths in a multilayer structure. To achieve this multilayer structure, first raw ceramic flexible sheets (green sheets) are prepared for printing. After this, using conductive paste, the conductor and passive components (e.g., conductive vias to interconnect multiple layers, wiring patterns) are screen printed on the green sheets. These layers are aligned and stack together, and heat and pressure to laminate them using organic resin as adhesive for bonding the layers. After this step, the structures are cofired in two step process. Firstly, the organic binder in the ceramic tape is burned out (~500°C), then the ceramic material densifies (~850°C). Once the cofiring step is completed, additional thick or thin-film components can be deposited on the top and bottom surfaces.

Other special methods (e.g., jet vapour etching, laser micromachining, photoformable LTCC tape, embossing, casting) can be used for making various more complex three dimensional structures, cavities and channels in the LTCC module.

CHAPTER 4.
MEMS INDUSTRY STATUS, CHALLENGES AND OPPORTUNITIES

This chapter presents the initial results of our descriptive and field research. Through private interactions with MEMS/NEMS practitioners from industry, academia, and government (sometimes referred as the triple helix), and by performing an extensive literature review we were able to clearly understand current situation of the MEMS/NEMS industry. This first part of this chapter presents an analysis of the journey from MEMS/NEMS products to reach commercial markets. The second part presents an analysis where various challenges and opportunities within the MEMS/NEMS industry that were identified by our descriptive research work.

4.1. MEMS Commercialization Journey

A crucial factor during the commercialization journey is good management of the technological exploitation process while mitigating possible risks [80]–[82]. This is particularly important when working with disruptive technologies, like MEMS/NEMS [25]. New processes, standards, and characterization procedures need to be created, tested, and implemented. Amazing technologies are abandoned or remain on a shelf indefinitely, because products using new technologies cannot be mass produced in an economic fashion. In some cases, products miss the window of opportunity when there is a big need and a considerable market, which is eager to buy and use these products. It is important to provide a complete framework to support the three stages of every commercialization process; these three stages are broken down into constituent steps in Figure 4-1.

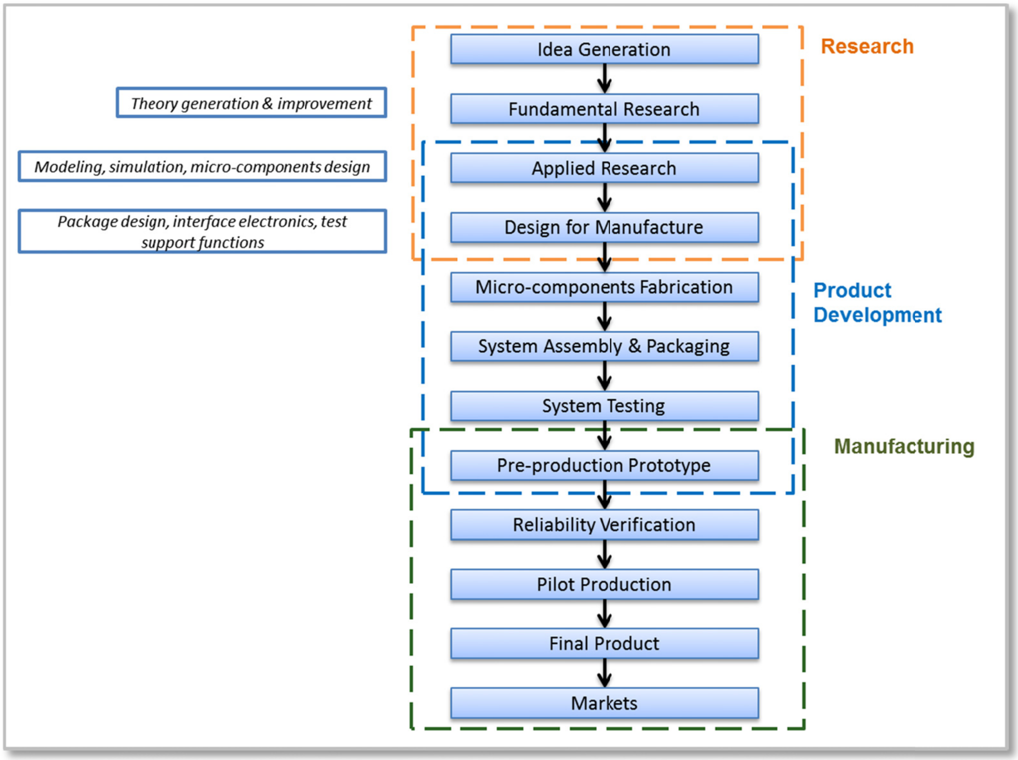


Figure 4-1: Microsystems Commercialization Path – Adapted from [25]

By means of private interaction with practitioners from the triple helix in the MEMS/NEMS ecosystem in combination with observation of development of several MEMS designs we were able to identify the main bottlenecks for the process of taking an idea into a commercial product. We defined six main phases for this process: *Physical Design, Simulation, Prototyping, Characterization, Process Up-Scaling* and *Mass Production*. A graphical interpretation of these phases, which illustrates the bottlenecks that were identified, is presented in Figure 4-2.

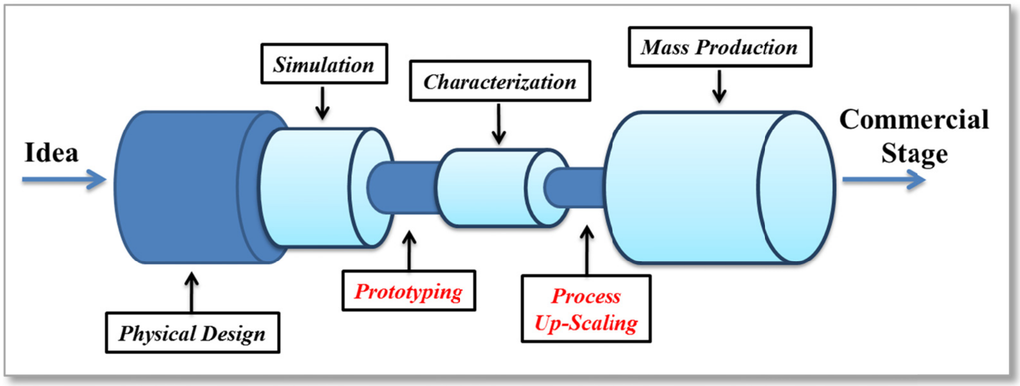


Figure 4-2: Idea to Commercial Stage Bottlenecks

For the first two phases (i.e., *Physical Design* and *Simulation*), there are many software tools to design and to simulate the performance of a MEMS device with a high degree of confidence [25]. These tools enable a relatively short and predictable physical development cycle. This is not the case for the third phase (i.e., *Prototyping*), as there are not as many tools that can assist designers finding the ideal set of processes to fabricate or prototype a MEMS design. There are quite a few standard tools to characterize and verify the outcomes of fabrication processes that can be used for MEMS (e.g., scanning electron microscope (SEM), atomic force microscope (AFM), gas adsorption analysis based on Brunauer–Emmett–Teller (BET) theory, two-dimensional surface topography, nano-indenter). Therefore, the *Characterization* phase is not as restrictive as the previous phase. The next phase (*Process Up-Scaling*), is another greatly restrictive phase, due the fact that it is not always easy to take a fabrication process at a lab scale that was used to create a MEMS prototype and to replicate the same process for high volume production [83]. In many occasions, it is not possible to adjust lab processes in order to transform them into mass production processes in an economic fashion, and sometimes it is not possible at all. If it is possible to scale-up lab processes into mass production processes, the actual execution of the high-volume production for MEMS (*Mass Production* phase) is not too difficult, as high production volume is one of the advantages of microsystems fabrication. The main bottlenecks perceived in the process of idea-to-market for MEMS devices are the *Prototyping* and *Process Up-Scaling*. Both of these phases are related to designing manufacturing processes in an efficient manner. In the next section, we "zoom-in" and analyse in more detail to better understand the development cycle for MEMS devices.

4.1.1. Understanding MEMS Development Cycle

Ideally, a start-up company working with microsystems should have all the required processes under one roof, well characterized and with well-established process capability indices. Unfortunately, this is not possible for most companies, especially the start-ups. Capital costs of specialized equipment, and a lack of statistical and characterization data makes this difficult to achieve. At the moment, there are few (perhaps no) single organizations or facilities that have all the equipment for every process required for microsystems manufacturing under one roof. In most cases the interaction of many organizations is necessary in order to address all the steps for a MEMS fabrication process.

Presently, while developing a new MEMS fabrication process, several attempts using a number of different configurations need to be performed. Not all of the successes and failures are recorded, and many times, a new researcher spends significant amounts of time trying configurations that have been tried already and failed (even within a single facility), but were not documented. As well, in many cases, when a research project is inherited from a previous researcher, critical details, important findings, and reference data are omitted and there is a lot of time wasted to compile that information all over again. If a system can keep track of previous work (both successful and not), as well as all the knowledge that has been generated by a research group, new researchers will be able to more effectively utilize previous knowledge to more quickly arrive at a complete product. The system must be capable of capturing the dynamism of the MNT industry and be flexible enough to allow the researchers to add new information to the existing knowledge-base.

It is possible to identify two main phases in the MEMS development cycle (Figure 4-3): the device design and the process design.

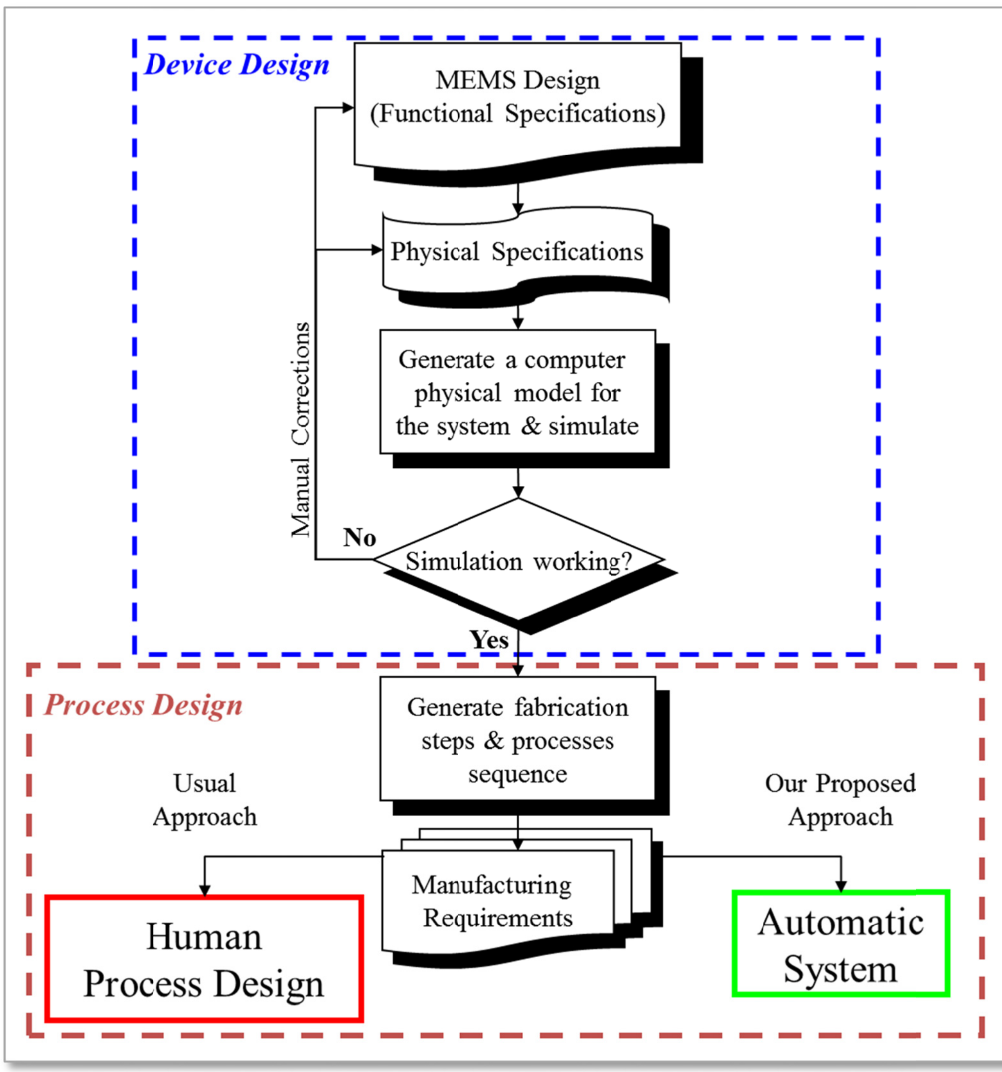


Figure 4-3: MEMS Development Cycle

For the device design, we focus on the functional specifications (i.e., what is the main function of the device?), which in turn will define the physical specifications (i.e., what should be the composition/form of the device in order to properly achieve the desire functionality?). Once these specifications have been completed, a computer model is generated and, if the proper simulation software is available, a simulation is performed to validate the physical design. If the simulation at the physical level is working, the process design starts. A process flow is assembled using various fabrication steps. Then, manufacturing requirements are established. At the moment, the usual way to assemble a process flow is doing it manually. The standard procedure to do this is shown in Figure 4-4. In this figure, it is possible to observe loops where much iteration is required, which results in loss of time and inefficiencies, to complete a process flow design.

As a result of the analysis that we performed to understand the current situation of the MEMS/NEMS industry, we were able to identify more specific challenges that developments on these technologies are facing to reach commercial markets. In order to better address these challenges, we categorise them and look for opportunities on how to mitigate them. In the next sections of this thesis, we present additional details of the challenges we found and various opportunities on which we can capitalise to provide tangible benefits to the MEMS/NEMS ecosystem.

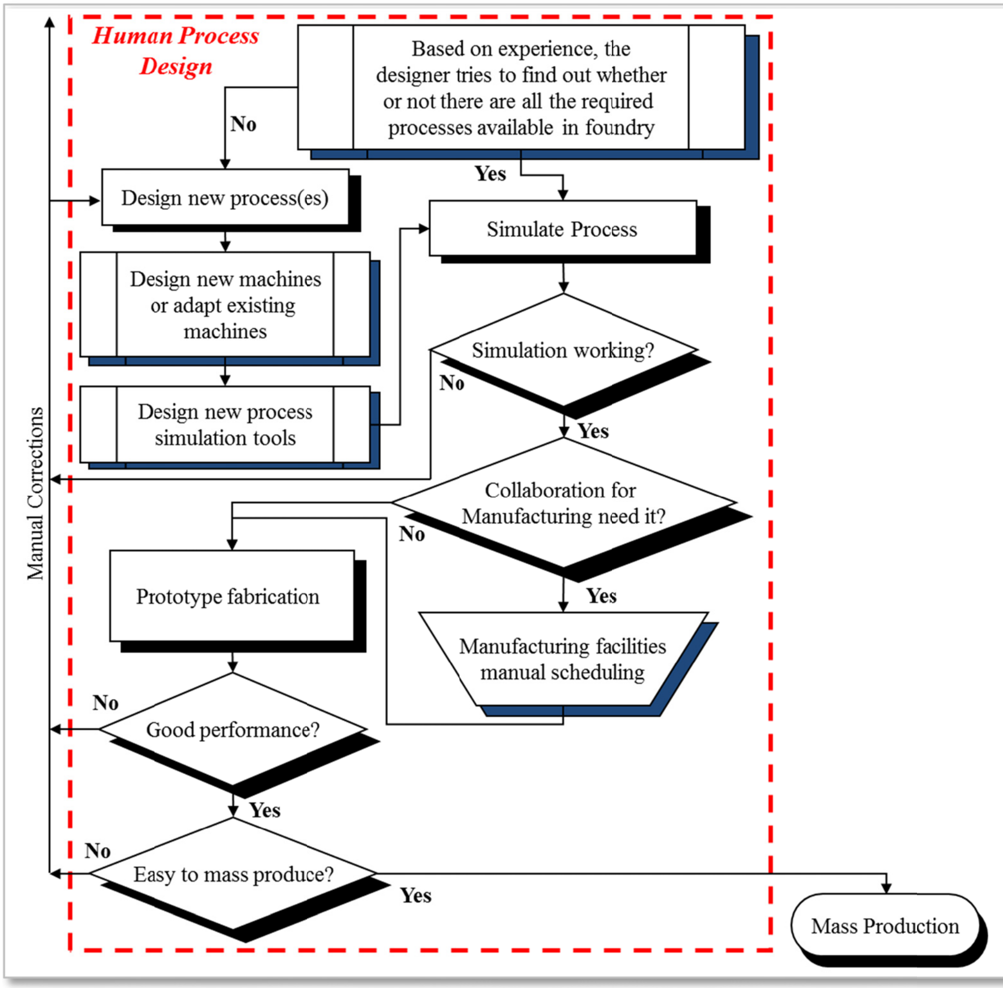


Figure 4-4: Traditional way of designing MEMS Manufacturing Process

4.2. Challenges

Despite all the benefits and potential that MEMS/NEMS technologies have, there are some challenges that need to be addressed. Two challenge types have been identified: *Technological* and *Managerial* challenges. Each one of those has subcategories that we discuss in detail in this section.

In order for an idea to break through most of the challenges aforementioned and reach the commercial stage (i.e., find a market), it is necessary for it to:

- provide a unique functionality,
- be reproducible and reliable, and
- provide economic benefits.

As shown in Figure 4-5, if an idea lacks of any of those components the potential of getting to a commercial stage is low, even if the idea is based on a strong technology.

According to Petersen [45], the most critical challenges (from a technology perspective) for the first fully actuating/sensing MEMS device [38], were: reproducibility and predictability of resonance frequencies, temperature stability, and potential limitations on lifetime due to fatigue. The first challenge is a manufacturing challenge. The fabrication processes used to build the device were not well characterized; hence controlling the process was problematic, impacting the reproducibility of the device. The second and third challenges had to do with problems on material selection and design considerations. Similar challenges are still present in many MEMS designs today.

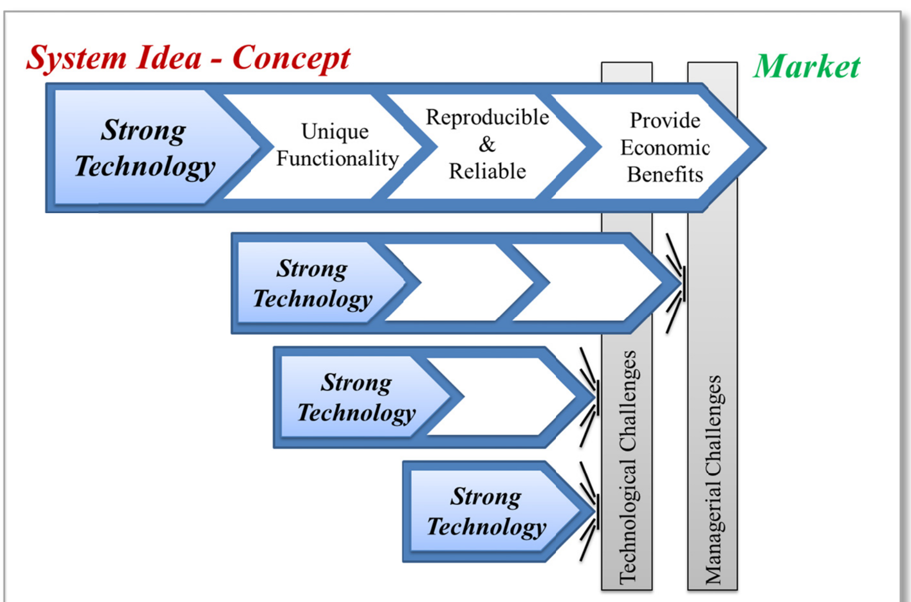


Figure 4-5: Characteristics required to reach the Commercial Stage

4.2.1. Technological challenges

4.2.1.1. Design Challenges

In order to develop a proper MEMS/NEMS device or component, it is important to account for some special considerations that should be kept in mind before and during the designing phase for MEMS/NEMS; failing to be aware and keep these special considerations in mind, can result on a useless design. Some of the main design challenges are presented next.

- **Scaling of micromechanical devices.**

Different physical effects manifest very differently in the macro and micro worlds because of system size differences. Scaling theory is a valuable tool that can help to decide what may work and what will not. It is important to understand how phenomena behave and change as the scale changes. Such changes on system behaviour can be appreciated in the work presented by the Committee on Advanced Materials and Fabrication Methods for Microelectromechanical Systems [84] where surface and interface effects are discussed. That work mentions the need of a more complete understanding of the effects of internal friction, Coulomb friction, and wear at solid/solid interfaces. Indeed, there is the need of better understanding the influence of interfaces on performance and reliability.

- **Internal components diversity.**

While the *integrated circuit* (IC) industry works with dimensions much smaller than MEMS, most designs for IC use the same principles from several decades ago. A key concern of the IC industry is to find ways to make a transistor smaller in order to fit more of them in a chip (i.e., continue the trend of Moore's Law). In the MEMS world, there are mechanical movable parts, acoustic components, micro channels to transport fluids, micro mirrors, many other components that comprise a modern MEMS device. A more diverse functionality means more variables will need to be understood and controlled.

- **Static vs. dynamic structures.**

The dynamic nature of MEMS structures marks an important difference relative to the IC industry. For the most part, MEMS are built for the purpose of executing mechanical motions in micro-structures, shaped in a variety of materials. IC devices, on the other hand, have no movable parts. Therefore, there is no need to develop procedures to form and release movable structures from the substrate in an IC device. In order to obtain repeatability in the performance of a MEMS device, free-standing or otherwise movable structures must have the same mobility characteristics (within tolerances) every time in every instance of the device.

4.2.1.2. Differences between IC Processes vs. MEMS Processes

During the MEMS fabrication process, the integration of mechanical elements with electronics on a common silicon substrate is required. This means that conventional IC processes need to be combined with highly specialized micromachining processes. The equipment used in both types of processes is quite similar; however, there are some important differences that need to be considered [85]:

- Some micromachining processes are incompatible with IC processes. For example, MEMS fabrication thermal process budgets must be carefully designed in order to retain the performance and reliability of the CMOS electronics.

- Processes sequences for IC fabrication are generally standardized and fixed (e.g. CMOS, Bipolar and BiCMOS). MEMS process sequences are usually much more customized, both in materials used and in the ordering of the processing steps.
- MEMS product development usually requires a significant R&D effort dedicated to development of a viable process sequence.
- The separation between design and fabrication in IC technology is clear-cut. MEMS design, process development, and fabrication are intertwined.
- IC manufacturing is typified by large volume production. Many MEMS applications will require small volume manufacturing.
- MEMS fabrication core competencies vary from site to site. Access to MEMS prototyping and manufacturing is limited.
- Many beneficiaries of MEMS do not have core competency in micro-fabrication. For instance, when microsystem started being used in the automobile industry, there were not many experts in that industry with good understanding of microsystems fabrication.
- Design tools and packaging are readily available in IC technology while they are very primitive or non-existent in MEMS.

To further drive home the point, Bryzek [86] carried out a survey on MEMS foundry customers' satisfaction and, in general, found that customers were not very satisfied with their experiences. This survey used the IC foundries as a point of reference. The results are shown in Table 4-1.

Table 4-1: IC Foundry vs. MEMS Foundry from customer perspective [86]

Item	IC Foundry	MEMS Foundry
Standardized processes	Available	Not available
Stable design rules	Available	Not available
Need for process debugging	None	Extensive
Cycle time to first production wafers	3-6 weeks	1-5 years
Effective cost of first production wafers	\$50k for 0.5µm CMOS	\$0.5 to \$5M
Yield	Predictable	Unpredictable
Quality of service and quoted price	On time delivery	Usually delayed
QA systems in place	All	Very few
Capacity	Almost unlimited	Limited
Fabless company needs	Design engineers	Design and process engineers
8" wafer cost/masking step	\$50	\$500

4.2.1.3. Obstacles in MEMS Manufacturing

As discussed in the remaining of this thesis, some of the most important challenges that are currently delaying the time-to-market for MEMS devices are related with manufacturing. In the following paragraphs, we present various examples of important challenges that are being faced during the fabrication stage for MEMS.

- **Catastrophic yield of single-crystal silicon (SCS).**

Despite the fact that a variety of materials are used to build microstructures, the predominant material for MEMS structures is single-crystal silicon (SCS). By analyzing the mechanical properties of SCS we can see that it is a brittle material. Because of this, it yields catastrophically, like most of the oxide-based glasses, rather than deforming plastically like most metals. Silicon wafers are even prone to break without apparent provocation and may also easily chip [87].

As a single crystal material, silicon has a tendency to cleave along the crystallographic planes, especially if there are imperfections that cause stress to concentrate and orient along cleavage planes. Defects on the edges in particular are responsible for wafer breakage [45]. Another cause of internal stresses in silicon is the high temperature processing and multiple thin film depositions that can occur during the fabrication process [ibid.]. Special care needs to be used when handling silicon microstructures, and desired geometries (e.g., contoured edges) should be considered during the design phase, in order to minimize the internal stresses that can lead to a device malfunctions.

- **Process order and priorities.**

Microstructures are typically integrated with electronics to form a working MEMS device. It is therefore necessary to consider the compatibility of the microstructure fabrication processes with the electronics. For bulk micromachining, compatibility issues normally arise from the incompatibility of these types of processes with the clean room environment [88]. A way to overcome this is to perform the micromachining after the electronics processes have been completed. In theory there are many ways to get to the same structure using different process flows. The main challenge here is to select the correct steps and in the correct sequences in order to minimize adverse effects from subsequent processes.

For surface micromachining, there are more compatibility considerations that need to be observed [89]:

  - Thermal budget: During surface micromachining, some layers may require annealing, meaning that the whole device will be exposed to high temperatures.

- Sacrificial etching: In surface micromachining, several layers of different materials are deposited. Producing free-standing structures involves the selectively removing previously deposited layers (i.e. etch sacrificial layers). At this point it is important to ensure that this removal procedure does not attack or modify the working properties of the mechanical layers or the electronics components.

- **Process sensitivity.**

Many MEMS fabrication processes are so sensitive that even the breath of a smoking person can affect the production outcome for a MEMS device. A colleague based in California, who has helped to develop many processes for MEMS manufacturing for different companies, reported that there was a case where every month, due to hormonal changes, the body of a worker in a production line was emanating gases that were interfering with the yield of the production. Another good example where the degree of sensitivity of MEMS processes can be observed, as reported by many of our colleagues in MEMS foundries and fabrication facilities have confirmed, when a change of supplier of a raw material (e.g., wafers, etchants, gases, etc.) is required; this change can alter your entire production outcome, even if the new supplier meets all the exact specifications from the previous supplier. These are just some of examples of how easily the behavior of the MEMS manufacturing processes can be affected. This process sensitivity is one of the key problems that arise when a MEMS process line needs to be moved to a different facility or needs to be replicated to increase production.

- **Lack of standardization.**

Many MEMS processes are constantly evolving and the MEMS industry is extremely dynamic. While it is possible to find some standardize unit processes, it is still not possible to standardize entire process flows. This fact represents an important challenge for the MEMS community. The variety in manufacturing processes is nearly as diverse as the number of new ideas for microsystems designs. There have been several initiatives to standardize the process flow [90] but the dynamism of innovative ways to produce MEMS and ideas for novel processes makes standardization very challenging [30], [33].

- **Specialized equipment required.**

The cost and availability of tools for handling materials with micrometer and nanometer dimensions are another big issue. At the moment, there are few vendors that can provide tools for MEMS manufacturing and characterization, and those that exist are very expensive. Because of this, even the largest foundries often need to collaborate with other organizations to complete a manufacturing process for a MEMS product.

- **MEMS packaging.**

Assembly and packaging represent more than 80 percent of the cost for some systems [84], and packaging challenges are the leading cause of system failure. The packaging is the interface between the MEMS/NEMS device and the macro world. Showing that a device component will function in an isolated environment is just a fraction of the work. Having a clear understanding of how the proposed component, device or system will interact with the macro world is extremely important at the very early stage of the design. The approach required for MEMS packaging is often approached by individual manufacturers on a specialized, application-specific basis in which problems are solved independently. Generic assembly and packaging is difficult due to the fact that MEMS/NEMS devices typically involve a number of applications in different physical domains. As well, many MEMS have non-electrical inputs and these must be transmitted through the package. At the same time, packaging should isolate external non-desired signals and protect the device for the (potentially harsh) environment where it will work.

The discrepancy between the ease with which batch fabricated MEMS can be produced, and the difficulty and cost of packaging and testing them, limits the speed with which new MEMS can be introduced into the market [91].

4.2.1.4. BioMEMS Challenges

Innumerable applications can be developed by using MEMS/NEMS devices in many different areas and industries. The number of ideas for MEMS to be used for diagnosis and therapeutic biomedical applications (BioMEMS) is increasing every day [92]. We have found some special challenges for MEMS devices that will be implanted inside of a living organism. This section presents some of these challenges.

- **Biocompatibility issues.**

The fact that MEMS are amenable to miniaturization makes them ideal to develop small, reliable, and less invasive sensors and actuators that can work with very little power consumption inside the human body. On the other hand, significant challenges arise when a whole system needs to comply with stringent regulations and legislation designed to protect the users (e.g., patients and doctors).

Materials must be non-toxic for biological cells and the materials surface must have a minimal effect on cell growth and cell proliferation. The metallic materials must be corrosion resistant and no degradation of inorganic or organic materials should occur during chronic implantation. The material properties and the shape of the device must not cause damage to surrounding tissues. This will impact virtually every aspect of the MEMS/NEMS device lifecycle, from conception to development and design, then on to fabrication, testing, and packaging. Detailed knowledge of the ultimate biological environment and the resulting requirements (and a solid understanding of the limitations of existing technologies) is required when designing bioMEMS devices [93]. Many bioMEMS devices will encounter harsh environments that will promote deformation, friction, wear, dissolution, etc. of the device, which can eventually result in failure. Decisions on material selection should be correlated with functional specifications and the characteristics of the working environment, which is dictated primarily by the physiology of the patient where the microsystem will be used [94], [95]. Other considerations to account for include:

- How many sensing/actuating cycles per year is the device required to perform (e.g., 10^5 for peristalsis, $5x10^7$ for heart contractions, etc.)?
- Will the system be used to measure mechanical stress, say, in muscles (~4 MPa), tendons (~40 MPa), or ligaments (~80 MPa)?
- What is the local acidity of the working environment (e.g., pH=1 for gastric content, pH=7.2 for blood, pH = 4.5 to 6.0 urine)?

- **Sterilization issues.**

If a MEMS device is to be used inside the human body or in an operating room where everything needs to be clean and sterile, then the device will need to conform to this requirement as well. Furthermore, if the device is reusable, then it must be able to support several sterilization processes without degradation. In order to be able to select the most appropriated sterilization method for a MEMS device, a deep analysis of the device itself should be performed to consider factors like geometry, constituent materials, maximum temperature supported by the device, etc. There is no universal sterilization method for every system [96].

4.2.2. Managerial Challenges

4.2.2.1. Commercialization Challenges

Presently, the proportion of MEMS/NEMS devices that make it from the R&D phase to become commercially successful is small [97]. This is due in part not only to the challenges mentioned previously, but also from challenges in the commercialization process.

- **Important features for new products.**

New technologies must compete with existing technologies, which keep evolving and improving (i.e., incremental progress). Based on our observations, we believe that it is possible to generalize the features observed by Petersen [45] for successful micro machined devices, to the majority of totally new (i.e., disruptive) technologies that seek to reach (and stay in) commercial markets and displace an existing technologies; such technologies must provide the following characteristics:

  - Implement functions that cannot easily be duplicated by existing or conventional technologies.
  - Must have a satisfactory degree of reliability and reproducibility.
  - Provide a positive economic impact.

If a new product does not provide all of these characteristics it would be extremely hard to achieve commercial success.

- **Focus on components instead of whole systems.**

An additional impediment for MEMS/NEMS devices attempting to reach the commercial stage is the fact that many research projects focus only on components of a system, not on whole systems. This can be easily verified by reviewing the typical paper or presentation in the leading MEMS/NEMS journals and conferences. We estimate that 80 to 90 percent of the publications are related to components or parts of a system, only a small minority are focused on system integration or whole system designs. An integrated approach is required in order to speed the process of taking a MEMS/NEMS device from idea to market. When the design of a component occurs independently, without taking in account packaging issues and how to interact with the macro world, since the beginning of the product development cycle, it is very likely that a re-design must occur when that component needs to be integrated into a complete system. This will delay commercialization and may even halt it altogether.

- **Solid commercialization infrastructure.**

MEMS commercialization has been a slow, inefficient, and expensive process. We can combat this by promoting more direct collaboration between industry and academia, so academics have a better understanding of the commercialization process and so industry can provide better direction to those pushing new technologies. The main barrier to develop any commercialization strategy is the absence of infrastructure that supports the three main areas of the commercialization process [25]: research, product development, and manufacturing.

4.2.2.2. Information Challenges

Good quality information is known to be the most important element of a decision-making process [98]. Decisions occur in every step of a development process and having clear, timely and relevant information is of upmost importance for any development. However, due the points discussed below, MEMS/NEMS can face hurdles that can hinder the process of reaching markets fast enough to become a successful commercial product.

- **Need of a common process specification language for MEMS/NEMS manufacturing.**

Micro and nano technologies are interdisciplinary fields. A development of a single MEMS/NEMS device may require a team with expertise in many different areas (e.g., chemistry, physics, mechanical engineering, electrical engineering, materials engineering, process engineering, etc.). The technical argot for each of these members may have substantial differences in how they address the technology. Different terms may be used to refer to the same object, or vice versa, a common term could mean totally different things in different disciplines. This is also true for inter-organization collaboration. Therefore, we feel that it is important to develop a MEMS/NEMS-specific process specification language in order to remove ambiguities and prevent misinterpretations.

- **Lack of Information on process characterization.**

There is a plethora of variables that can affect the production yield of manufacturing MEMS/NEMS devices, and so they must be precisely controlled through the entire fabrication process. Understanding what all these variables are and how they influence the manufacturing process is very important, but it is very expensive to perform this type of analysis. In order to identify these variables, several iterations and intensive research work needs to be done. Most of the new MEMS/NEMS products are emerging technologies and until they are proved to have an extensive market (i.e., several million units) there is not enough volume production, thus, not enough resources to perform this characterization in an industry setting.

- **Information dissemination.**

A common practice for MEMS manufacturing foundries is to tune processes by trial and error. Once processes are working within tolerances the working parameters and final settings are kept as trade secrets. This has led to what is known in the microsystems community as the “one product, one process” rule [99]. This is totally understandable from the business perspective, as it provides a competitive advantage over potential competitors. However, it is totally unfavorable for technology development as a whole. The perceived challenge here is that, in many educational institutions, there is an increasing demand to generate economic benefit from as many projects as possible and this is, erroneously, interpreted as a need to consider academic (public) research as a trade secret. Anecdotal evidence, collected during private interactions with researchers and professors from various universities and research centres, suggests that the number of publications that disseminate information and educate the community is significantly reduced. This is due to the fact many university professors are reluctant to publish what may be important findings until their intellectual property is secured and commercialization opportunities have been explored. In the same way, collaboration among universities and research institutes is decreased. This is detrimental for the main purposes of educational institutions: knowledge generation and dissemination.

MEMS/NEMS can be applied widely in many different industries (e.g., medical, energy, agriculture, defense, etc.), but there is very little knowledge at the corporate level on what such technology can provide to improve existing technologies. Stronger efforts need to be made to educate industry on the potentials and opportunities available from MEMS/NEMS.

4.2.2.3. Management of Disruptive Technology Challenges

Disruptive technologies are those that introduce a very different set of attributes from the one that mainstream customers historically value. Furthermore, at least at the introductory stage, they often perform far worse along one or two dimensions that are particularly important to those customers [100].

Based on the previous definition, it is not hard to understand why mainstream customers are unwilling to use a disruptive product in applications they know and understand. However, as also stated by Bower & Christensen [100], most companies that are well-managed, established, and are consistently leaders of their industries developing and commercializing new technologies, are those that present technologies which address the next-generation performance needs of their customers. Conversely, these same companies are rarely at the forefront of commercializing new technologies that don't initially meet the needs of mainstream customers and appeal only to small or emerging markets. Many MEMS/NEMS devices suffer from this, as there is a lack of understanding in what a full development cycle for a MEMS/NEMS product implies and what the real benefits of the proposed systems are. At the moment, questions like: what is the total cost of the development?, is it possible to develop the system using existing infrastructure?, how long is going to take to have an initial prototype?, how easy/hard is to scale-up and mass produce an existing prototype?, etc., are difficult to answer for MEMS/NEMS developments. There is an important need to develop tools that assist answering these questions.

At the same time, another critical challenge is the lack of a system that can be used to quantitatively explore potential opportunities and support the decision-making on where to allocate resources for product developments based on disruptive technologies. It is important to remember that at least one element of the opportunity recognition paradigm is driven by technology, especially by emerging and often disruptive technologies acting as the source of entrepreneurial opportunity [101]. Most of the existing management tools are not suitable for disruptive technologies. In the next section we discuss in more detail why some of the existing traditional tools used to manage knowledge and product development are not suitable for MEMS/NEMS specifically.

4.2.2.4. Challenges for Traditional Managerial Tools while Working with MEMS/NEMS

Presently there are a plethora of tools to assist with knowledge management, with material, manufacturing and resource planning, and with product development. In the MEMS industry, some devices have evolved from emergent technologies into widely adopted and fully emerged mass produced technologies (e.g., DLPs, air-bag systems, ink jet heads, MEMS-based microphones, etc.). For these applications, traditional tools can be (and have been) used in the traditional manner common of other industries with high-volume production levels. However, there are many MEMS/NEMS devices still under development, i.e., emerging technologies [25], for which most traditional tools cannot be used without further adaptations. A clear example of this need to adapt existing tools or take new approaches when dealing with emerging technologies and applications is manifested in what's happened with technology roadmaps. Technology roadmapping is a tool that has been widely used since the mid-1980s to identify technology development paths and describe future technology requirements and research needs. However, when it comes to applying roadmapping to micro and nano technologies, significant changes are needed [102]–[105]. For example, in order to design a useful roadmap for these technologies, crucial technological prerequisites that are not necessarily in the same technological realm but are related to the technology being examined (i.e., enabling technologies) need to be investigated. In many occasions, it is not easy to recognize these connections to enabling technologies with applications being developed based on MNT. Therefore, it is required to perform an intermediate analysis to connect these enabling technologies and determine how they integrate into new applications, products, or processes of the technology being examined in the roadmap.

Furthermore, as concluded by Percival & Cozzarin [106], it is important that implementation dependencies of a computer-based technology related to manufacturing (i.e., *advanced manufacturing technologies* (AMT)) are conducted at the industry level rather than within an individual company or institution, otherwise the environmental differences may provide misleading results. Enterprise resource planning (ERP) systems are another example of an existing widely used business tool that cannot simply be borrowed by the MEMS/NEMS industry without considering the complexity and specifics of vastly different business processes. ERP systems may face significant challenges due to two reasons: the technical complexity of the solution that requires a great deal of expertise, and the mismatch between technical specification of the system and the business requirements of the organization [107]. These two factors are prevalent in the MEMS/NEMS industry during the product development stage.

As we could see in previous sections, there are many variables that can affect the MEMS/NEMS technologies development which are not yet well characterized. Fundamental knowledge on the physical limits of existing fabrication processes needs to be compiled for these technologies, as there is often insufficient statistical data to predict how certain processes will behave when looking at a single fabrication facility (or even several) in isolation. Furthermore, there are few comprehensive databases of established suppliers that can provide materials or services needed to fabricate various devices. There is a need to be able to efficiently use the MEMS/NEMS infrastructure that is already in place but widely scattered in universities, research institutes, and foundries around the world. At the same time, these tools need to be able to capture new knowledge as it is generated by new process linking various process steps with the fabrication facilities capable of performing meeting the requirements in question.

4.3. Opportunities for the MEMS Industry

There is an old maxim that states "where there is a challenge, there is an opportunity". For all the challenges mentioned in the previous chapter, there is a room for improvement and an opportunity to develop new and creative solutions. The opportunities presented here are mainly related to business and managerial activities, as we know that providing assistance in these areas makes it possible to positively impact technological and managerial challenges. In this chapter, we use a success story in the MEMS industry, the *Digital Light Processor* (DLP) technology developed by Texas Instruments [108] as a case study to clearly illustrate some of the opportunities for the MEMS industry.

4.3.1. MEMS Attractiveness from Business Perspective

The MEMS industry has evolved greatly in the last 40 years. The economic impact that MEMS-based integrated circuit products have created is significant. In 2005, the venture capital industry invested an estimated US$ 1 billion into MEMS-based companies which, by then, had created a market of US$8 billion [31]. 2008 and 2009, with revenue decreases of 5% and 8%, respectively, are the two years when the MEMS industry experienced its first downturn in 20 years. During the economic downturn, the strong MEMS companies became stronger and a lot of weak companies disappeared [109]. However, more recent economic analyses [110]–[112] confirmed that the trend for MEMS-related economic activity is recovering and improving in many areas (e.g. medical, aerospace, energy, etc.), with mobile/consumer electronics market as the main locomotive of the industry. There is a diversification of markets, and MEMS companies in different industry segments have emerged. This means that there are several opportunities ranging from high volume low mix applications (e.g., mobile/consumer electronics) to low volume high mix applications (e.g., medical, aerospace, etc.) that need to be developed, where MEMS can provide smart and elegant solutions.

One additional aspect to consider as an important opportunity for MEMS development, from the business perspective, is that most of the initial patents covering the main concepts for MEMS devices are expiring or about to expire (i.e., they were issued in the late 1980s or early 1990s). It is possible to take advantage of that and use proven knowledge to build new devices. Another advantage for MEMS, from the business perspective, is the fact that equipment in the IC industry evolves at a faster pace leaving behind obsolete equipment which can be used/adapted for MEMS fabrication. By doing this it is possible to reduce start-up costs for new companies and, by the same means, it is possible for universities and government laboratories to obtain equipment at reduced cost.

4.3.2. Identification of Important Features for Commercialization

Why did DLPs evolve into a successful commercial product, while other MEMS/NEMS applications were not able to reach the commercial world? What are the key factors that differentiate the DLP commercialization journey from so many other products that were not capable of reaching commercial markets? Using the DLP commercialization process as a case study, it is possible to identify some of the specific elements mentioned in the previous chapter that contributed greatly to the DLP success (Figure 4-6).

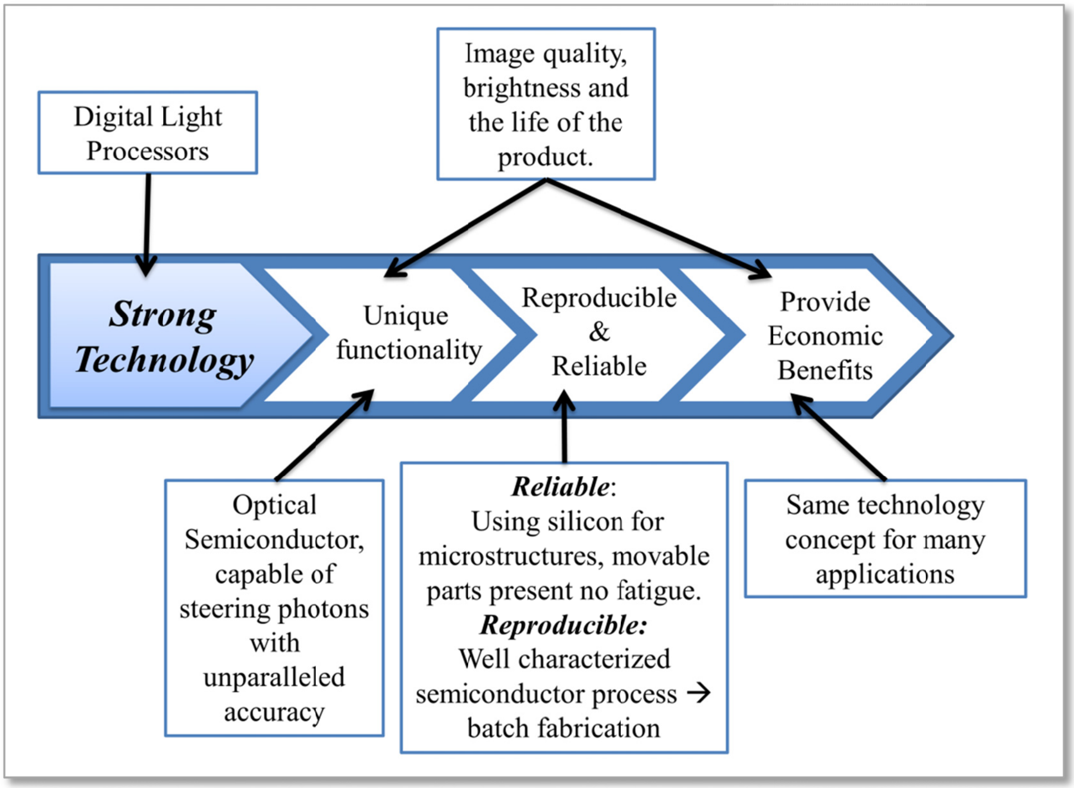


Figure 4-6: DLP key aspects to become a successful MEMS product

The success of Texas Instruments' DLP was not instantaneous. After Dr. Hornbeck developed the *Digital Mirror Device* [44], Texas Instruments decided to form the *Digital Imaging Venture Project* in order to explore the commercial viability of this new technology. The technology was named "Digital Light Processing" and a division was established to unlock the potential for commercial projection display applications. Immediately after that, prototypes of projectors using this technology were created, and from there, a number of important milestones were reached [108]. A solid infrastructure that supported the various stages of the commercialization process was developed. Not all companies will have the resources to build such an infrastructure around a product in a very early stage, but if a tool could be developed to evaluate ideas and designs from this perspective, it could mean the difference between success and failure for some applications.

4.3.3. Consolidate and Standardize Unit Processes

One way to mitigate several of the technological challenges presented in Section 4.2.1 is by standardizing unit processes as much as possible and using them as building blocks. Currently, custom processes represent almost the entirety of the commercial MEMS fabrication processes. Throughout the commercialization journey for microsystems-based products, a lot of money and time are used simply in developing and tuning manufacturing processes. Often the ability to mass produce MEMS/NEMS is presented as a great advantage. This is partially true, as very little quantities of raw materials are needed in order to fabricate hundreds, or even thousands or millions of devices. However, getting to the point where a manufacturing process is well-enough understood, characterized, and controlled in order to have a good production yield is not a trivial matter. In many industries, standardization has improved technology development and promoted better economic benefits for companies involved and the economy as a whole [113], [114]. But while the importance of standardized processes for MEMS has been identified [86], [90], [115], [116] little progress has been made in towards this goal [30]. In order to accelerate the process of standardizing existing and new processes, it is important to develop MEMS-specific methodologies and techniques to manage processes [117].

4.3.4. Dissemination of Information and Knowledge

Significant efforts have been made towards providing guidance and assistance to the MEMS/NEMS community to identify potential areas of opportunity [28], [30], [45], [78], [101], [105]. Nevertheless there is still a lot of misconception and lack of understanding within many industrial sectors of the potential that MEMS/NEMS have in providing solutions and improvements. The positive impacts to society from sharing information and knowledge are obvious. A clear example of that is what Petersen achieved with his publication of "Silicon as a Mechanical Material" [45]. Many consider this work to be the beginning of the *MEMS Era* [118]. Another good example of knowledge dissemination is by the Institute of Electrical and Electronics Engineers, edited by Trimmer [78]. One of the most relevant works about commercializing MEMS/NEMS is the work done by Walsh et al. [28], where more than 450 contributors made possible the compilation and organization of MEMS related information. There is a great opportunity to keep working on capturing information and knowledge, to analyse and synthesize research literature and to inform industry how to apply MEMS/NEMS based technologies to their problems. However, there needs to be a more concerted effort to compile and translate the highly technical contributions that arise from academic and industrial research labs to a form that can be more readily categorized and digested by commercial entities that may seek to develop new products.

4.4. Goals and Motivation

As direct result of the analysis we performed about the current status of the MEMS/NEMS industry and by understanding the challenges and opportunities that exist in this industry, we realized there is significant room for improvement in how the MEMS/NEMS products are being developed presently.

The primary contribution or our research is to provide a greater understanding and insights into MEMS/NEMS commercialization process, as well as to present alternatives to the conventional methods and tools that are being used for this endeavour. Our research work also aims to reduce the time and effort required during the MEMS/NEMS development cycle.

In order to achieve these goals, we are proposing a system capable of increasing efficiency and effectiveness in the idea-to-market process from MEMS/NEMS base products, by assisting the process flow creation in a more automated manner (labelled as *Automatic System* in Figure 4-4). The conceptual design of this system and the implementation of some of its modules are discussed in the remaining of this thesis.

CHAPTER 5.
SYSTEM FOR RESEARCH, KNOWLEDGE, AND TECHNOLOGY MANAGEMENT

We propose a software system to provide help to MEMS researchers and designers during the research, product development, and manufacturing stages (Figure 5-1).

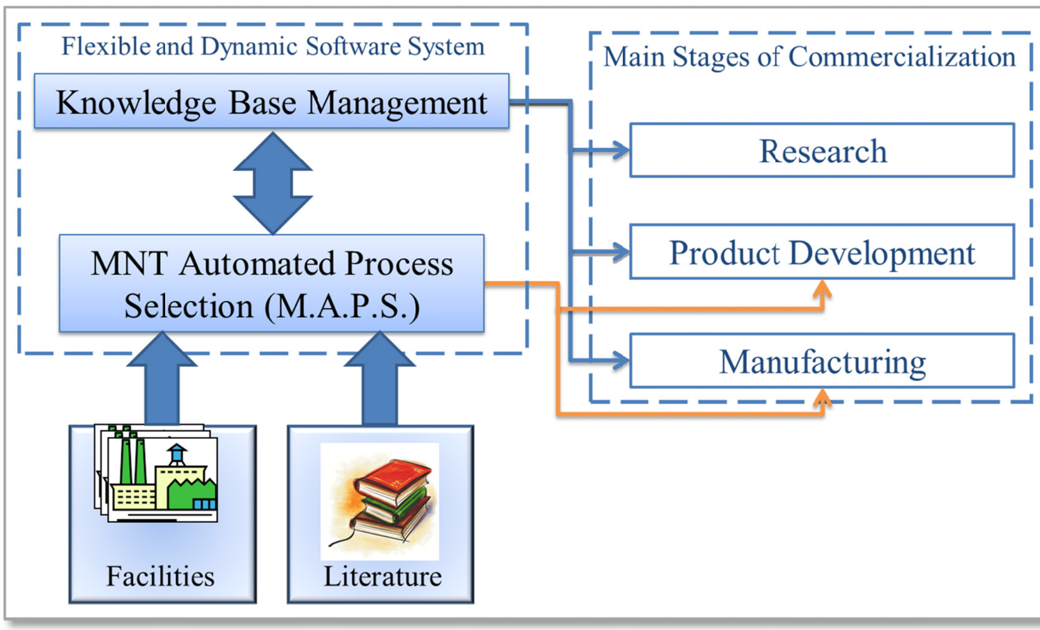


Figure 5-1: Support system for the MEMS commercialization process

This system will ultimately be implemented in a software tool that will help a researcher (or anyone else seeking to take a MEMS/NEMS device through development to commercialization) to select the specific equipment and manufacturing facilities that will best complete the various fabrication steps to prototype and manufacture MEMS. The two main components of this system are the *Knowledge Base Management* (KBM) module and the *MNT Automated Process Selection* (MAPS) module.

5.1. Knowledge Base Management (KBM) Module

The KBM module is meant to capture and improve the distribution and the use of the knowledge generated throughout all the steps of the commercialization process. It will capture tacit and explicit knowledge and use it to enrich three main dynamic databases:

- ***Processes Operating Parameters database*:** This database includes the minimum information required per process to be replicated successfully.
- ***Processes Available database:*** This is a collection of processes available in all catalogued facilities, divided into three main categories:
    - Proven processes
    - Theoretical processes
    - New processes
- ***Facilities database:*** This database compiles all data on known facilities, including specific equipment and the processes they are capable of carrying out (and any relevant parameters that might be specific to the equipment or facility).

These databases are used by the MAPS module, which processes the information in order to generate an optimal manufacturing path. If it is not possible to generate a complete manufacturing path, the portions of it that were successfully created will be provided and possible alternatives for the unsatisfied process steps will be suggested to the user for consideration. Based on the exploratory/descriptive research we have done in the first part of this work, it was possible to enrich the initial design proposed by Nakashima-Paniagua et al. [119] and to include specific features in the system. A diagram with the conceptual functionality of the improved system is presented in Figure 5-2.

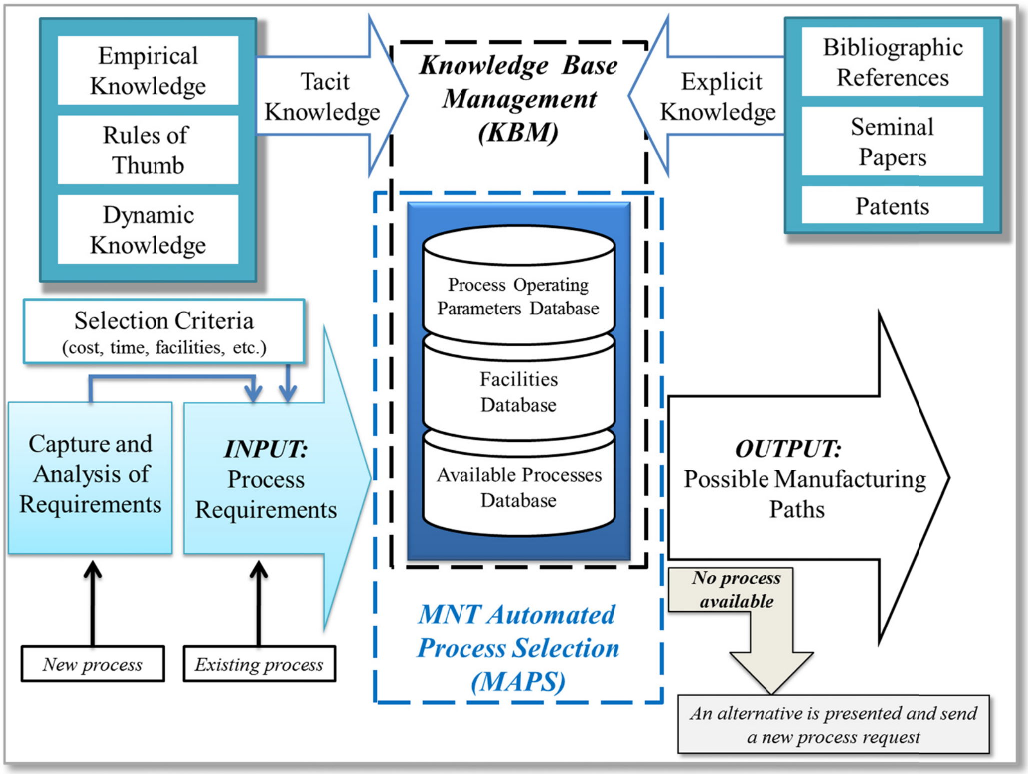


Figure 5-2: KBM and MAPS interaction

Successes and failures could happen at any step of the commercialization journey, meaning that relevant knowledge can be generated at any time. Hence, the KBM should be able to capture knowledge in every step of the MAPS process. In order to facilitate this and to collect data as widely as possible, we would ideally provide remote access to users and facilities, who would be encouraged to add to the various databases as appropriate.

The following steps explain how the KBM will capture and organized knowledge:

Step 1. Log into the system using a remote computer (or a mobile device).

Step 2. Categorize new knowledge based on the stage of the commercialization process (i.e., research, product development, or manufacturing) where it was generated.

Step 3. Categorize the knowledge based on the specific steps of the commercialization process.

Step 4. Generate links to these references from specific parts of the fabrication process.

Step 5. Update the pertinent databases.

There are many collections and sources we can go to in order to obtain an enormous quantity of explicit knowledge (e.g., library systems, electronic journals, patent offices, etc.). However, many of these sources are not concise and, even with sophisticated techniques, a lot of time is required to peruse and compile data and distil it into useable knowledge. Another feature is that users will be encouraged to provide learning and knowledge generated as a result of unsuccessful attempts at new MEMS/NEMS processes or new recipes to adapt existing processes for new applications. This is especially important, as this information is not commonly published in academic literature. At the same time, the system provides a means to map resource usage and identify traits of potential success for a specific project based on the use of existing infrastructure and known methods. This is particularly important for funding organizations where decisions are often made by committees in light of limited information about feasibility of the technological implementation. In an ideal scenario, the people with decision-making power will know nearly as much as the technical experts (or at least have that knowledge available in an easily accessible format) [120].

Major delays can arise in the production process if a specific instrument or machinery required by the manufacturing process is missing or out of service. Having that information updated in real time within the proposed system can be extremely useful. In order to do this, it is particularly important to encourage as many facilities as possible to provide reliable information.

During the conception phase of this system, we were able to find various commercial tools, as well as open source tools, which can be adapted to provide the functionality to capture and manage knowledge (e.g., [121]–[124]). Because of this reason we decided to focus our prescriptive research to develop and implement the MAPS module.

5.2. MNT Automated Process Selection (MAPS) Module

By using the *System Development Life Cycle* methodology [125], [126], [98] and based on the conceptual functionality required, we developed our automatic information system, MAPS, to perform as a virtual broker to support the MEMS development process. Four main modules are the core of our system: *Manufacturing Path Selection Module*, *Scheduling Module*, *Process Proposal Module* and *Process Request Module*. Figure 5-3 presents a flow diagram with the various modules that constitute the MAPS system and their interaction in the process of generating manufacturing process flows.

This system is not meant to be used to validate the physical design of a device; rather it will provide a means to assist MEMS researchers and designers to identify facilities, generate potential manufacturing paths for the proposed process flow, and get a better idea of the manufacturability of a MEMS device or component in nearly real time. The MAPS software system acts as a virtual broker to make efficient use of the existing fabrication equipment and facilities for MEMS prototyping and fabrication. It allows MEMS practitioners to perform a check for availability of fabrication facilities.

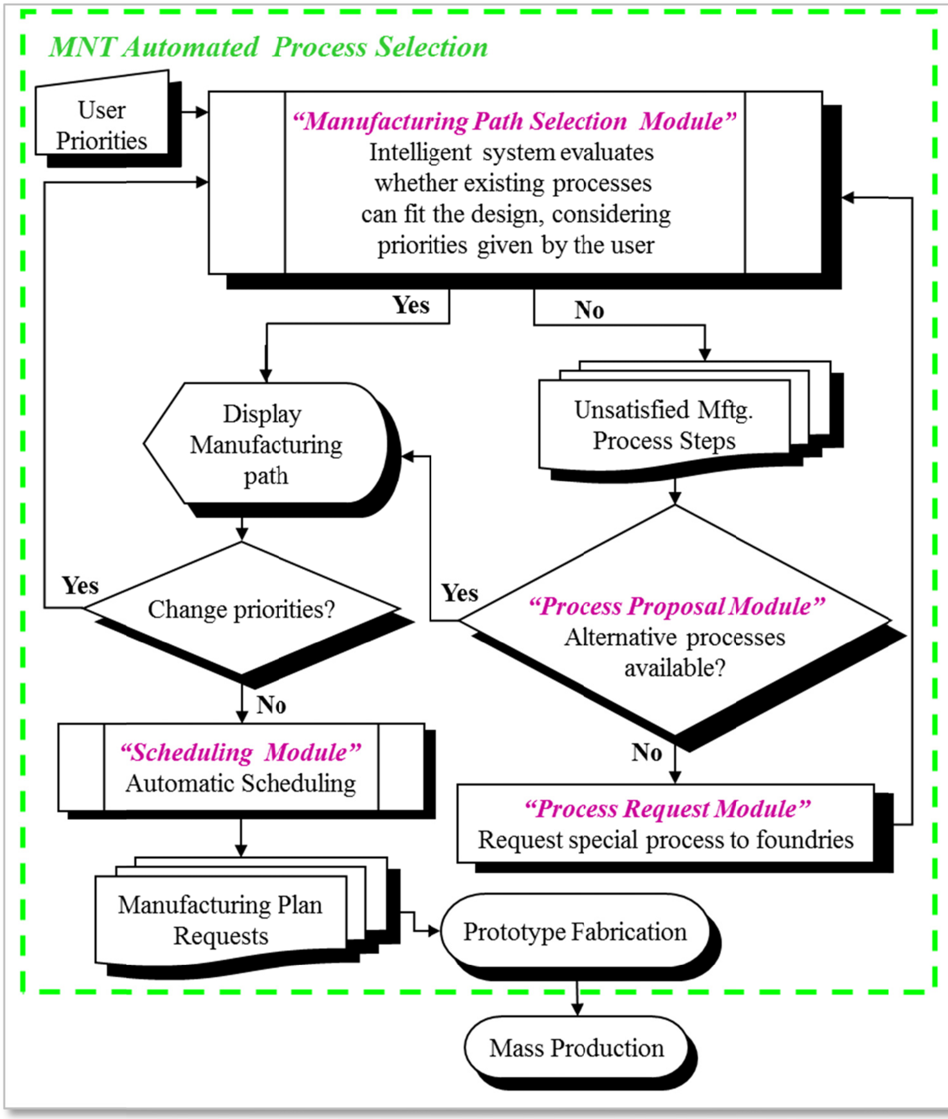


Figure 5-3: MNT Automated Process Selection

The procedure in the MAPS module for generating the optimal manufacturing path is as follows:

Step 1. Understand the requirements of the process flow that will be analysed, going from the generic to the specific (i.e., a top down approach). Validated processes will be presented as options, guiding the user with tips and comments from the databases.

Step 2. Select the required processes from a list generated using the existing processes in the database. If there is no process in the data base that matches a required process step required by the user, a "new process request" starts.

Step 3. Indicate the priorities to generate the selection path (e.g., processing costs, processing time, number of facilities, etc.).

Step 4. Once the information is captured, it is analysed and options are evaluated based on the priorities the user defined in the previous step.

Step 5. Generate and optimize the manufacturing path selected (e.g., via fuzzy inference techniques).

Step 6. Detect process steps that were not found or satisfied completely.

Step 7. Generate a process request for the relevant facilities to verify viability.

Step 8. If a reply is received from facilities, this information is introduced in the Process Available database and the user is notified.

In the following sections the modules and sub-modules of the MAPS system are discussed in more detail.

5.2.1. Manufacturing Path Selection Module

The Manufacturing Path Selection Module analyses a process flow in combination with a priority list given by the user to identify available facilities able to perform the required process steps. The flow diagram that illustrates the functionality of this module is presented in Figure 5-4.

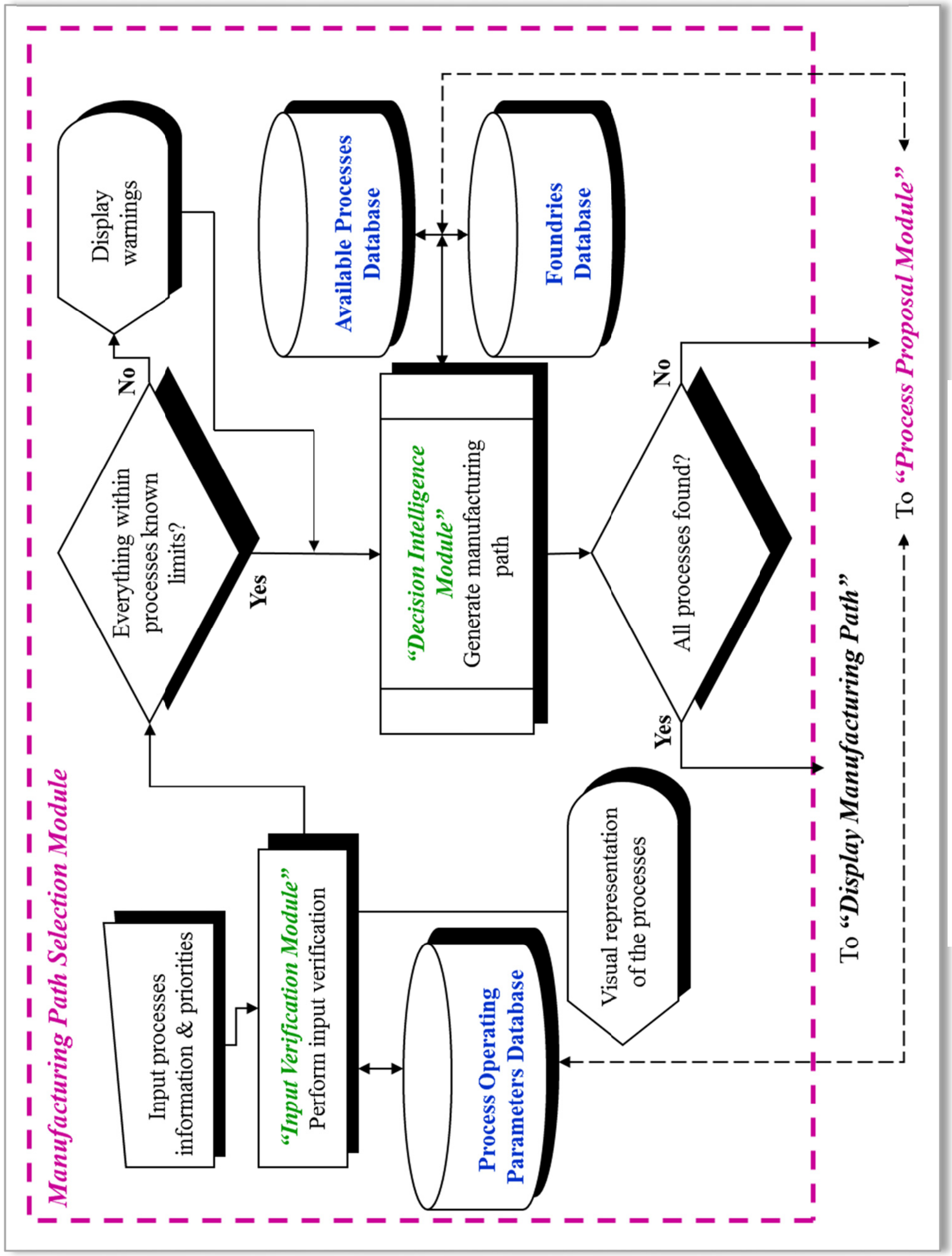


Figure 5-4: Manufacturing Selection Module

The Manufacturing Path Selection module performs the following main task:

- A verification of the user's priorities to assemble the process flow. Different users may have different needs regarding the most important considerations they would like to use as base for their fabrication process steps selection. This initial verification prepares that all subsequent verifications to use the proper metrics for the ranking multiple possible options.
- Evaluation and matching of various existing processes compatible with the processes required. Once the verifications are performed, the options for fabrications process are evaluated and a process flow is generated including all the available process steps found. If there are some process steps that were not found within the system a list is generated with these.

Two main sub-modules, the *Input Verification Module* and the *Decision Intelligence Module*, interact with three dynamic databases: *Processes Operating Parameters*, *Processes Available*, and *Foundries*. The initial content of the databases should consist of explicit knowledge from several references, as well as information gathered directly from researchers working with microfabrication. As starting point, it makes sense to include information from local fabrication facilities. For our case, these would be the *University of Alberta's Nanofabrication facility* (NanoFab), the *Alberta Centre for Advance MNT Products* (ACAMP), and the *National Research Council Canada-National Institute for Nanotechnology* (NRC-NINT).

5.2.1.1. Input Verification Module

In order to clearly understand the actual process flow it is required to validate the input provided by the user. Validating semantically and syntactically process flow structures could be a daunting task as there exist many possible ways to represent a single process flow; there could be many ambiguities, lack of clarity and discrepancies in a process definition. In this thesis, we propose a formal language to describe process flows (see CHAPTER 6). The *Input Verification Module* (Figure 5-5) analyses the structure of the process flow and validates the sequence of steps that represents the process flow. If in the process flow being examined there is a critical or fatal error, which may cause human harm (e.g., combining chemicals that may result as an explosion hazard) or damage the equipment, an error code is generated, the user is informed and the system tries to find a process that could potentially replace the process step with the critical error. If there are no available replacement processes the system interrupts the execution and informs the user. If non-critical errors are found, warnings are display for the user and a confirmation to continue is requested. If no errors are found, or non-critical errors are acceptable, a visual representation of the process is generated and the validated process flow is sent to the next module for further processing.

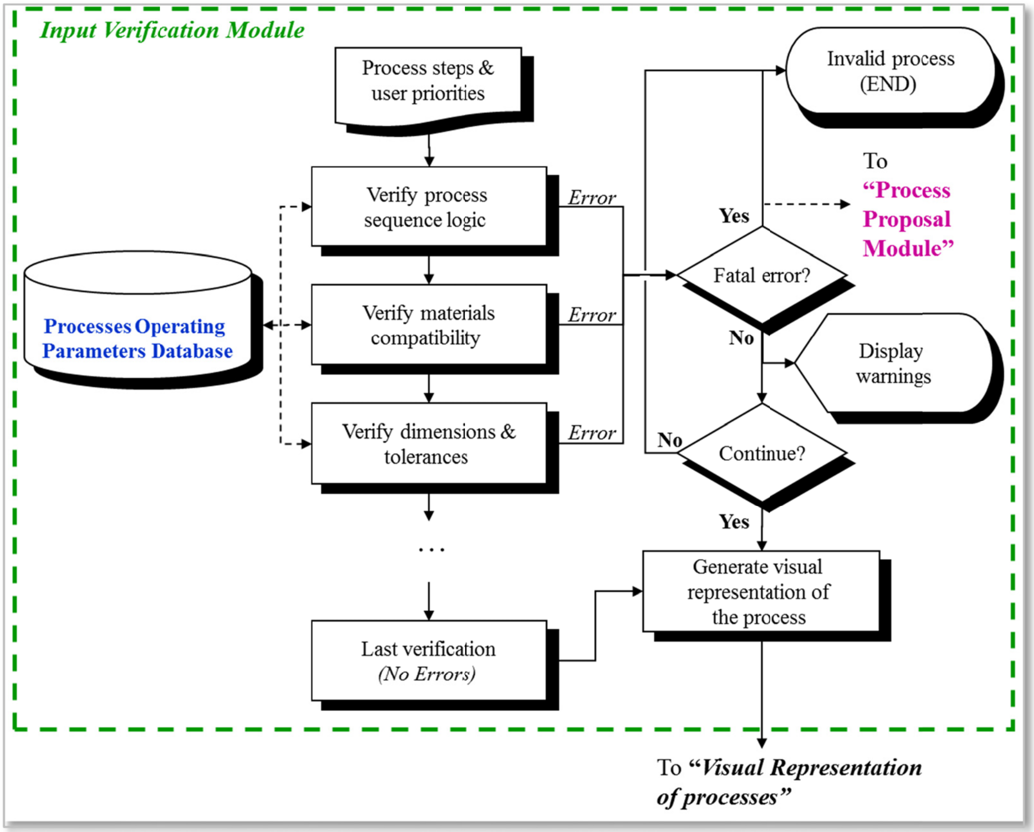


Figure 5-5: Input Verification Module

5.2.1.2. Decision Intelligence Module

Once the process flow has been validated at the semantic and syntactic level, the process flow is sent to the *Decision Intelligence Module*. This module assists the decision-making process of selecting the most suitable process according to the users' preferences. A quick verification is performed to verify what processes are known and available. If multiple viable process steps are found, these will be ranked by using a fuzzy inference system (FIS) based on the priorities and user's preferences. Once the alternatives are ranked, these are presented to the user in order. The user selects the best process flow from the options finalizing the process flow, which is then passed to the Scheduling Module.

If there are some process steps that are not found within the databases of the system, the Process Proposal Module compares the requirements for those processes not found with similar existing processes and tries to find a substitute process able to generate the same outcome. If there are no similar processes capable to generate a similar outcome, then the Process Request Module sends out a request to various facilities with the missing process steps in order to verify if any of the facilities in the system is able to provide the service for those process steps that were not found or to provide a potential alternative. If a positive reply is received from any of the facilities, the databases are updated and this new option is included in a new process flow that is presented to the user.

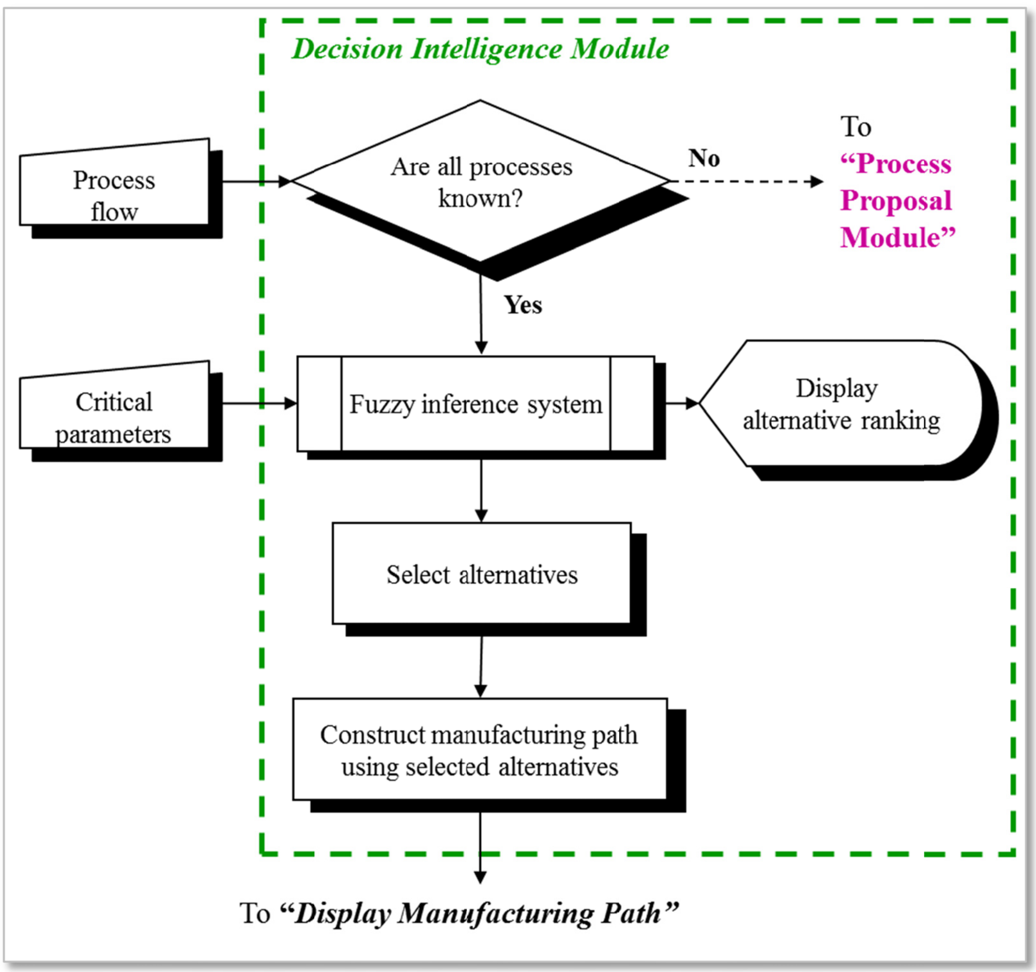


Figure 5-6: Decision Intelligence Module

5.3. Scheduling Module

The Scheduling module is in charge of verifying availability of the required equipment within the selected facilities. Once the final process flow has been examined and created, the Scheduling module sends a request to the foundries that were found to be the most appropriate for the various process steps, in order to book fabrication time. Figure 5-7 shows the block diagram of the process and the interaction with the Foundries Database.

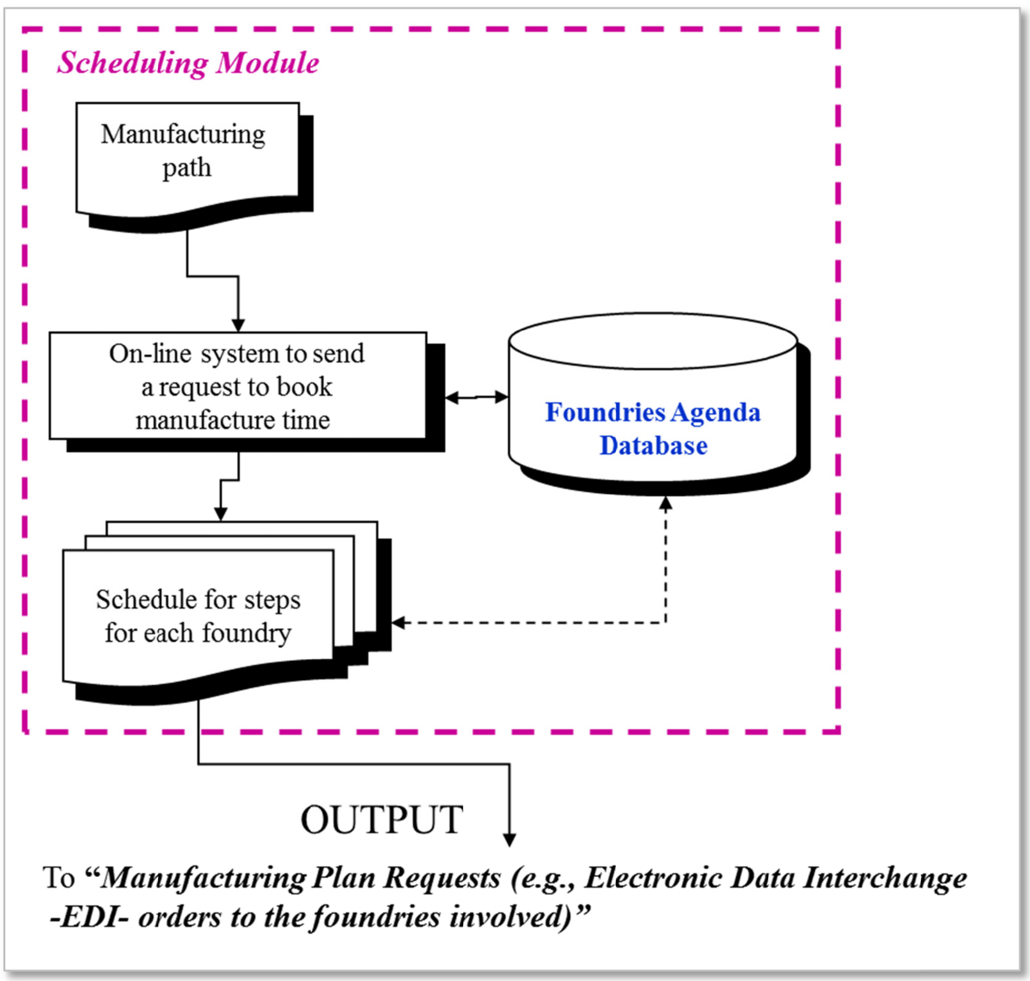


Figure 5-7: Scheduling Module

One of the main challenges for the implementation of this module is the fact that not all the fabrication facilities have automated scheduling systems for their manufacturing equipment. Furthermore, many of those fabrication facilities that have an information system do not allow for direct scheduling of their facilities or equipment. Furthermore, delays may occur in previous steps in different facilities, potentially impacting the schedule of all subsequent steps in other facilities.

5.4. Process Proposal Module

The Process Proposal Module takes as an input a list of manufacturing process steps that were not found exactly as originally described in the user's process flow and process steps that the system identified as potential critical errors (e.g., that may cause human harm or damage the equipment). Each of this process steps is analysed and, based on the desired outcome of the process, a potential alternative is presented (Figure 5-8). This module is the most knowledge intensive module in the system, hence one of the most difficult to implement.

In order for this module to be reliable, a critical mass of expert knowledge should be included and used. Full doctoral dissertations are about characterizing and understanding a single process parameter of a process step and new methods and processes are being discovered on a regular basis. In order to assist the process of capturing this expert knowledge, the system used in the module of Decision Intelligence (Section 5.2.1.2) can be used to perform comparisons among existing similar processes. The full functionality of the core of this module (i.e., the fuzzy inference system), is presented in CHAPTER 7.

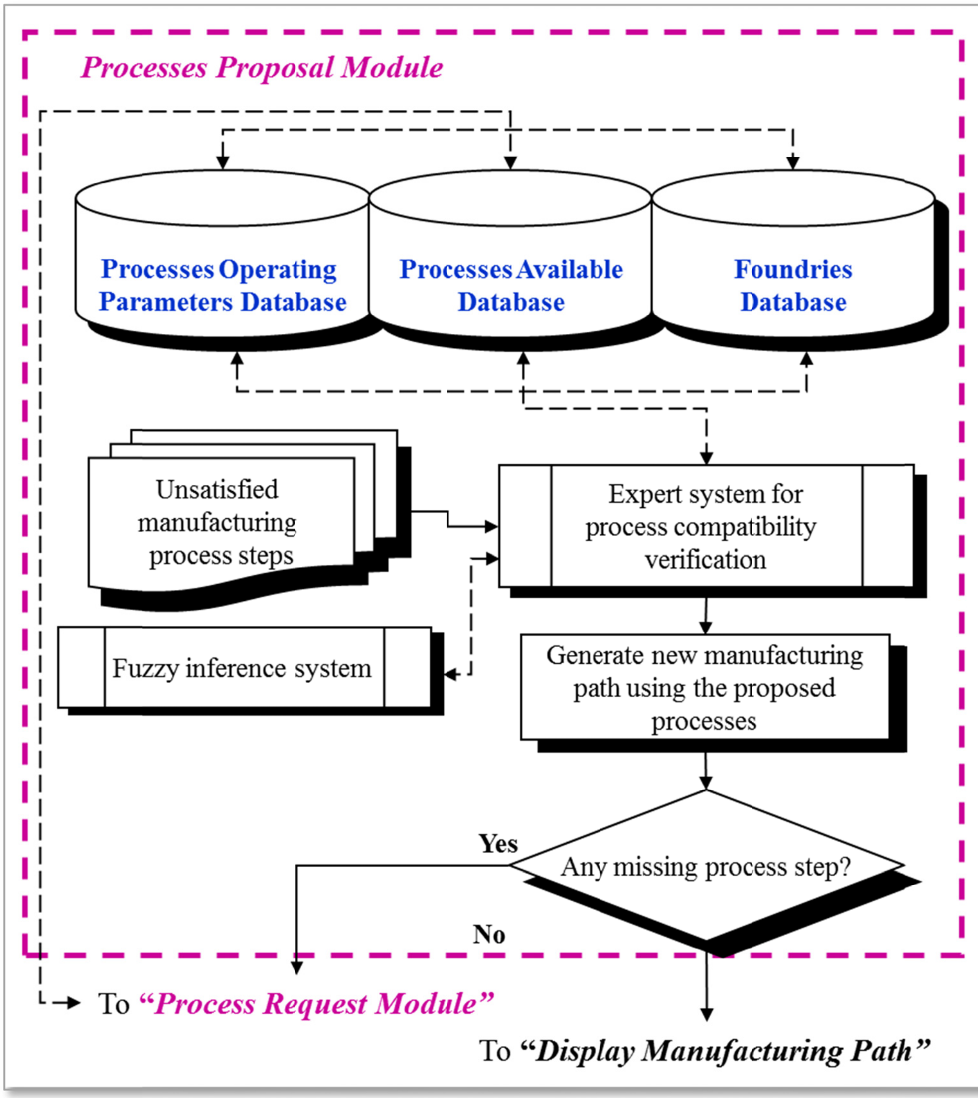


Figure 5-8: Process Proposal Module

5.5. Process Request Module

If after the analysis for the process flow it was not possible to find the exact process step or any potential process step replacement, the Process Request Module sends out a broadcast message to the foundries in the system. These messages includes the process step information and the desired outcome with the hope that some of the fabrication facilities can provide a solution to fully execute the process needed or to provide an alternative to replace this process step. If this is possible the Process Available and

Foundries databases are updated, making that specific process available for further verifications (Figure 5-9).

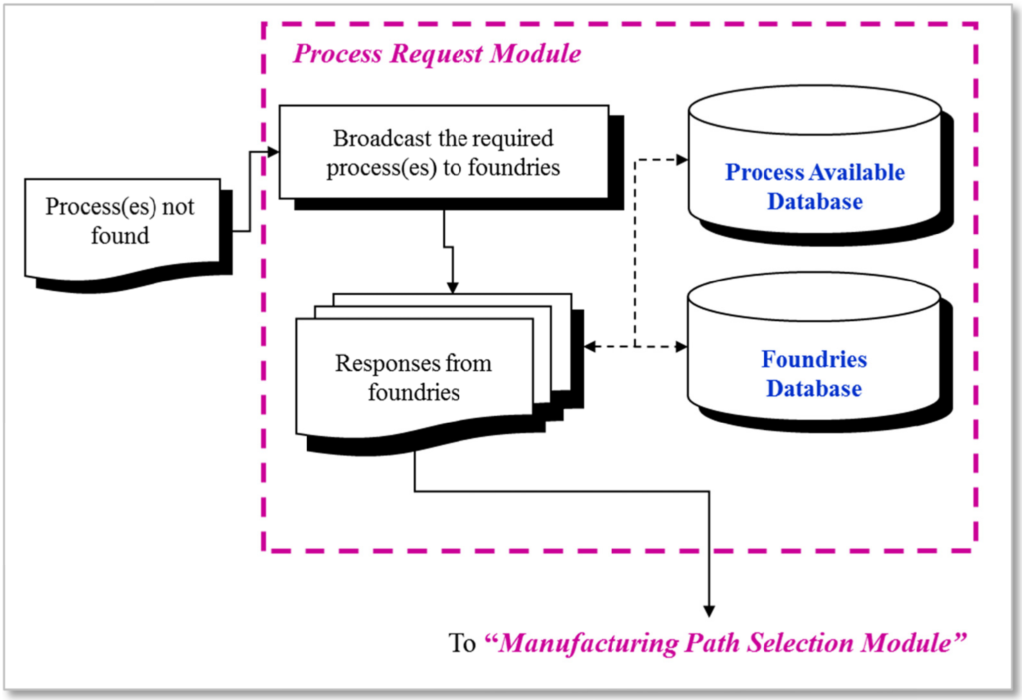


Figure 5-9: Process Request Module

5.6. Case Study

As an initial case study, the basic fabrication process flow of a basic piezoresitive pressure sensor (Figure 5-10) is used to exemplify the system functionality. We manually analysed the fabrication process flow to understand validate our methodology of our proposed information system. The equipment included for this initial case is equipment available at the NanoFab facility (open facility) and at Dr. Walied Moussa's laboratory (private facility), both from the University of Alberta.

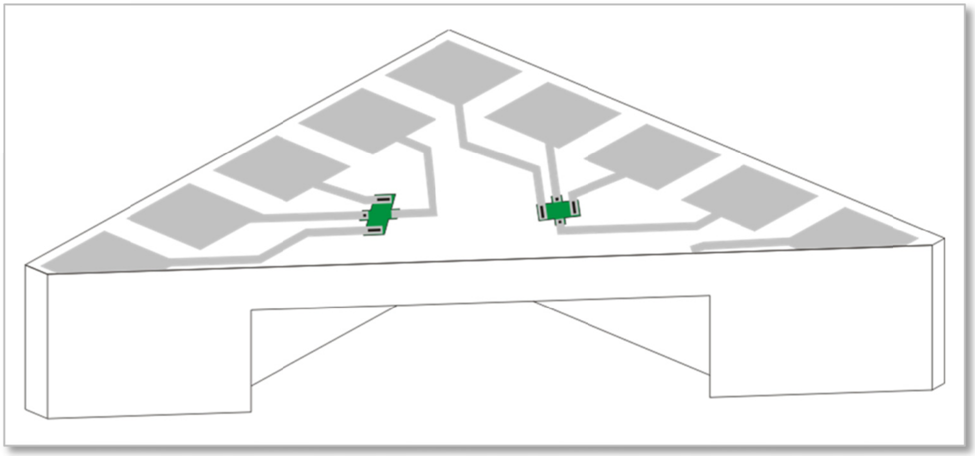


Figure 5-10: Pressure Sensor [Courtesy of Dr. David Benfield]

The process flow we are using as an initial case for manufacturing the piezoresistive pressure sensor includes these fabrication steps:

1. Standard wafer cleaning
2. Thermal Oxide growth
3. Lithography using mask #1, (to trace doping portals)
4. Reactive Ion Etching (RIE) (to open doping portals)
5. Thermal Boron Diffusion
6. Re-grow Oxide Layer
7. Lithography using mask #2, (to trace electric contacts)
8. Reactive Ion Etching (RIE) (to open the electric contact portals)
9. Aluminum Sputtering
10. Lithography using mask #3, (to pattern electric contacts)
11. Wet Etch to pattern metal contacts
12. Wafer cleaning
13. Wafer's backside Thermal Oxide Growth
14. Lithography using mask #4, (for backside silicon etching)
15. Backside silicon Etch
16. Final Cleaning.

We performed the analysis on this process flow to identify what process steps could be performed using the infrastructure available (i.e., facilities and equipment). At the same time, we wanted to estimate the total fabrication time and cost for the full process.

We manually emulated the system and processed the sixteen steps mentioned above. This is a summary of important information that was obtained after processing the input process flow:

- ✓ In order to perform these 16 fabrication steps, 36 sub-processes are needed.
- ✓ 5 comments from previous users and 3 system warnings were considered to generate the necessary sub-processes.
- ✓ From those 36 sub-processes, 34 can be performed in the NanoFab facilities at the University of Alberta and the remaining 2 need to be performed in Dr. Walied Moussa's Lab.
- ✓ **Total billable hours for equipment used: 57 hrs**
- ✓ **Total Cost $943.00**

The full details on how the input for this pressure sensor (i.e., process flow) was processed are presented in the next paragraphs.

User INPUT >>
Material required:
  4 inch, (100) ***n-type*** silicon substrate.
  Double side polish.
  Primary flat along <110>.
  Thickness 500 μm ± 25μm.
  Total thickness variation < 1μm.
  Bulk resistivity 10 Ω·cm.

System processing>>
The system will send this information to the "Input Verification Module" and will check a list of suppliers that can provide the material required. This information will be stored for later processing in the "Artificial Intelligence Module".

User INPUT (Fabrication process, step 1)>>
Standard wafer cleaning.

System suggestion for process (from a previous successful process)>>

Piranha cleaning for 15 minutes *(U of A, Nanofab facilities, Wet Process – WD Aisle 2, Academic rate: $33/hr).*

Dump and rinse 5 times *(U of A, Nanofab facilities, Wet Process – WD Aisle 2, Academic rate: $33/hr).*

System suggestion for sub-process (from a user comment):

"In order to have more uniform oxide growth, clean any possible oxide in the surface by a short – 2 min- BOE".

Buffered Oxide Etch (BOE) for 2 minutes *(U of A, Nanofab facilities, Wet Process – DD Aisle 1 or 2, Academic rate: $33/hr).*

Spin-Rinse-Dry *(U of A, Nanofab facilities, Spin Rinse Drier, Wet Aisle #2).*

User INPUT (Fabrication process, step 2)>>
Thermal Oxide growth: 1200 nm

System processing>>

If the thickness is the same of one in a process already in the knowledge base, this process is suggested to the user. If the thickness is different than the ones in the knowledge base, the user can stipulate the time and temperature to be used or the user can ask the system to calculate these parameters.

System suggestion for process (from a previous successful process)>>

Wet thermal oxidation, 8 hours at 1000 °C, Wet N_2 atmosphere *(U of A, Nanofab facilities, Minibrute Top/Middle furnace, Academic rate: $10/hr)*

User INPUT (Fabrication process, step 3)>>
Lithography using mask #1, -for doping portals-

System suggestion for process (from a previous successful process)>>

System suggestion for sub-process (from a user comment):

"To ensure a good adhesion of the photo resist in the silicon oxide it is necessary to use adhesion promoter. If the photo resist will be place on top of a metal layer no promoter is needed".

Add photo resist adhesion promoter, hexamethyldisilazane (HMSD), 15-20 min *(U of A, Nanofab facilities, YES HMDS oven, Academic rate: $15/hr).*

Rehydrate (cool down) for 10-15 min.

System suggestion for sub-process (from previous successful process):
"First Spread at 400 rpm for 10 seconds, and then spin 4000 rpm for 40 seconds. Thickness of the photo resist 1.3 μm".

Spin on photo resist *(U of A, Nanofab facilities, Solitec Spinner, Academic rate: $25/hr).*

System suggestion for sub-process (from previous successful process):
"Use the Solitec hotplate contact for soft-bake, 90 seconds at 115 °C".

Pre-bake photo resist *(U of A, Nanofab facilities, Solitec Spinner –hotplate, Academic rate: $25/hr).*

Rehydrate (cool down) for 10-15 min.

System suggestion for sub-process (from previous successful process):
"Expose for 3 seconds".

Align mask for UV exposure *(U of A, Nanofab facilities, Oscar Mask Aligner #1, Academic rate: $33/hr).*

System suggestion for sub-process (from previous successful process):
"Use 354 developer for 20-25 seconds".

Develop photo resist *(U of A, Nanofab facilities, Oscar Mask Aligner #1, Academic rate: $33/hr).*

Spin Rinse and Dry *(U of A, Nanofab facilities, Spin Rinse Drier, Wet aisle #1 or #2).*

User INPUT (Fabrication process, step 4)>>
Reactive ion etching (RIE) to open the doping portals

System suggestion for process
(from a previous successful process)>>
RIE using OxiTest recipe, 6:45 minutes *(U of A, Nanofab facilities, Reactive Ion Etching STS, Academic rate: $15/hr)*

System suggestion for ALTERNATIVE process >>
Buffered Oxide Etch (BOE) can be used for this step (U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck, Academic rate: $33/hr).

User INPUT (Fabrication process, step 5)>>
Thermal Boron Diffusion

System "Input Verification Module" WARNING for process flow>>
"Before the thermal diffusion, it is necessary to strip off the photo resist from the wafer".

> Place wafer in Acetone for 30 minutes *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck, Academic rate: $20/hr).*
>
> IPA Rinse *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*
>
> Dump and rinse 5 times *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*
>
> Spin-Rinse-Dry *(U of A, Nanofab facilities, Spin Rinse Drier, Wet aisle #1 or #2).*

System suggestion for process
(from a previous successful process)>>

System suggestion for sub-process (from a user comment):
"The use of solid Boron source, instead of gas/liquid dopant sources, it is simpler and safer to work with".

Pre-deposition, using solid Boron source *(U of A, Dr. Moussa's lab, FURNANCE).*

Doping drive-in, 15 min at 1100 °C *(U of A, Dr. Moussa's lab, FURNANCE).*

User INPUT (Fabrication process, step 6)>>
Re-grow Oxide Layer

System suggestion for process
(from a previous successful process)>>

System "Input Verification Module" WARNING for process flow>>
"To ensure uniformity and good patterning when re-growing the next oxide layer it is a advisable to remove the previous oxide mask and clean the wafer".

RIE using OxiTest recipe, 6:45 minutes is enough to remove all the remaining oxide layer *(U of A, Nanofab facilities, Reactive Ion Etching STS).*
[System suggestion for ALTERNATIVE process >>]
Buffered Oxide Etch (BOE) can be used for this step (U of A, Nanofab facilities, Wet Processing - Aisle 1 wet deck).

Place wafer in Acetone for 30 minutes *(U of A, Nanofab facilities, Wet Processing - Aisle 1 wet deck).*

IPA Rinse *(U of A, Nanofab facilities, Wet Processing - Aisle 1 wet deck).*

Dump and rinse 5 times *(U of A, Nanofab facilities, Wet Processing - Aisle 1 wet deck).*

Spin-Rinse-Dry *(U of A, Nanofab facilities, Spin Rinse Drier, Wet aisle #1 or #2).*

System suggestion for process (from a previous successful process)>>

Wet thermal oxidation, 8 hours at 1000 °C, Wet N_2 atmosphere *(U of A, Nanofab facilities, Minibrute Top/Middle furnace)*

User INPUT (Fabrication process, step 7)>>
Lithography using mask #2, -for contacts-

System suggestion for process (from a previous successful process)>>

System suggestion for sub-process (from a user comment):
"To ensure a good adhesion of the photo resist in the silicon oxide it is necessary to use adhesion promoter. If the photo resist will be place on top of a metal layer no promoter is needed".

Add photo resist adhesion promoter, hexamethyldisilazane (HMSD), 15-20 min *(U of A, Nanofab facilities, YES HMDS oven).*

Rehydrate for 10-15 min *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

System suggestion for sub-process (from previous successful process):
"First Spread at 400 rpm for 10 seconds, and then spin 4000 rpm for 40 seconds. Thickness of the photo resist 1.3 µm".

Spin on photo resist *(U of A, Nanofab facilities, Solitec Spinner)*

System suggestion for sub-process (from previous successful process):
"Use the Solitec hotplate contact for soft-bake, 90 seconds at 115 °C".

Pre-bake photo resist *(U of A, Nanofab facilities, Solitec Spinner –hotplate).*

Rehydrate for 10-15 min *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

System suggestion for sub-process (from previous successful process):
"Expose for 3 seconds".

Align mask for UV exposure *(U of A, Nanofab facilities, Oscar Mask Aligner #1).*

System suggestion for sub-process (from previous successful process):
"Use 354 developer for 20-25 seconds".

Develop photo resist *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck)*
Spin Rinse and Dry *(U of A, Nanofab facilities, Spin Rinse Drier, Wet aisle #1 or #2)*

User INPUT (Fabrication process, step 8)>>
Reactive Ion Etching to open the contact portals

System suggestion for process (from a previous successful process)>>
RIE using OxiTest recipe, 6:45 minutes is enough to remove all the remaining oxide layer *(U of A, Nanofab facilities, Reactive Ion Etching STS).*
[System suggestion for ALTERNATIVE process] >>
Buffered Oxide Etch (BOE) can be used for this step (U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).

User INPUT (Fabrication process, step 9)>>
Aluminum Sputtering

System "Input Verification Module" WARNING for process flow>>
"Before the sputtering it is necessary to strip off the photo resist from the wafer".

Place wafer in Acetone for 30 minutes *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

IPA Rinse *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

Dump and rinse 5 times *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

Spin-Rinse-Dry *(U of A, Nanofab facilities, Spin Rinse Drier, Wet aisle #1 or #2).*

System suggestion for sub-process
(from previous successful process):
–Aluminum thickness 500nm– *"700 V DC, 20 sccm Argon, 3 e -3 Torr".*

RF biasing 10 minutes *(U of A, Nanofab facilities, Sputtering System #1 (Bob), Academic rate: $15/hr).*

System suggestion for sub-process
(from previous successful process:
*"300 W, 20 sccm Argon, 3 e -3 Torr"***)**
Sputter Aluminum for 30 minutes *(U of A, Nanofab facilities, Sputtering System #1 (Bob), Academic rate: $15/hr)*

User INPUT (Fabrication process, step 10)>>
Lithography using mask #3, -for contacts-

System suggestion for process
(from a previous successful process)>>
System suggestion for sub-process
(from previous successful process):
"First Spread at 400 rpm for 10 seconds, and then spin 4000 rpm for 40 seconds. Thickness of the photo resist 1.3 µm".

Spin on photo resist *(U of A, Nanofab facilities, Solitec Spinner).*

System suggestion for sub-process
(from previous successful process):
*"Use the Solitec hotplate contact for soft-bake, 90 seconds at 115 °C"***)**.

Pre-bake photo resist *(U of A, Nanofab facilities, Solitec Spinner –hotplate).*

Rehydrate for 10-15 min *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

System suggestion for sub-process (from previous successful process):
"Expose for 3 seconds"

Align mask for UV exposure *(U of A, Nanofab facilities, Oscar Mask Aligner #1).*

System suggestion for sub-process (from previous successful process):
"Use 354 developer for 20-25 seconds"

Develop photo resist *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

Spin Rinse and Dry *(U of A, Nanofab facilities, Spin Rinse Drier, Wet aisle #1 or #2)*

User INPUT (Fabrication process, step 11)>>
Wet Etch to pattern metal contacts

System suggestion for process (from a previous successful process)>>
System suggestion for sub-process (from previous successful process):
Aluminum Etch to visible end point ~ 15 minutes *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

Dump and rinse 5 times *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

Place wafer in Acetone for 5 minutes *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

IPA Rinse *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

Dump and rinse 5 times *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

Spin-Rinse-Dry *(U of A, Nanofab facilities, Spin Rinse Drier, Wet aisle #1 or #2).*

User INPUT (Fabrication process, step 12)>>
Wafer cleaning

System suggestion for process
(from a previous successful process)>>

Place wafer in acetone for 30 min *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

IPA Rinse *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

Dump and rinse 5 times *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

Spin-Rinse-Dry *(U of A, Nanofab facilities, Spin Rinse Drier, Wet aisle #1 or #2)*

User INPUT (Fabrication process, step 13)>>
Wafer's backside Thermal Oxide Growth

System suggestion for process
(from a previous successful process)>>

Wet thermal oxidation, 8 hours at 1000 °C, Wet N_2 atmosphere *(U of A, Nanofab facilities, Minibrute Top/Middle furnace).*

User INPUT (Fabrication process, step 14)>>
Lithography using mask #4, -for backside silicon etching-

System suggestion for process
(from a previous successful process)>>

System suggestion for sub-process
(from a user comment):

"To ensure a good adhesion of the photo resist in the silicon oxide it is necessary

to use adhesion promoter. If the photo resist will be place on top of a metal layer no promoter is needed".

Add photo resist adhesion promoter, hexamethyldisilazane (HMSD), 15-20 min *(U of A, Nanofab facilities, YES HMDS oven).*

Rehydrate for 10-15 min *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

System suggestion for sub-process (from previous successful process:
"First Spread at 400 rpm for 10 seconds, and then spin 4000 rpm for 40 seconds. Thickness of the photo resist 1.3 μm".

Spin on photo resist *(U of A, Nanofab facilities, Solitec Spinner).*

System suggestion for sub-process (from previous successful process):
"Use the Solitec hotplate contact for soft-bake, 90 seconds at 115 °C".

Pre-bake photo resist *(U of A, Nanofab facilities, Solitec Spinner –hotplate)*.
Rehydrate for 10-15 min *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck)*

System suggestion for sub-process (from previous successful process):
"Expose for 3 seconds".

Align mask for UV exposure *(U of A, Nanofab facilities, Oscar Mask Aligner #1).*

System suggestion for sub-process (from previous successful process):
"Use 354 developer for 20-25 seconds".

Develop photo resist *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

Spin Rinse and Dry *(U of A, Nanofab facilities, Spin Rinse Drier, Wet aisle #1 or #2).*

User INPUT (Fabrication process, step 15)>>
Backside silicon Etch

System suggestion for process
(from a previous successful process)>>
Reactive Ion Etching using OxiTest recipe, 6:45 minutes, for the initial etching step *(U of A, Nanofab facilities, Reactive Ion Etching STS)*

System "Input Verification Module" WARNING for process flow>>
"Before the DRIE it is necessary to strip off the photo resist from the wafer"

Place wafer in Acetone for 30 minutes *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

IPA Rinse *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

Dump and rinse 5 times *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

Spin-Rinse-Dry *(U of A, Nanofab facilities, Spin Rinse Drier, Wet aisle #1 or #2).*

System suggestion for process
(from a previous successful process)>>
Deep Reactive Ion Etchin using Precision recipe, Chamber conditioning for ~20 cycles, Silicon etching ~80 cycles *(U of A, Nanofab facilities, STS ICP DRIE, Academic Rate $30/hr)*

User INPUT (Fabrication process, step 16)>>
Final Cleaning

System suggestion for process
(from a previous successful process)>>
Place wafer in Acetone for 30 minutes *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

IPA Rinse *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

Dump and rinse 5 times *(U of A, Nanofab facilities, Wet Processing – Aisle 1 wet deck).*

Spin-Rinse-Dry *(U of A, Nanofab facilities, Spin Rinse Drier, Wet aisle #1 or #2).*

CHAPTER 6.
PROCESS SPECIFICATION LANGUAGE FOR MEMS MANUFACTURING

At this point we have theoretically confirmed that indeed the proposed algorithms and modules are working and it is possible to extract important information using our methods. The remaining of this thesis focus on the development and implementation of the *Manufacturing Path Selection Module*, more specifically the sub-modules *Input Verification Module* and *Decision Intelligence Module*, as these are the most critical modules required to assist the main bottlenecks that were previously identified. In order to properly verify the input, it is required to outline a standard representation to remove potential ambiguities and improve the clarity of the process flow definition to be evaluated. This is presented in this chapter.

In order to assist the decision-making process, it is required to use an intelligent system that provides easy and fast means to evaluate potential alternatives. CHAPTER 7 includes details of a system that we developed in order to do this.

6.1. Why Standardization is Important for MEMS

Standardization has been proven to have positive impacts in several areas ranging from technology development to economic growth and productivity [113], [114], [116]. In the field of MEMS, it has been difficult to advance on process, materials, integration, interconnection and packaging standardization [90], [91], [127]. This lack of standardization makes it complicated to have a common language to define all the different processes utilized for MEMS fabrication.

More often than not, collaboration among organizations is required for prototyping and fabricating MEMS-based devices; therefore, information needs to be shared among numerous facilities and research groups. During this collaboration, knowledge is interchanged between organizations and standardization is of particular relevance to the knowledge transfer process [128]. Without formal process specification, a lot of unnecessary additional information is created and, in many cases, ambiguities remain in the process requirements handed from one organization to the next. A standard form of process specification is needed in order to provide an appropriate representation of MEMS manufacturing process semantics. By developing a standard process specification for MEMS, it would be possible to avoid misunderstandings while more efficiently conveying fabrication parameters and requirements to manufacturing facilities. Hence, consistency and repeatability during MEMS fabrication may be improved.

There have been several attempts to standardize MEMS at various levels [90], [115], [116]. However, the complexity and dynamism of microsystems have made standardization difficult to accomplish. In order to promote, and eventually achieve standardization in MEMS fabrication, one of the first and most important steps is to represent processes and sub-processes in a common language for all entities working with MEMS. This language should be able to communicate the right semantic meaning and remove ambiguities and misinterpretations for all the activities during a process flow for MEMS fabrication.

The need for a language that allows clear description of processes is not exclusive to MEMS. Several existing representations of process information and their characteristics have been analysed [129]. In this reference, twenty-four different tools were thoroughly analysed (Table 6-1); two additional tools were minimally examined because a lack of available expertise and literature at the time the analysis was performed. Nearly all the representations studied focused on the syntax of the process specification instead of the semantics (i.e., meanings) of terms. This could be sufficient when process information exchange is occurring within a single domain. Nevertheless, exchange of process models among different domains creates many situations where the same term can have different meanings [129]. Arguably, the most common form of behaviour specification is flow models which have some limitations regarding semantic representations. This is an important limitation in process specification, even more so for an industry such as MEMS, where collaboration is often necessary and information on requirements and specifications is transferred from one place to another several times throughout the various stages of the manufacturing cycle. Furthermore, the positive impact of technological capability (i.e., the ability to develop, absorb and apply technical skills generated from the technological knowledge of scientific research) has been shown to strengthen the competitive edge for high-technology companies [130].

Table 6-1: Existing Process Representations Examined in [129]

Name
ACT
A Language for Process Specification (ALPS)
AP213
Behavior Diagrams
Entity Relationship (E-R)
Functional Flow Block Diagrams (FFBD)
Gantt Charts
Generalized Activity Network (GAN)
Hierarchical Task Networks (HTN)
IDEF0
IDEF3
<I-N-OVA> Constraint Model
JTF- Core Plan Representation (CPR)
Knowledge Interchange Format (KIF)
O-Plan Task Formulation
OZONE
Product-Activity-Resource Model for Realization of Electro-Mechanical Assemblies: Version 2 (PAR2)
ISO 10303- Part 49
Program Evaluation and Review Technique (PERT) Networks
Petri Nets
Process Flow Representation (PFR)
Process Interchange Format (PIF)
Quirk Model
Visual Process Modeling Language (VPML)

We have defined a formal methodology to define a process description language specific for MEMS fabrication. The fundamentals of this work are based on the *Process Specification Language* (PSL), created by the *National Institute of Standards and*

Technology (NIST), which is now an international standard [16]. We are usinng PSL concepts to facilitate complete and correct process information to be exchanged among MEMS manufacturing systems.

6.2. Process Specification Language (PSL)

The *Manufacturing Systems Integration Division* (MSID) at the NIST has been involved on the development of a language in order to define a neutral representation for manufacturing processes that supports automated reasoning [131]. The main outcome of these efforts is the process specification language [132]–[136] which evolved and became an international standard [16]. This standard defines a generic language for process specifications in manufacturing applications. By using PSL as runtime representation it is possible to reduce ambiguities and enable more powerful abstractions. However, in order to be inclusive and able to capture the essence of various manufacturing processes, PSL is generic and only provides the fundamentals concepts to develop extensions for specific processes. When it is used to define specific applications, explicit extensions should be developed and tailored. By developing new extensions is possible to describe a broad range of specific process representations and to share process information related to manufacturing during all the stages of the production process.

During the literature review for this work, it was noticed that most of the articles referring to PSL, including some recent ones, mention that the underlying language of the PSL-Ontology is the Knowledge Interchange Format (KIF) [137]. However, the last few versions of the ontology, including the most recent one –at the time of writing this thesis: version 2.8 [138], uses the Common Logic Interchange Format (CLIF) to write the set of axioms used by the PSL-Core. CLIF is one of the three languages (also referred as dialects) described in the standard ISO/IEC 24707 [139]. Despite the fact that CLIF itself is based on KIF, it can be considered as a separate language in its own right that provides an update and simplified form of KIF version 3.0 [137], [139]. Another important difference is that CLIF shares a single uniform semantics with the other two languages in the standard (i.e., Conceptual Graphs Interchange Format [CGIF] and eXtensible Common Logic Markup Language [XCL]). This allows all the language within the family to be transcribed into the common abstract syntax making all of them being inter-translatable with each other while preserving meaning.

The PSL Ontology's structure version 2.8 is shown in Figure 6-1. The PSL Ontology is formed by a set of fundamental concepts: the PSL-Core which provide a scaffold to define the universe of discourse for the manufacturing processes (i.e., the range of activities, activity occurrences, times and objects that are expressed, assumed, or involved in the manufacturing process) and extensions (definitional and nondefinitional) which are used to introduce new terminology for specific applications to define detailed, and more complex, operations for particular manufacturing operations. The following sections describe in more detail each of these components.

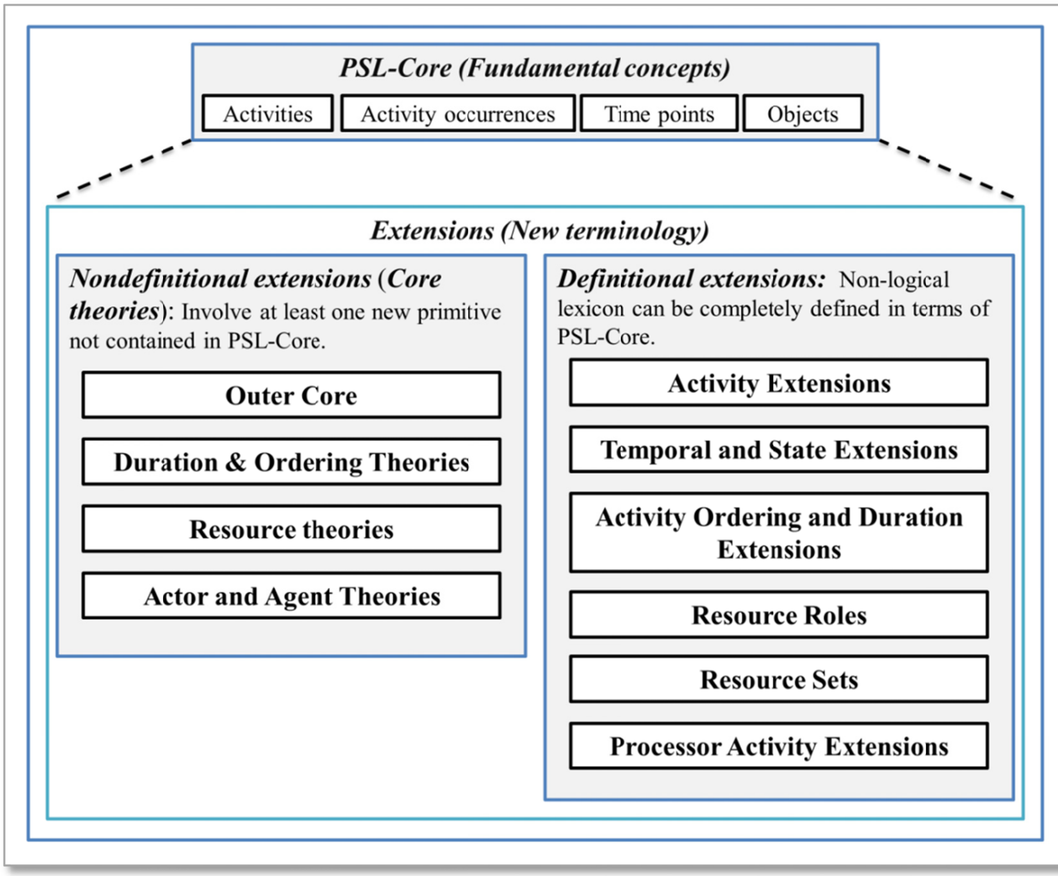


Figure 6-1: Process Specification Language Ontology Version 2.8

Another discrepancy found during the literature review was the fact that many authors consider the nondefinitional extensions different than the core theories. Nevertheless, nondefinitional extension is a synonym of core theories [131].

6.2.1. PSL-Ontology

After reviewing several definitions of the word ontology presented elsewhere [140]–[142], we consider the following ontology definition as the most suitable for PSL in the MEMS realm: A set of formal concepts and relationships for explicit specification of a shared conceptualizations, which are common and understood within a domain. Furthermore, in this work we are proposing an ontology to reason about the properties of the MEMS domain, and may be used to describe the domain itself. PSL provides a definition using first-order logic of language ontology. It is possible to clearly define the PSL components and the specific function of each of these components.

6.2.2. PSL Core

An axiomatic set of basic and intuitive meaningful building-blocks (i.e., semantic primitives) are enclosed in the PSL-Core. These are used to describe the fundamental concepts of manufacturing processes. The simple nature of these building-blocks makes the logical expressiveness rather weak. However, the PSL-Core is adequate for describing the fundamental concepts of manufacturing processes in general.

There are four intuitions that are the base for the basic ontological commitments of PSL-Core [143]. The first intuition mentions that there are four entities that are used to reason about processes: *activities, activities occurrences, timepoints* and *objects*. An important notion is the *atomic* activity which corresponds to a set of basic or primitive activities. The second intuition refers to the occurrences of these activities: there are activities that may have *multiple occurrences* in a given process, or there may be activities that *do not occur at all* (i.e., zero occurrences). The third intuition states that the timepoints are linearly ordered, forward into the future and backwards into the past. The four and last intuition mentions that the activity occurrences as well as the objects are associated with specific timepoints that are used to mark the beginning and the end of the occurrence or object. In addition to the four entities the PSL-Core is constituted of two functions (i.e., *beginof* and *endof*) and seven relations (i.e., *before, occurrence_of, between, before-eq, between-eq, is-occurring-at, participates-in* and *exist-at*) [143].

6.2.3. PSL Extensions

In order to be inclusive and being able to describe the fundamentals of manufacturing processes the PSL-Core is generic by nature. However, for more complex processes it is required to be more specific, provide further details and introduce new terminology for individual manufacturing steps. For these purposes PSL provides two types of modular extensions which provide additional resources: *Definitional* and *Nondefinitional* extensions. A definitional extension is one in which all the non-logical lexicons can be defined completely in terms of the PSL-Core, hence they do not add any expressive power to it but are used to specify the semantics and terminology in the domain application. The nondefinitional extensions are also called “core theories” and these involve at least one new primitive that is not included in the PSL-Core, hence they do add expressive power to it and are used to describe more complex operations. By using these extensions, users can tailor the language to precisely define the needed expressions. As an example of how nondefinitional extensions can be used to improve the precision of semantics for new terms, consider the following. We can define the axiom “The addition of two time durations (i.e., d1 and d2) is equivalent to a single time duration”, expressed in PSL using CLIF (Figure 6-2). The PSL-Core, by itself, does not provide a means to explicitly express this concept of time durations. Nevertheless, there are many contexts where this notion is useful, even essential.

CLIF uses the Extended Backus-Naur Form (EBNF) notation to formally describe its syntax. The detailed explanation of the EBNF notation is presented elsewhere [144] and it is beyond the scope of this thesis. For understanding the structures of the expressions on this work, suffice it to say that they follow the prefix notation (sometimes called Cambridge Polish Notation) where the first element of the expression is the operator and the remaining elements are treated as data. It is also possible for an expression to be a nested list of small expressions.

```
(forall ( ?d1 ?d2)
(if   (and  (timeduration ?d1)
            (timeduration ?d2))
      (timeduration (add ?d1 ?d2 ))))
```

Figure 6-2: Use of a nondefinitional extension.

6.3. MEMS Specific Developed Methodology

6.3.1. Importance of a Standard Representation at the Semantic Level.

For the MEMS industry it has been difficult to establish an international consensus on standard language for process definition and representation. One important reason why this occurs is the fact that in the MEMS field is where several disciplines converge and experts with different backgrounds work at the same time using their own discipline argot to refer to various terms. Moreover, companies or working groups will develop their own terminology and vocabulary for particular activities or objects with which they often work. As these people and companies with different background try to collaborate in a common project two types of communication problems may arise [145]: Use of the same term to refer to different concepts (semantic problem), and use different terms to denote the same entity (syntax problem). In order to avoid these types of problems when collaborating to fabricate a MEMS it is required to develop an unambiguous form of communication and representation for manufacturing processes. In the current approach for information exchange involving *n* different parties working on a common project, an ontology translator must be written for every two-party and this requires $O(n^2)$ translators. A major improvement can be achieved by using a common interchange ontology to reduce the number of required translators to only $O(n)$ [132].

6.3.2. Methodology Implementation

As explained by Gruninger [140] a process ontology provides the underlying semantics for the process terminology that is common to the many disparate domains and software applications. Based on the PSL methodology [133], we will be using a first order logic, to specify a rigorously-developed semantics and is based on the following three main actions: Defining what is the process we would like to described identifying its activities, objects and interactions among them; refining in mathematical structures the fore mentioned interactions; and defining a logical language to express the interactions in an unambiguous way. This is implemented by following these steps:

Step 1. Declare the resources

Step 2. Define instances for the classes

Step 3. Create time points to create sequence of activities

Step 4. Specify activities

Step 5. Occurrences are assigned to activities, to allow each activity to be ordered within the sequence.

After Step 4, a set of concepts called occurrence tree will be generated, this covers all possible occurrences of all atomic manufacturing activities that can happen for a given MEMS process. Then, on step number 5, the designer of a specific MEMS fabrication process will write constrains on which of these occurrences are allowed for that process simply by defining the sequence of execution. As the process design evolves constrains become tighter (i.e., for initial designs constrains are looser than those used to define the final specification of the process). Although an occurrence tree describes all the sequences of activity occurrences, not all the sequence will be physically possible making necessary a legal occurrence tree. This is a subtree tree containing only the possible sequences of activity occurrences. The relation to specify that an atomic activity occurrence o is an element of the legal occurrence tree is *legal* (o). The general form of process description for atomic activities which contains the legal occurrence tree is defined as [140]:

$$(\forall o)\, occurrence\_of(o,a) \wedge \; legal(o) \supset \Phi(o) \qquad (1)$$

where:

a is an activity

o is an activity occurrence, and

$\Phi(o)$ is a formula that specifies the constrain on the legal activity occurrence.

6.4. MEMS Processes Taxonomy

In order to reap the benefits of the PSL mentioned above, it is required to have a taxonomic classification of the manufacturing processes that it is inclusive and that new process can be added orderly. The most common classification of MEMS processes is the one presented in the work by Walsh et al. [28], which separate MEMS processes in bulk processes and surface processes. However, this classification is not convenient when trying to identify intuitions in manufacturing operations going from the generic to the specific as required by the PSL ontology.

We have developed new taxonomic levels of abstraction for MEMS where we group all the processes in three main categories: *additive processes*, s*ubtractive processes* and *transformative processes.* This new classification allows us to group practically all MEMS processes in a generic way. A class diagram for these new taxonomic levels is presented in Figure 6-3 where some examples of processes are grouped in the main categories (a more comprehensive list of process examined for this thesis is presented in APPENDIX "A") . By doing this, we are looking to develop a robust foundation for MEMS process modelling; one that is able to characterize the general process pattern, describe by specification and, simultaneously, characterize the class of possible instantiations of that pattern. We also aim to clearly represent constrains during the process execution. The MEMS taxonomy we developed is based on the material relation and interaction between the process input and output. This material interaction is easy to identify allowing an easy and unambiguous classification of the MEMS processes.

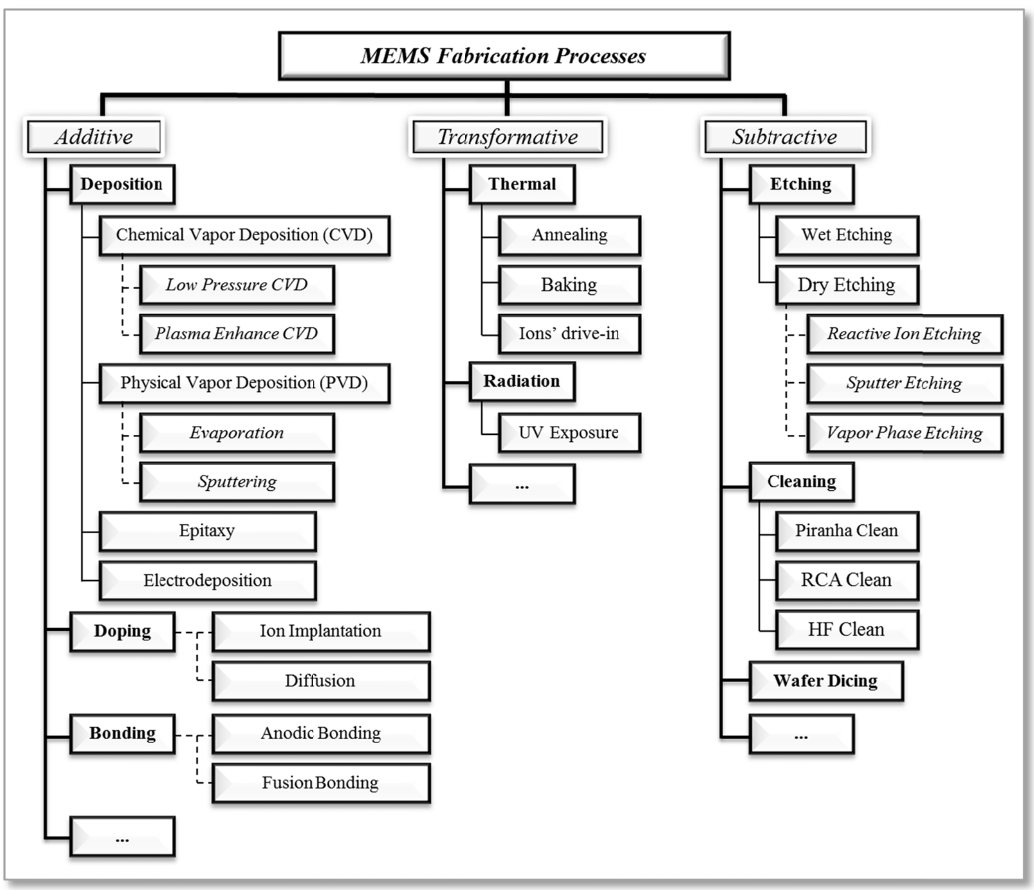


Figure 6-3: Taxonomic Classification for MEMS Processes

6.4.1. MEMS Primitive Processes and Material Interaction.

We illustrate our newly defined process-material relationships as follows:

In the *additive process* (Figure 6-4a) different materials are combined in order to form a new entity that may be the input for a new subprocess. We use this process definition in terms of the atomic activity of adding two or more materials to obtain a new entity formed as a combination of them. We define the *transformative process* as that one where the properties (*e.g.*, chemical, physical, optical, *etc.*) of a material are modified, but there are no additions or removals of material (Figure 6-4b) For the *subtractive process* the input is considered a single entity and the atomic activity is defined as material withdrawal (Figure 6-4c)

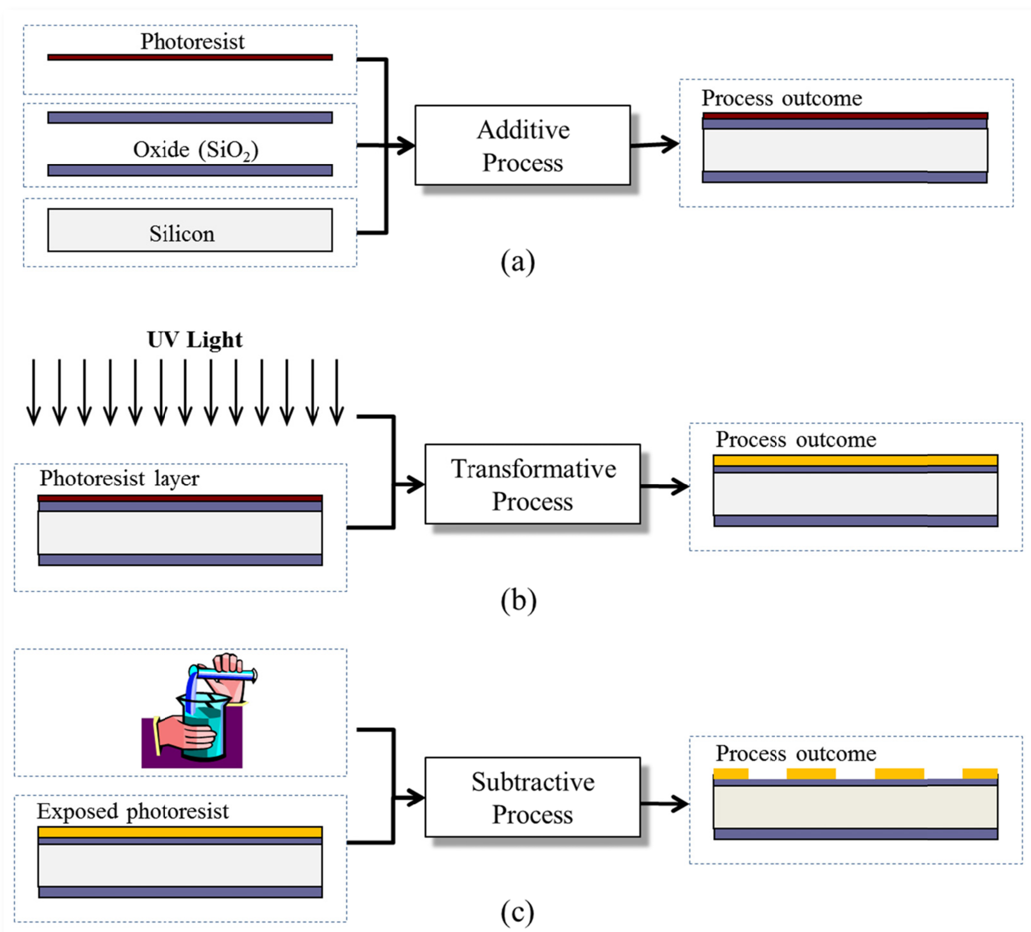


Figure 6-4: MEMS Process-Material Correlation

6.5. MEMS Processes Information Description

As per the first intuition, which stipulates the four entities that are used to reason about processes: *activities, activities occurrences, timepoints* and *objects*, we need to identify these basic entities. The first one to be identified is a repeatable pattern of behaviour defined as *activity* (e.g., steps required for photolithograpy process). The next one is *activity occurrence* which corresponds to a concrete instantiation of the pattern of behaviour. Activities may have various occurrences or zero occurrences (i.e., activities that never occur). It is important to know that any activity occurrence corresponds to a unique activity; this is represented by the relation: *occurrence_of* (*o*,*a*).

Each activity occurrence is associated with unique timepoints that mark the length of the occurrence. For that purpose PSL uses two functions: *beginof* and *endof*. All the timepoints form a set that is linearly ordered, defining forward into the future and backwards into the past. It is important to note that while activity occurrences have preconditions and effects, timepoints do not. We will use the core theory $T_{duration}$ as a metric for the timeline by mapping into a new entity called *timeduration* that satisfies the axioms of algebraic fields.

The vast majority of MEMS fabrication processes are sequential in nature and the outcome of a previous stage is the input for the next one. The whole fabrication process can be seen as a system with given inputs (i.e., a set of resources) and outputs. At the same time, every single sub-process of the whole fabrication process receives specific inputs and produces specific outputs (Figure 6-5).

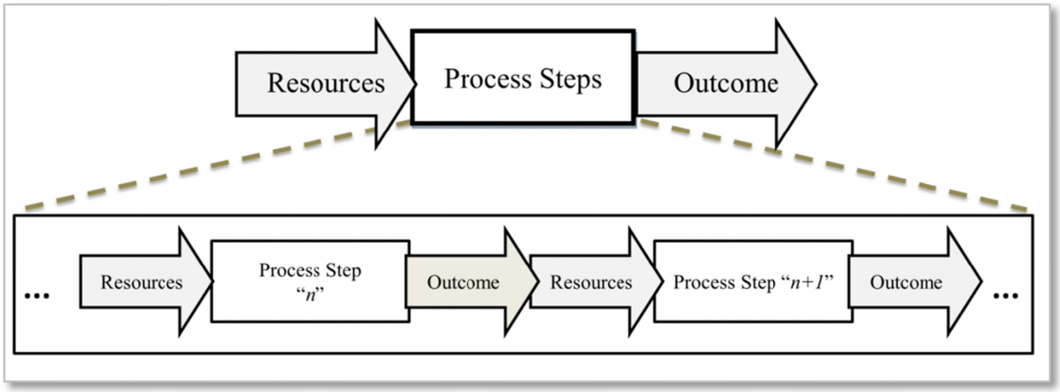


Figure 6-5: Structure of MEMS sequential fabrication process

It is possible to find parallel processes happening at the same time when multiple wafers are being processed simultaneously for a future bonding operation. Furthermore, there could be a case where multiple steps should happen and need to be completed before continuing to the next step. An example of two MEMS sub-processes that required to be completed in order to move to the next step is the preparation of chemical baths while the wafer is being exposed to UV light in order to transform the properties of the photoresist, to provide selectivity for the next step.

These two configurations for MEMS manufacturing can be described using PSL extensions based on the extensions defined by [134][146]. The first and most common configuration in MEMS manufacturing, is the sequential order relation, where a set of activities occur one after another. Based on the relation *follows* of the PSL extension it is possible to define the relation *seqMEMS* to represent sequential order relation. Figure 6-6 defines that the ending time of any occurrence of Activity 1 (`a1`) must be earlier than or equal to the beginning time of any Activity 2 (`a2`).

```
defrelation seqMEMS (?a1 ?a2) :=
      (forall (?a1 ?a2)
            (and (exists ?a3)
                  (follows ?a1 ?a2 ?a3)))
```

Figure 6-6: Formal definition for sequential activities.

The case where multiple activities happen in parallel and need to be completed in order to move to the next step is shown in the PSL expression in Figure 6-7. This expression specifies that when an activity occurs, all of its subactivities occur as well.

```
(defrelation parMEMS (?a) :=
 (and (activity ?a)
   (forall (?occ ?a1)
     (=> (and (occurrence-of ?occ ?a)
       (subactivty ?a1 ?a))
         (exists (?occ1)
          (and (occurrence-of ?occ1 ?a1)
              (subactivity-occurrence ?occ1 ?occ)))))))
```

Figure 6-7: Formal definition for parallel activities.

6.6. MEMS Processes Resources Requirements

We define resources within the MEMS manufacturing realm as those entities that are used to implement activities. Many resources may be used to complete a given activity and one resource may be used for various activities. In order to provide some structure to the use of resources we define a set of resources called *Resource Classes.* This whole set is considered as a single entity when assigned to an activity, when this happens, all the resources included on the set are also assigned and used to perform the activity. This group of resources should be able to provide full service and solution to the designated activity. The corresponding relation between a resource set and an activity is called *Resource Use*. Specific properties can be assigned to the resource set through *Resource Instances*. By doing this operational details for the resource set can be defined.

6.7. Case Study

The proposed methodology mentioned in the previous section was utilized to describe the process steps for the "Piranha Cleaning" process. The tool utilized to represent the PSL semantic and illustrate the implementation of the proposed methodology is the *Extensible Markup Language* (XML) in combination with the *Resource Description Framework* (RDF).

In order to get enough information about the Piranha Cleaning procedure, three different Standard Operating Procedures (SOPs) were examined [147]–[149]. After reviewing these documents, important differences were found, which reaffirm the assertion of the need for a standardized process specification language for MEMS processes. Discrepancies include: the required concentration of the substances, the pouring order of substances, how substances should be mixed, whether or not agitation of the mixture is required, etc. This lack of clarity and differences at the semantic level are common while describing MEMS fabrication processes, frequently leading to misunderstandings and erroneous processes.

Following the methodology proposed in the previous section we start by clearly defining the activities required to complete the process. The process of generating the activities should be hierarchical; complex activities may consist of subactivities in different levels of execution and specific timepoints will be assigned to maintain correct occurrence time. Eight different activities were created to complete the full process description. These activities are listed in Table 6-2.

Table 6-2: Activities required in the Piranha Cleaning Process

ID	Activity Identifier	Activity level
a1	Clean wafer	Main activity (level 1)
a2	Piranha cleaning	Subactivity (level 2)
a3	Measure solutions	Subactivity (level 3)
a4	Mix solutions	Subactivity (level 3)
a5	Place wafers on the bath	Subactivity (level 3)
a6	Wait Time	Subactivity (level 3)
a7	Rinse wafers	Subactivity (level 3)
a8	Dry wafers	Subactivity (level 2)

This hierarchical organization can be defined in PSL as demonstrated on Figure 6-8, where some activities are subordinate to the previous level and some are identified as primitive activities which mean they do not have proper subactivities.

```
(activity CleanWafer)
      (subactivity PiranhaCleaning CleanWafer)
            (subactivity MeasureSolutions PiranhaCleaning)
                  (primitive MeasureSolutions)
            (subactivity MixSolutions PiranhaCleaning
                  (primitive MixSolutions)
            (subactivity PlaceWaferOnBath PiranhaCleaning)
                  (primitive PlaceWaferOnBath)
            (subactivity WaitTime PiranhaCleaning)
                  (primitive WaitTime)
            (subactivity RinseWafer PiranhaCleaning)
                  (primitive RinseWafer)
      (subactivity DryWafer CleanWafer)
```

Figure 6-8: Activities, subactivities and primitive definitions for piranha cleaning.

Once the activities are defined, a set of *Resource Classes* needs to be also defined. The *Axiom 1* of the *Theory of Resources Requirements* of PSL-Core defines the relation “requires” [150] which is used to define the various resources. The representation of this axiom in PSL is presented in Figure 6-9 which states that there is an activity “?a” which requires the resource "?r". Another piece of information given in the expression is that there is an atomic subactivity "?a1" which happens consecutively after the occurrence "?s" and this is used to define that resource is available immediately after activity "?a".

```
(forall (?a ?a1 ?r ?s)
    (if  (and (requires ?a ?r)
         (subactivity ?a1 ?a)
         (atomic ?a1)
         (holds (available ?r ?a1) ?s))
       (exists (?occ)
         (and (occurrence_of ?occ ?a)
           (subactivity_occurrence (successor ?a1 ?s) ?occ)))))
```

Figure 6-9: Axiom 1 of the Theories of Resources Requirements

Based on the relation demonstrated in the Figure 6-9, it is possible then to define the specific resources required for a manufacturing step. An example of a declaration of a resource for our case study is shown in the Figure 6-10, where the resource *TeflonCarrier* is define as an object required by the subactivity "a5" *PlaceWaferOnBath.* The same structure shown in Figure 6-10 is used to declare all the resources for our process (Table 6-3).

```
(defrelation resource (?TeflonCarrier):=
       (and (object ?TeflonCarrier)
       (exists (?PlaceWaferOnBath)
       (requires ?PalceWaferOnBath ?TeflonCarrier))))
```

Figure 6-10: Declaration of resource used by the activity "PlaceWaferOnBath"

Table 6-3: Resource Classes and Instances for Piranha Cleaning Process

Resource Classes
TeflonCarrier NitrogenGun DeIonizedWater SulphuricAcid ConcentrationH_2SO_4 → 96% HydrogenPeroxide ConcentrationH_2O_2 → 30% PiranhaBath TimePiranhaBath (tPB) → 15 min

It is not required to define all the axioms every time they are needed. We explicitly described the axiom where the relation "requires" is defined (Figure 6-9) only for illustrative purposes on how it is possible to build on existing axioms and definitions. There exist many axioms and definitions within PSL core theories that can be used without having to explicitly define them [138]. It is important to keep in mind that all extensions within PSL must be consistent extensions of PSL-Core, and may be consistent extensions of other PSL extensions. However, not all extensions within PSL need be mutually consistent [16].

Once the resources have been defined, it is required to coordinate the occurrences of the activities and this is done by defining an ordered set of timepoints. These timepoints will establish the start and end of the different activities (Table 6-4).

Table 6-4: Time points for the Piranha Cleaning Process

ID	Time Points
p1	start
p2	done placing wafers in teflon carrier
p3	done measuring H2SO4 and H2O2
p4	done mixing liquids
p5	done placing carrier in solution
p6	done waiting time
p7	done rinsing wafers
p8	done drying wafers

6.7.1. Code for Information Handling.

In this section we use XML and RDF scheme to generate a code that holds the information of the final structure of the process with the underlying PSL semantics. At the same time, it is possible to use the XML code to generate a visual representation of the process structure. For illustrative purposes some extracts of the code are presented here. The first entity example presented here is the resources definition using the RDF schema. Figure 6-11 shows some visual indicators, within the code, used to define the resources and their properties. This is with the intent to help the reader to visually correlate with Figure 6-12, which illustrate what is happening in the code (i.e., what resources and properties are being defined).

```
<rdf:RDF>

      <Class ID="TeflonCarrier"/>                  1

      <Class ID="NitrogenGun"/>

      <Class ID="DeIonizedWater"/>
                                                     2
      <Class ID="SulphuricAcid"/>
      <Property ID="concentration">
            <rdf:range rdf:resource="#ConcentrationH2SO4"/>
            <rdfs:domain rdf:resource="#SulphuricAcid"/>
      </Property>
                                                     3
      <Class ID="HydrogenPeroxide"/>
      <Property ID="concentration">
            <rdf:range rdf:resource="#ConcentrationH2O2"/>
            <rdfs:domain rdf:resource="#HydrogenPeroxide"/>
      </Property>
                                                 4
      <Class ID="PiranhaBath"/>
      <Property ID="time">
            <rdf:range rdf:resource="#TimePiranhaBath"/>
            <rdfs:domain rdf:resource="#PiranhaBath"/>
      </Property>

      <Class ID="ConcentrationH2SO4"/>
      <p:ConcentrationH2SO4 rdf:ID="96"/>

      <Class ID="ConcentrationH2O2"/>
      <p:ConcentrationH2O2 rdf:ID="30"/>

      <Class ID="TimePiranhaBath"/>                              5
      <p:TimePiranhaBath rdf:ID="15"/>

      <p:SulphuricAcid rdf:ID="cH2SO4">
            <p:concentration rdf:resource="96"/>
      </p:SulphuricAcid>

      <p:HydrogenPeroxide rdf:ID="cH2O2">
            <p:concentration rdf:resource="30"/>
      </p:HydrogenPeroxide>

      <p:PiranhaBath rdf:ID="tPB">
            <p:time rdf:resource="15"/>
      </p:PiranhaBath>

      <p:NitrogenGun rdf:ID="nitrogengun"/>

      <p:DeIonizedWater rdf:ID="diwater"/>

</rdf:RDF>
```

Figure 6-11: Resources Classes and Instances Definition using RDF

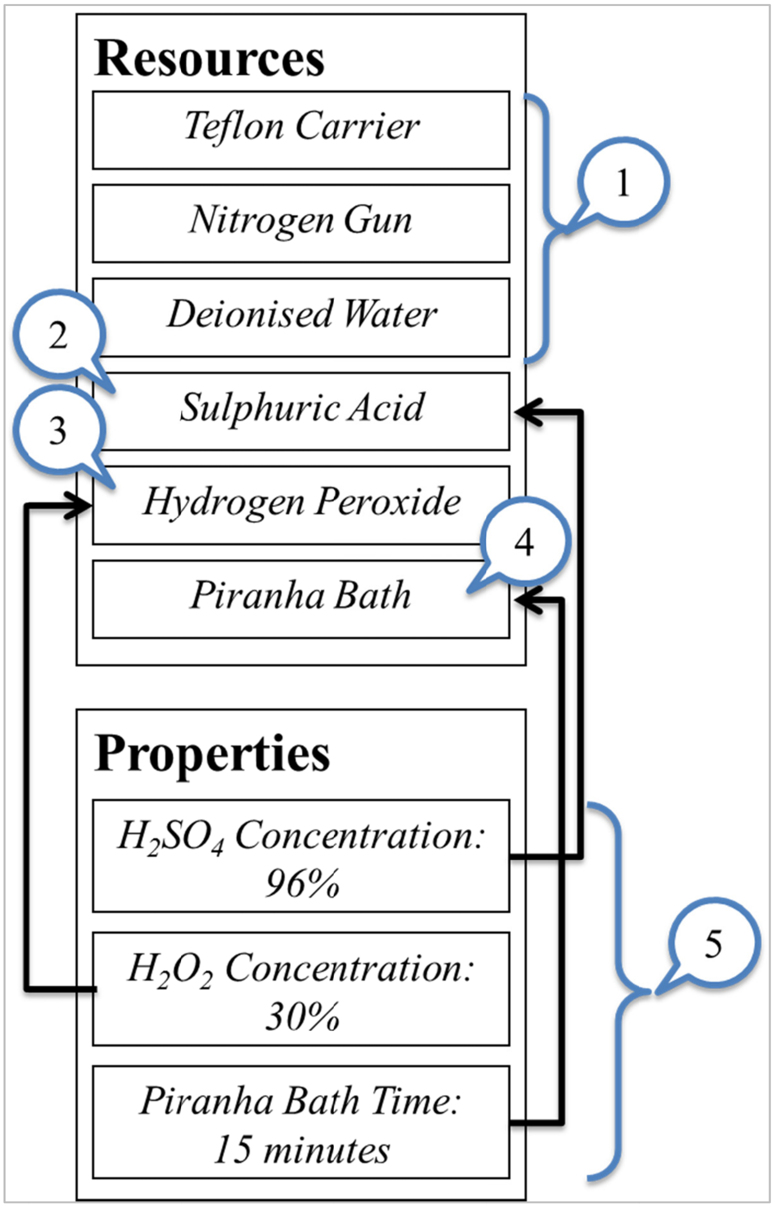


Figure 6-12:Graphical interpretation of the code in Figure 6-11

The second extract of code shown here is used to define the timepoints for the activities involved in the piranha cleaning process (Figure 6-13). This code assigns specific identifiers to the end of the occurrence activities. The assignments done in this code are summarized in Table 6-4 previously presented.

```
<points>
   <point id="p1">start</point>
   <point id="p2">done placing wafers in teflon
   carrier</point>
   <point id="p3">done measuring H2SO4 and H2O2</point>
   <point id="p4">done mixing liquids</point>
   <point id="p5">done placing carrier in solution   </point>
   <point id="p6">done waiting time</point>
   <point id="p7">done rinsing wafers</point>
   <point id="p8">done drying wafers</point>
</points>
```

Figure 6-13: End of activities definition

The following partial code in Figure 6-14, shows the inner structure of the process; the relation of the main activity with the subactivities within it and specifying what are the resources required for each of the activities. The last extract of code shown in Figure 6-14, demonstrates how the occurrences of the different activities should evolve in order to complete the process in the desired order.

```
  <activities>
    <activity id="a1">
      <name>Clean wafer</name>
      <subactivities>
        <activity id="a2">
          <name>Pirahna Cleaning</name>
          <subactivities>
            <activity id="a3">
              <name>Measure solutions</name>
              <requires>
               <resource rdf:resource="#SulphuricAcid"/>
               <resource rdf:resource="#HydrogenPeroxide"/>
              </requires>
            </activity>
            <activity id="a4">
              <name>Mix solutions</name>
              <requires>
               <resource rdf:resource="#SulphuricAcid"/>
               <resource rdf:resource="#HydrogenPeroxide"/>
              </requires>
            </activity>
            <activity id="a5">
              <name>Place wafers on the bath</name>
              <requires>
               <resource rdf:resource="#TeflonCarrier"/>
               <resource rdf:resource="#PiranhaBath"/>
              </requires>
            </activity>
    …
  …
…
```

Figure 6-14: Activity and Subactivity Structure

6.7.2. Code Validation

It is possible to describe all the steps of the Piranha Cleaning process using the logic from PSL core theories and definitional extensions. The sections of the PSL ontology used for this end are part of the ISO standard 18629: *"Industrial automation systems and integration –Process specification language"* and are shown in Table 6-5.

Table 6-5: PSL sections relevant for MEMS processes

Category	Description	ISO Standard
Core theories	PSL-Core	ISO 18629-11
	Outer core	ISO 18629-12
	Duration and ordering theories	ISO 18629-13
	Resource theories	ISO 18629-14
Definitional extensions	Activity extensions	ISO 18629-41
	Temporal and state extensions	ISO 18629-42
	Activity ordering and duration extensions	ISO 18629-43
	Resource extensions	ISO 18629-44

The current theories and extensions at the time of writing this thesis correspond to the PSL ontology version 2.8. Consistency proofs and verification have been completed for all of the theories and extensions used as foundation in our case study [138]. The Manufacturing System Integration Division from the National Institute of Standards and Technology, provides the various portions of the PSL ontology version 2.8 in a number of formats [151] and as well provides the links to different automated theorem provers (e.g., Pando [152], Tau [153] and Vampire [154]) that may be used to verify the syntax and correctness of the definitions. The tool we used to verify the logic for new definitions and relations in our case study was Tau. Our preference for this parser was mainly due its simplicity of use and on-line availability of Tau.

Once the adaptation of the relevant logic definitions of the various parts of the ISO 18629 standard were made to describe the application in our case study, we developed XML code to handle and capture specific information regarding the Piranha Cleaning process. In order to visually observe and validate the correct semantic captured, we used the eXtensible Stylesheet Language (XSL) to generate a style sheet that was able to present graphically the structure of the information coded in XML. Putting together all the different parts of the XML code mentioned in the previous section and using them to fill the XSL, makes it possible to represent the structure of the process. At the same time, it was possible to observe the sequence of occurrences of the various activities and subactivities, the resources required in all the activities and the value of specific parameters (Figure 6-15).

Activity Specifications					
Activity	a1				
Name	Clean wafer				
Consists of		Sub Activity	a2		
		Name	Pirahna Cleaning		
		Consists of		Sub Activity	a3
				Name	Measure solutions
				Requires	#SulphuricAcid
				Requires	#HydrogenPeroxide
				Sub Activity	a4
				Name	Mix solutions
				Requires	#SulphuricAcid
				Requires	#HydrogenPeroxide
				Sub Activity	a5
				Name	Place wafers on the bath
				Requires	#TeflonCarrier
				Requires	#PiranhaBath
				Sub Activity	a6
				Name	Wait Time
				Requires	#TeflonCarrier
				Requires	#PiranhaBath
				Sub Activity	a7
				Name	Rinse wafers
				Requires	#DeIonizedWater
		Sub Activity	a8		
		Name	Dry wafers		
		Requires	#NitrogenGun		
		Consists of			

Figure 6-15: Structure of Piranha Cleaning

CHAPTER 7.
FUZZY INFERENCE SYSTEM FOR EVALUATING ALTERNATIVES

Even though a standard process specification is achieved and ambiguities can be removed while describing a MEMS process flow, there could be various alternatives to execute a process step while fabricating a device. Frequently, when trying it identify the best possible alternative to execute a process step, wrong decisions are made which leads to misuse time and resources. In order to address this challenge, we present another important contribution of this research work: the development of a method based on fuzzy logic to help MEMS practitioners to identify the most appropriate alternative when different options are presented to complete a fabrication step. In this chapter we introduce a fuzzy inference system that we have developed to evaluate and rank alternatives for MEMS fabrication processes.

The vast majority of the processes utilized for MEMS manufacturing have to be tuned by trial and error. This tuning is based heavily on empirical knowledge. These facts significantly slow the product development and time to market for MEMS-based devices, discouraging many entrepreneurs from pursuing new ideas. There is a general concern to develop initiatives to assist the implementation of knowledge management and to help with decision-making processes while developing a new product [155]–[159]. MEMS practitioners require a system that introduces a level of abstraction for process design, allowing them to develop devices with more certainty of the manufacturability of their design. To achieve this, it is important to evaluate various alternatives for multiple process steps required to complete a process flow of a device.

7.1. Process Flow Representation for MEMS

The fundamental principles used in this system are based on the assumption that a process flow is a set of sequential fabrication steps, β, that are performed in a bare substrate using various equipment; the output for one fabrication step is the input for the next one. The last process step yields the desired device structure. Using a state abstraction commonly used in process modelling frameworks [160], the fabrication process can be represented as:

$$\beta_i(s_i) = s_{i+1}, \tag{2}$$

where s_i are discrete states representing the current state of the device being fabricated, s_0 is the initial substrate, and s_n is the complete device. It is possible to represent the process flow P_d required to fabricate device d as a sequence of fabrication steps:

$$P_d = [\beta_0, \beta_1, \beta_2, \cdots, \beta_{n-1}] \tag{3}$$

Starting from s_0, we perform β_0, which takes us to state s_1, then β_1 is performed which leads us to state s_2, and so on until the device is complete:

$$s_1 = \beta_0(s_0) \tag{4}$$
$$s_2 = \beta_1(\beta_0(s_0)) \tag{5}$$
$$\vdots$$
$$s_n = \beta_{n-1}(\beta_{n-2}(\cdots(\beta_2(\beta_1(\beta_0(s_0)))))) \tag{6}$$

Using a similar state-space notation as the one used by [161], a process flow characteristic to the device, s_n, may be expressed as a set of fabrication steps operating in sequence on s_0 as:

$$P_d(s_0) \equiv s_n = \boxed{\bigotimes}_{i=0}^{n-1} \beta_i(s_0) \tag{7}$$

The synthesis problem consists of identifying facilities to perform all of the required fabrication steps in a process flow (or as many as possible) to successfully complete a device. There are many simple processes available in many fabrication facilities. If on average there are k facilities able to perform the n fabrication steps, then there are $x=k^n$ possible fabrication paths. These many paths will generally produce multiple solutions. The set of different possible process flows is $\boldsymbol{G} = \{P_1, P_2, P_3, \ldots, P_x\}$,and the total number of possible process flows can increase rapidly. For instance, for a simple MEMS device with n=10 fabrication steps and k=5 facilities able to perform the fabrication steps, the cardinality of $\boldsymbol{G}$ would be: $\boldsymbol{G} = 5^{10}$. Hence, random-type searches are inadequate.

We propose that it is possible to perform the search more efficiently by using systematic algorithms, which we put forward in this work. These algorithms are based on taxonomic classification combined with user defined priorities. The taxonomic classification for MEMS we are using in our algorithms is the one we proposed in [162], illustrated in Figure 6-3. A well-organized taxonomy for fabrication steps, careful naming of the classes and subclasses, and hierarchical menus permit a specific fabrication step to be quickly located, even in a large library. For instance, under the idealized assumption that at each of the three main classifications shown in Figure 6-3 there are five subclasses in five levels, any object could be located in a library with more than 9,300 objects by making just five choices. More details for these systematic algorithms are presented in the next section.

7.2. Systematic Process Flow Generation

Equation (3) shows that an orderly sequence of process steps will yield a device, *d*. This specific order is important; the construction of MEMS devices is highly sequential as there are typically very few operations that can be performed in advance or in parallel. We use a binary relation which is irreflexive, antisymmetric, and transitive (see Table 7-1) to express the order precedence: If process step β_i is performed before step β_j, irrespective of whether it is performed immediately afterwards or later, it is possible to say that β_i precedes β_j, or in short notation: $\beta_i \prec \beta_j$ or $\beta_j \succ \beta_i$.

Table 7-1: Binary relation "Precedes"

Properties Definitions
Irreflexive: $\forall \beta \in P_d, \neg(\beta \prec \beta)$
Antisymmetric: $\forall \beta_i, \beta_j \in P_d, (\beta_i \prec \beta_j) \wedge (\beta_j \prec \beta_i) \Rightarrow (\beta_i = \beta_j)$
Transitive: $\forall \beta_i, \beta_j, \beta_k \in P_d, \left(\beta_i \prec \beta_j\right) \wedge \left(\beta_j \prec \beta_k\right) \rightarrow (\beta_i \prec \beta_k)$

There are many ways of searching for facilities available to provide the fabrication service for the multiple process steps required. For the system described here, the initial step is to identify the available processes suitable for the fabrication flow of the user. A list of process steps needed by the user should be generated. In order to avoid ambiguities while introducing process steps, a set of pre-defined operations are presented to the user in the form of hierarchical menus. In this way, the user can build the entire process flow specification with clearly defined and understood process steps. An alternative input approach is to import the process flow from a data file. By using this approach it is possible to read a file with the description of a process flow. The refinement of this feature is not a simple matter, as a standardized format to represent manufacturing processes for MEMS is required. Initial steps have been taken in that direction [162].

The algorithm will take three lists as inputs: *priority_list*, *hierarchical_selection_list* and *fabrication_list_selection*. The first list contains the user's preferences for analysing which alternative is the most desirable in the event that more than one alternative is found for some process step(s). The second input list contains the classes and subclasses from the taxonomic structure for MEMS processes selected by the user during the input of the fabrication steps; by using this taxonomic levels it is possible to perform a smart and efficient search instead of using a brute force algorithm to check every alternative. The third input list is the actual list of process steps for process flow P_d selected by the user. The algorithm developed to process this list is shown in Figure 7-1.

```
function    RankingFabSteps    (hierarchical_selection_list,
fab_step_selection)
       /* the selections made by the user while entering the
       fabrication steps will define the search path in the
       taxonomic classification*/
begin
  if (piority_list = NULL) then piority_list ←
  default_ piority_list;
  sorted_priorities_list ←
  AssignWeightsForPriorities (piority_list);
  foreach (β ∈ fab_step_selection) do
    available_fab_steps_list ←
    SelectAvailableProcesses (hierarchical_selection_list);
    not_found_fab_steps_list ←
    SelectAvailableProcesses (hierarchical_selection_list);
    foreach (γ ∈ available_fab_step_list) do
      RankingAlgorithm;
      ranked_fab_step_list ←
      UpdateHighest(current_highest,sorted_priorities_list.[φ]);
    end foreach
  end foreach
  return (ranked_fab_step_list, not_found_fab_steps_list);
end
```

Figure 7-1: Algorithm for process flow generation

Immediately after examining the process flow input it is possible to identify which processes were found in the database and which processes were not. An ordered list, sorted by the user's priorities, is generated for the processes found. The following lists are examples of the lists generated where three out of the ten process steps were not found using the specified criteria:

- Internal list of the found processes, including multiple instances of the process steps where there is more than one option (identified by the subscripts *a, b, c…)*:

  available_fab_steps_list = [β_{0a}, β_{0b}, β_{0c}, β_{1a}, β_{1b}, β_{3}, β_{4}, β_{6a}, β_{6b}, β_{7}, β_{8a}, β_{8b}, β_{8c}, β_{8d}]

- Output list of the processes found, where only the top-ranked process steps are included:

  ranked_fab_steps_list = [β_{0b}, β_{1a}, β_{3}, β_{4}, β_{6a}, β_{7}, β_{8d}]

- Output list of the processes not found using the specified criteria:

  not_found_fab_steps_list = [β_{2}, β_{5}, β_{9}]

A fundamental part for the algorithm shown in Figure 7-1 is the *RankingAlgorithm*, which performs the evaluation of different alternatives. Complete details of how this process works is given in Section 7.3.

7.3. Systematic Ranking Algorithm

For any given process flow P_d, suppose that there is a finite set $\boldsymbol{A}=\{a_1, a_2, a_3, \ldots, a_m,\}$ of alternatives for each of the β_{n-1} process steps, where each process step is evaluated according to n criteria, expressed by $\boldsymbol{C}=\{c_1, c_2, c_3, \ldots, c_n,\}$.

Discussion with microsystems designer colleagues identified specific criteria that are relevant for manufacturing or prototyping devices: *Cost*, *Use of Known Process, Accessibility of Facility*, and *Complexity*. It is often possible to fully evaluate an alternative using only these criteria; however, in some cases we require definition of additional criteria for specific parameters that are critical to the evaluation of the performance of a process step (e.g., if a process was successful or not in the context of a specific application for which the device is being developed). We refer to the criteria for such parameters as *Performance of Critical Parameter X*, where $X \in \mathbb{N} | X = 1 \ldots m$, for m critical parameters required to ensure a sufficient degree of functionality.

A list of criteria for this work and a description of the evaluation metrics for these are summarized in Table 7-2.

Table 7-2: Criteria for process ranking

Criteria Name	Evaluation Metric
c_1: Cost	Total cost required to complete the fabrication step.
c_2: Use of Known Process	Commonness Process Index (i.e., Degree of current usage, more details in **Table 7-5**).
c_3: Accessibility of Facility	Level of how easy/hard is to access and use the required facilities. (e.g., own by the user, in-campus facilities, existing agreements and collaborations, etc.).
c_4: Complexity	Level of complexity for the fabrication step.
$c_{5 \ldots n}$: Performance of Critical Parameter X	Degree of compliance of the process from the critical parameter perspective.

A rating of the performance of alternative a_i with respect to criterion c_j is measured by a degree of satisfaction, expressed by $DoS_j(a_i), \forall \in \boldsymbol{A}$, and $\forall \in \boldsymbol{C}$. Hence, the evaluation for an alternative $a \in \boldsymbol{A}$, can be defined by a vector of the form:

$$DoS(a) = [DoS_1(a), DoS_2(a), \ldots, DoS_n(a)], \tag{8}$$

which includes all the performances of this alternative on the n criteria.

One additional aspect to consider when generating a ranking is the user's preferences (i.e., user's relative importance weighting of the criteria). This is done by using a weighting factor $\{w_j|(\forall c_j \in \boldsymbol{C})\exists w_j\}$, where $0 \leq w_j \leq 1$. The set $\boldsymbol{W}=\{w_1, w_2, \ldots, w_n\}$, includes all the weights for the criteria. If all the weights have the same value it means that there is no preference from the user. If some of the weights are zero, the criteria associated with those weights will not be considered by the ranking algorithm.

For new microsystem development, it is difficult, if not impossible, to find a precise, or "crisp", values for most of the criteria; some parameters are imprecise by nature and strongly subjective. For the system that we are proposing in this work, we have some pre-defined criteria to evaluate (see c_1 to c_4 on Table 7-2). However, these criteria may not be enough to evaluate a particular design. That is why we include the capability to define additional parameters. These parameters will be defined and evaluated in the criteria set *Performance of Critical Parameter X*. Ideally, it would be desired to have enough statistical data and well-defined process capability indices (C_{pk}) for every single process required to implement the various process steps for MEMS fabrication, in order to easily evaluate all the parameters of interest. Unfortunately this information is not available for many MEMS processes as these have not been thoroughly characterised and there is not enough previous information to build a probability distribution on the behaviour of these processes. Furthermore, many critical parameters will have a working range, not a single specific value. Hence, performance is often evaluated as "not good enough", "marginally good", "average", "good", etc. Vagueness is also present in the *Use of Known Process, Accessibility of Facility* and *Complexity* criteria (c_2, c_3 and c_4). *Cost* (c_1) is perhaps the only criterion that could be treated as a crisp or precise value, as these values are often available directly from facilities or can be estimated from prior data.

7.4. Fuzzy Inference System

As mentioned in the previous section, traditional tools used for evaluating performance of processes and parameters of interest have important shortcomings when used for MEMS fabrication processes. The problem at hand is that we need to evaluate *n* criteria in order to rank various alternatives with little statistical data (if any), considering a high degree of subjectivity in what each MEMS designer considers a "good" design, and with most of the evaluation criteria having vague and imprecise values, which makes it difficult to make direct comparison. A suitable approach when dealing with these situations is the use of *fuzzy sets* [163], [164]. The fuzzy sets framework provides a natural way of dealing with problems of imprecisely defined object class membership. Many applications in the areas of decision-making, process control, optimization, and expert systems, have been successfully developed using this type of approach [21], [165]–[169]. In this work, we have developed a methodology based on fuzzy sets, and more specifically using a fuzzy inference system, which we test on two case studies to demonstrate the potential applicability of our method.

When using fuzzy logic, knowledge is interpreted as a collection of elastic constraints on a collection of variables, and inference is considered to be a process of propagation of these elastic constraints. Fuzzy analysis is quite useful for decision-making problems which involve multiple criteria or multiple goals [170]. The ability to linguistically describe a process or a phenomenon and then represent that description with just few flexible rules is what gives the fuzzy set theory its power [171].

Fuzzy inference is the process of formulating the mapping from a given input to an output using the fuzzy logic concepts. The resulting mapping provides a set of bases from which decisions can be made [172]. The *fuzzy inference system* (FIS) is a computing framework founded on the concepts of fuzzy reasoning and consists of three conceptual components [173]: 1) rule base containing a set of fuzzy rules, 2) a database or dictionary that defines the *membership function* (MF) used in the fuzzy rules, and 3) a reasoning mechanism that performs the inference procedure. A generic block diagram of how a FIS works is shown in Figure 7-2. The system takes inputs, which could be crisp values or fuzzy definitions, and map them to an output space. This non-linear mapping is accomplished by a group of fuzzy *if-then* rules, each of which defines the local behaviour of the mapping. More specifically, the antecedent of a rule (e.g., $\bar{x}$ is A_1) defines a fuzzy region in the input space, while the consequent (e.g., y is B_1) specifies the output in the fuzzy region. This set of rules is the heart of the fuzzy system in the sense that all other elements in the system are used to implement these rules in a reasonable and efficient manner [22]. All the individual results from the rules are then combined (by the aggregator) to generate an aggregated MF, and then a *defuzzifier process* is performed to translate the fuzzy output into a crisp value.

We have developed a FIS combining two methods which are based on Zadeh's approach [164], namely, Mamdani's fuzzy inference method and the Sugeno method of fuzzy inference process (sometimes referred as the Takagi–Sugeno–Kang method or TS method). These two methods are arguably the most popular FISs [171], as they provide the basis for many applications, with a large number of papers in the literature citing them as their core methodology, which then modified and adjusted for various applications [174]–[183].

Mamdani's method was initially proposed by [184] as an attempt to implement a control system by synthesizing a set of linguistic control rules obtained from experienced human operators.

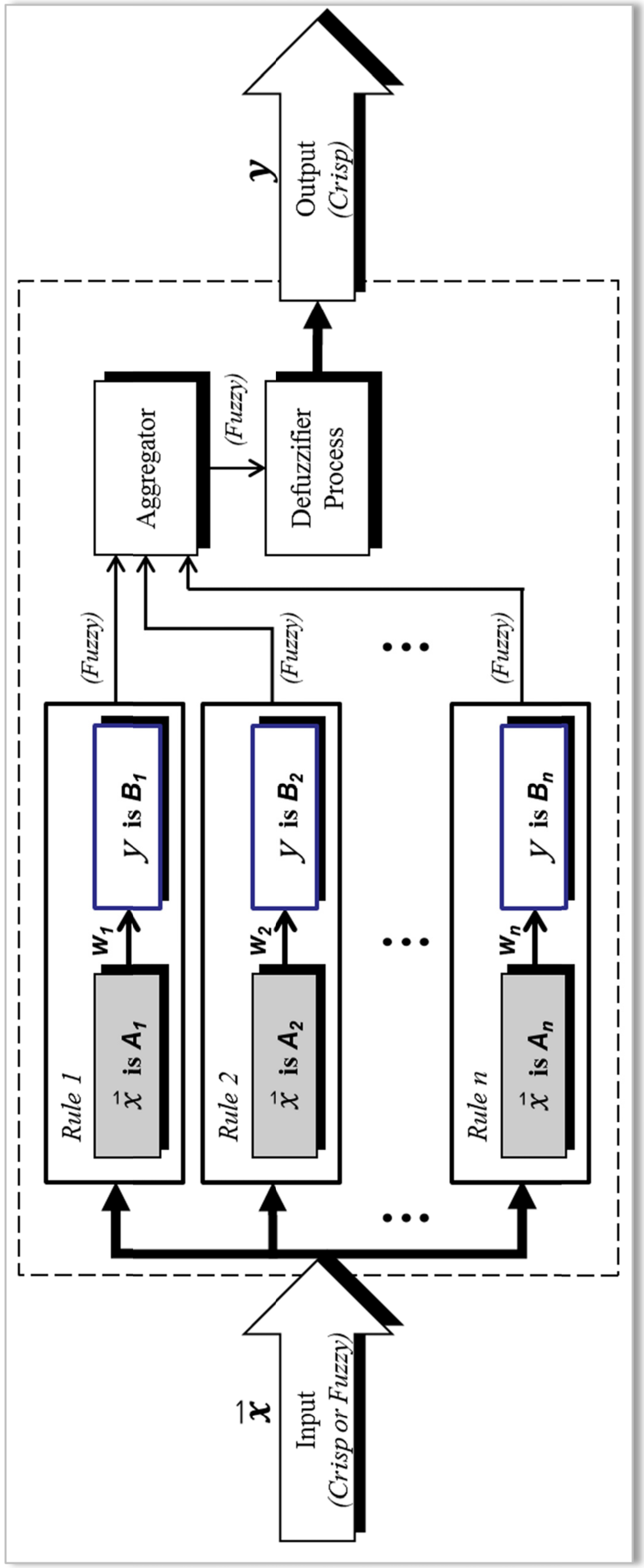


Figure 7-2: Fuzzy Inference System

In this type of system, the canonical structure for the rules will have the following structure:

IF *x* is *A* and *y* is *B* THEN *z* is *C*,

where *A* and *B* are fuzzy sets in the antecedent, and *C* is a fuzzy set in the consequent.

The Sugeno method that we build on was proposed by [185]. It is known for its computational efficiency, suitable for optimization and adaptive techniques, and it is well suited for mathematical analysis.

A typical canonical fuzzy rule for this method has the following structure:

IF *x* is *A* and *y* is *B* THEN *z= f(x,y)*,

where *A* and *B* are fuzzy sets in the antecedent, and z = *f(x,y)* is a crisp function in the consequent. Typically, *f(x,y)* is a polynomial in the input variables *x* and *y*, but it can be any other function that appropriately describes the output of the system within the fuzzy region specified by the antecedent of the rule. For instance, we use the zero-order form of the Sugeno model where the output level *z* is a constant.

In a similar way to the one described by [186], we consider criteria to be either tangible or intangible. For instance, from the criteria mentioned in Table 7-2, all are considered intangible except for *Cost*, which is tangible. In order to define a value for each alternative and generate a ranking for them, we combine the aforementioned methods through use of a zero-order Sugeno FIS, where each rule's consequent is specified by a fuzzy singleton (a fuzzy set with a membership function at a single particular point on the universe of discourse and zero everywhere else). In order to make our system more computationally efficient, we have segmented our inputs in two sets based on the sharpness that can be used to describe the output behaviour. We use the Sugeno FIS for all those input variables (i.e., criteria being evaluated) for which we can define crisp values for the desired output. For those variables whose outputs are more difficult to clearly describe using crisp values, we use a Mamdani approach, which allows us to define the output space using fuzzy values. This second method requires more computational processing, as a defuzzification process is needed in order to generate a crisp value. For our system, in order to defuzzify a set A of a universe of discourse Z, we use the defuzzify strategies described by (9) and (10).

For the Sugeno method, we use the *weighted average,*

$$WA = \frac{\sum_{i=1}^{N} \mu_A(z_i) z_i}{\sum_{i=1}^{N} \mu_A(z_i)}, \tag{9}$$

where N is the number of rules, and $\mu_A(z_i)$ is the aggregated firing strength for the singleton for the *i-th* rule.

For the Mamdani method we use the *centroid of area* (CoA) also known as the *center of gravity* (CoG),

$$CoA = \frac{\int_z \mu_A(z) z\, dz}{\int_z \mu_A(z) dz}, \tag{10}$$

where $\mu_A(z)$ is the aggregated output MF.

In Section 7.3, we defined the inputs for our system as the various alternatives for process steps to be used in a manufacturing process flow. Each of these alternatives will be evaluated according the criteria mentioned in Table 7-2. As discussed previously, we make a clear distinction between those variables for which the output behaviour is better known (i.e., *Cost* and *Use of known process*) for which the output can be represented as a fuzzy singleton (i.e., constant value) and for which we can use the Sugeno method; and those variables for which the output behaviour is defined as an imprecise range and presents a degree of vagueness requiring a membership function (MF) different than a fuzzy singleton (i.e., *Accessibility of facility*, *Complexity* and *critical parameters defined by the user*) and for which the Mamdani method would be a more appropriate approach. The method proposed here is combining these two approaches in two modules to deal with the different types of inputs (Figure 7-3) in order to define how suitable an alternative is.

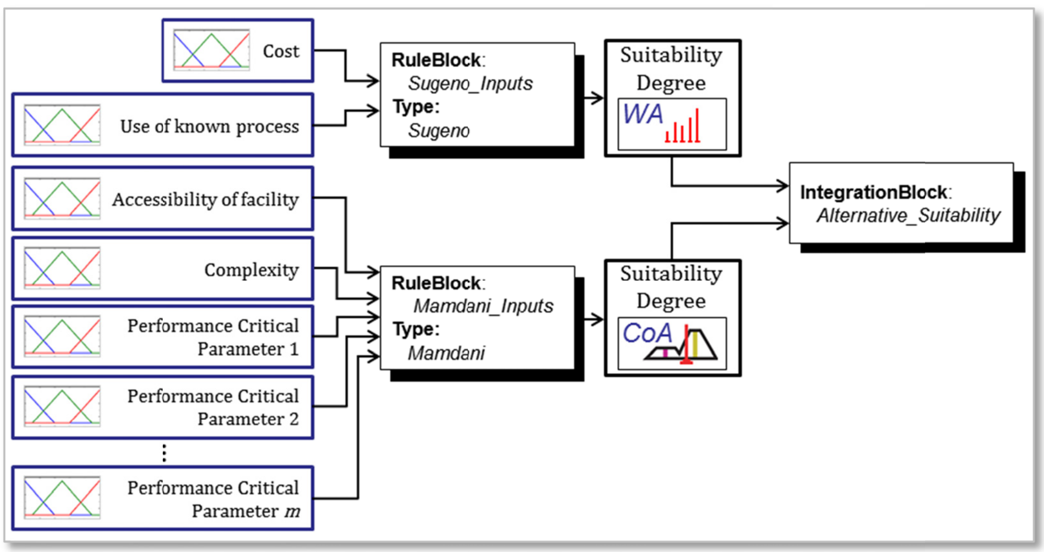


Figure 7-3: Structure of the FIS for analysing alternatives

Based on our private interactions with experts in the microsystems fabrication industry and by observing the development of process flow constructions over the last several years (see Section 1.4.1), it was possible to empirically define linguistic scales to be used for each of the criteria to properly describe the possible fuzzy sets. The fuzzy inference method and the linguistic terms associated with each criterion are shown in Table 7-3

In order to formalize the membership function, we define U as the universe of discourse, which is a finite set of k fuzzy numbers: $U=\{\tilde{u}_1, \tilde{u}_2, \ldots, \tilde{u}_k.\}$. These are used to express an imprecision level and are mapped to k linguistic terms. The value of k is selected based on the granularity requirements for each variable (i.e., amount of detail needed to truthfully express the behaviour of the variable). We treat the problem of constructing the membership functions (i.e., defining their shapes and intervals) to adequately capture the meanings of linguistic terms implied for this application (Table 7-3) as a *knowledge engineering* problem. We have elicited the knowledge of interest from experts in the field to express the behaviour of various variables when evaluating alternatives for MEMS processes in terms of propositions expressed in natural language. When defining the MFs for the variables on our system, we aim for simplicity and generality (i.e., the membership functions selected can be used for many cases that share the same behaviour). The specific details for our system regarding the MFs definition for the inputs and outputs variables, and the rule block for the Sugeno and Mamdani modules are presented in the next subsections.

Table 7-3: Fuzzy inference and defuzzification types

Method	Linguistic scale
Cost *(Sugeno)*	{Unacceptable, Expensive, Average, Convenient, Excellent}
Use of Known Process *(Sugeno)*	{New, Literature, Facility, User, Regular}
Accessibility of Facility *(Mamdani)*	{Unacceptable, Poor, Marginal, Average, Good, Great, Excellent}
Complexity *(Mamdani)*	{Simple, Complex}
Performance of Critical Parameter X *(Mamdani)*	{Unacceptable, Poor, Marginal, Average, Good, Great, Excellent}

7.4.1. Sugeno Model

We use the Sugeno module to simultaneously analyse the variables *Cost* and *Use of Known Process*, due to the fact that it is possible to define crisp values (i.e., singletons) for the desired outputs of these two variables, in order to obtain a normalized output value between 0 and 1. We name this output value *Process Suitability*, which will be the result of aggregating the effects of the input variables according to the rules defined for each.

The criterion *Cost* can be intuitively associated with a dollar value, ideally simple to arrive at. However, if more details are factored in (e.g., the cost of raw materials for various processes alternatives, shipping and handling costs for outsourced processes, the loss of devices due to transportation, etc.), it is not necessarily a trivial number. Hence, it is useful to fuzzify this input. Five fuzzy numbers should be associated with five linguistic levels:

$\{\tilde{u}_1,\tilde{u}_2,\tilde{u}_3,\tilde{u}_4,\tilde{u}_5\}=\{Unacceptable, Expensive, Average, Convenient, Excellent\}$.

Several fuzzifiers were tried and the most appropriate that we could identify for mapping the input value to the fuzzy set for this criterion was a fuzzifier using triangular MFs defined by (11). The intervals for these MFs were carefully selected in order to obtain the proper influence on the overall process ranking for the *Cost* criterion using the least complex MFs inputs, to facilitate processing. The graphical representations of the membership functions, μ_{uk}, are illustrated in Figure 7-4(a).

$$\mu_{u_1}(x) = \begin{cases} 0 & x < 0 \; or \; x > \frac{1}{4} \\ 1-4x & 0 \le x \le \frac{1}{4} \end{cases}$$

for k = 2, 3, 4:

$$\mu_{u_k}(x) = \begin{cases} 0 & x \le 0 \; or \; x \ge \frac{3}{4} \\ 4x-(k-2) & \frac{k-2}{4} < x \le \frac{k-1}{4} \\ k-4x & \frac{k-1}{4} < x < \frac{k}{4} \end{cases} \tag{11}$$

$$\mu_{u_5}(x) = \begin{cases} 0 & x \le \frac{3}{4} \; or \; x > 1 \\ 4x-3 & \frac{3}{4} < x \le 1 \end{cases}$$

The general behaviour of the output should be an increasing linear trend, as the more cost-effective the alternative being evaluated is, the more suitable that alternative will be, i.e., the degree of satisfaction (DoS) will be higher. To achieve this behaviour, five singleton output functions were defined in Table 7-4 and correlated with the input using the following rules:

IF (*Cost* is *Unacceptable*) THEN (*Process Suitability* is *Unacceptable*)

IF (*Cost* is *Expensive*) THEN (*Process Suitability* is *Marginal*)

IF (*Cost* is *Average*) THEN (*Process Suitability* is *Average*)

IF (*Cost* is *Convenient*) THEN (*Process Suitability* is *Good*)

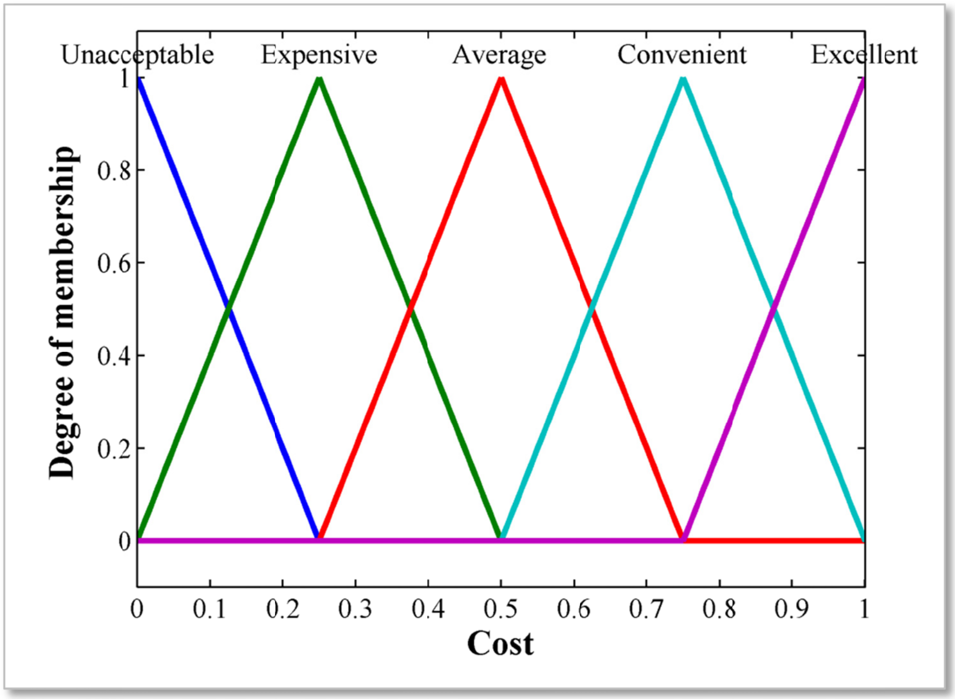
IF (*Cost* is *Excellent*) THEN (*Process Suitability* is *Excellent*)

Table 7-4: Output MFs (singletons) for "Cost"

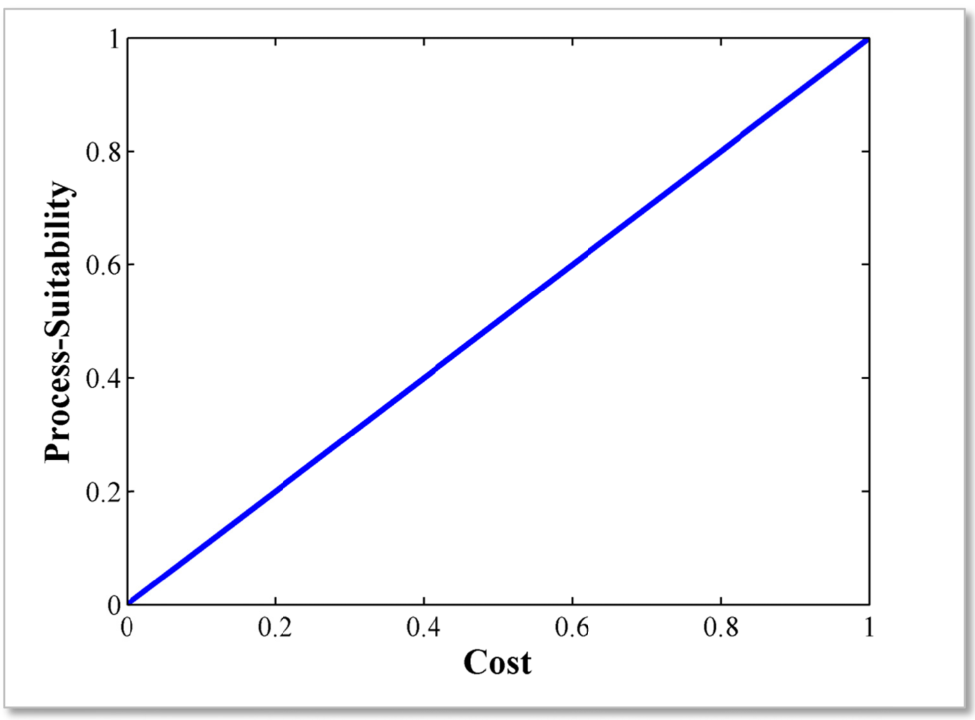
Output Singleton	Value
Unacceptable	0
Marginal	0.25
Average	0.5
Good	0.75
Excellent	1

In order to verify that we are achieving the desired response for the *Cost* criterion within our FIS, it is possible to generate a graphical interpretation of the fuzzy relation that we created. We plot a graph of the behaviour by sweeping the whole *Cost* range [0 to 1] using many values and observing the response of *Process Suitability*. Effectively, a linear increasing trend is achieved for the output (Figure 7-4 (b)). More details about graphical interpretation of fuzzy relations can be found in [187].

The evaluation metric for the *Use of Known Process* criterion we have developed is the *Commonness Process Index* (CPI), which defines how common a specific process is. CPI roughly represents the initial rate of success based on previous usage history of the process in question. By using observational techniques and tracking multiple developments for MEMS products (see Section 1.4.1), we were able to identify a specific behaviour for this relation, which we used to create Figure 7-5. In this figure, we can observe how new processes have a low CPI, while commonly used processes have a higher CPI. Table 7-5 shows a description of the five different scenarios and the typical CPI values we used in our work.



(a)



(b)

Figure 7-4: (a) Membership functions for criterion *"Cost"*; (b) Effect on the output for the criterion *"Cost"*

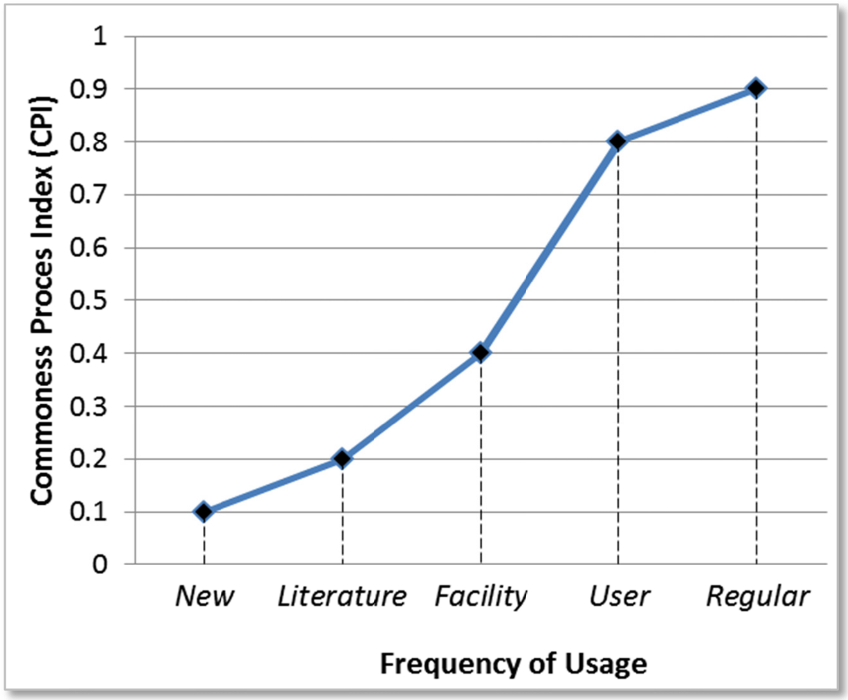


Figure 7-5: CPI membership function

Table 7-5: Commonness Process Index (CPI) values

Definition of Frequency of Usage	CPI Value
Process has never been tried before (Linguistic variable = *New*)	0.1
Process referenced in literature as successful process, but never tried before in the facility to be used. (Linguistic variable = *Literature*)	0.2
Facility: Process performed before in the fabrication facility to be used (not in regular basis) (Linguistic variable = *Facility*)	0.4
Process performed before in the facility to be used by the author of this recipe (Linguistic variable = *User*)	0.8
Process performed by several users in regular basis in the fabrication facility to be used (Linguistic variable = *Regular*)	0.9

In the same way as with the Cost criterion, an analysis was performed to find the most appropriate MFs for this variable. The mapping for the fuzzy set to linguistic terms is:

$\{\tilde{u}_1,\tilde{u}_2,\tilde{u}_3,\tilde{u}_4,\tilde{u}_5\}$ = {*New, Literature, Facility, User, Regular*}.

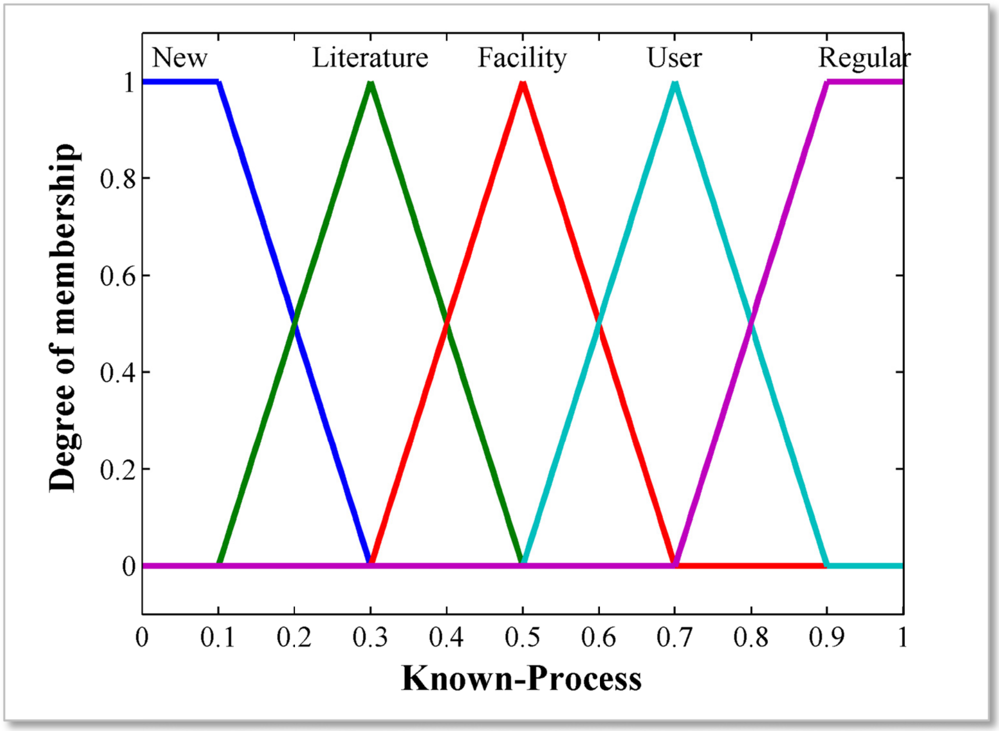
The best option we were able to find for the MFs that better describe the desired behaviour for the *Use of Known Process* input and minimize complexity at the same time are two special cases of trapezoidal MF for the extremes (R-function and L-function), and three triangular MFs. The two trapezoidal functions help to define the slow rate of change present in the lowest and highest ends of the relation of *CPI* vs. *Frequency of Usage* (Figure 7-5) . The formal definitions for these are stated in Equitation (12) and shown graphically in Figure 7-6(a). In similar way as with the previous criterion, to ensure the contribution to the output is as close as required, five singletons were defined empirically (Table 7-6).

$$\mu_{u_1}(x)=\begin{cases} 0 & x>\frac{3}{10} \\ \left(\frac{3}{2}\right)-5x & \frac{1}{10}\le x\le\frac{3}{10} \\ 1 & x<\frac{1}{10} \end{cases}$$

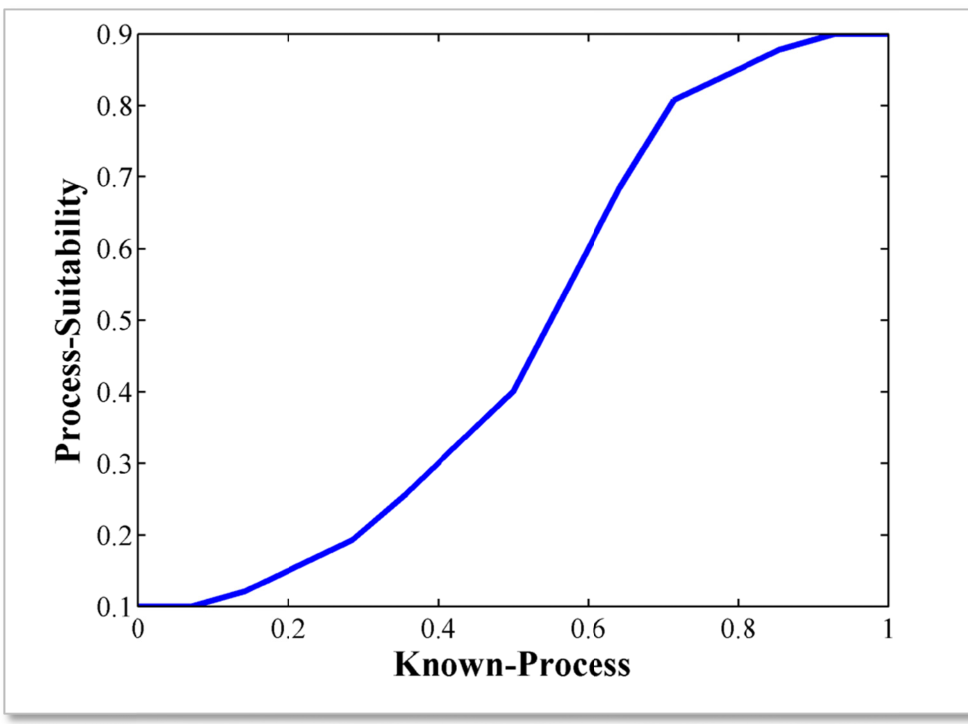
for k = 2, 3, 4

$$\mu_{u_k}(x)=\begin{cases} 0 & x\le\frac{1}{10} \text{ or } x\ge\frac{9}{10} \\ 5x-\left(\frac{3}{2}\right)+(3-k) & \left(\frac{k}{5}\right)-\frac{3}{10}<x\le\left(\frac{k}{5}\right)-\frac{1}{10} \\ (k-2)+\left(\frac{5}{2}\right)-5x & \left(\frac{k}{5}\right)-\frac{1}{10}<x<\left(\frac{k}{5}\right)+\frac{1}{10} \end{cases} \tag{12}$$

$$\mu_{u_5}(x)=\begin{cases} 0 & x<\frac{7}{10} \\ 5x-\left(\frac{7}{2}\right) & \frac{7}{10}\le x\le\frac{9}{10} \\ 1 & x>\frac{9}{10} \end{cases}$$



(a)



(b)

Figure 7-6: (a) Membership functions for criterion *"Use of Known Process"*; (b) Effect on the output for this criterion.

Table 7-6: Output MFs (singletons) for *"Use of Known Process"*

Output Singleton	Value
CPI1	0.1
CPI2	0.2
CPI3	0.4
CPI4	0.8
CPI5	0.9

The rules for *Use of Known Process* variable are:

IF (*Use of Known Process* is *New*) THEN (*Process Suitability* is *CPI1*)

IF (*Use of Known Process* is *Literature*) THEN (*Process Suitability* is *CPI2*)

IF (*Use of Known Process* is *Facility*) THEN (*Process Suitability* is *CPI3*)

IF (*Use of Known Process* is *User*) THEN (*Process Suitability* is *CPI4*)

IF (*Use of Known Process* is *Regular*) THEN (*Process Suitability* is *CPI5*)

Once again, in order to verify how the FIS is responding to the *Use of Known Process* input, we plot this input against the *Process Suitability* normalized output, using many values in the whole input range [0 to 1]. Figure 7-6(b) shows the results of this verification and it is possible to observe a close match of this graph with the expected behaviour (Figure 7-5). This is an explicit indication that the MFs defined for this input, the set of rules used for it, and the values of output singletons are the appropriated ones.

The aggregated output for the Sugeno module of our FIS, which is generated when operating simultaneously the *Cost* and *Use of Known Process* variables, can be observed in a three-dimensional graph. This is depicted in Figure 7-7, where we can observe that the most suitable process (i.e., the one with the highest *Process Suitability* value) will be the one with the most convenient *Cost* and where the *Use of Known Process* has the highest CPI.

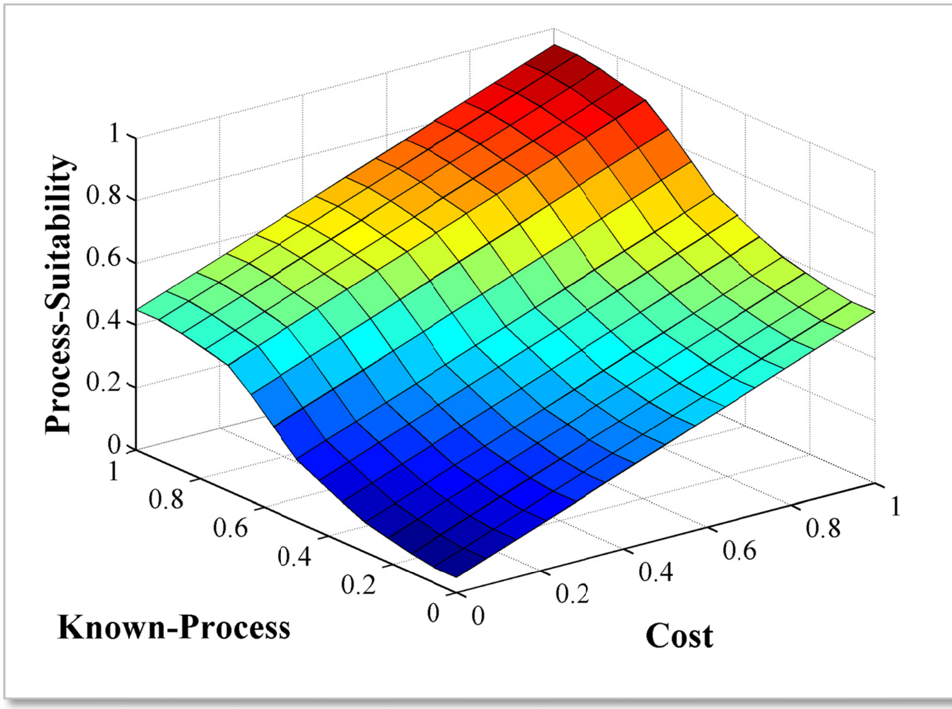


Figure 7-7: Output for the Sugeno component of the system

7.4.2. Mamdani Module

We use the Mamdani method when it is not possible to define output singletons as outputs of the inference system. This is the case for the *Accessibility of Facility* and *Complexity* criteria, and the *Performance for Critical Parameter X* criteria set. These inputs will be evaluated, aggregated, and defuzzified in order to generate a value for the *Process Suitability* output value and combined with the value obtained from the Sugeno module.

The *Process Suitability* output for the Mamdani module should be represented by a generic, descriptive, and normalized output, in order to identify the process suitability for a given alternative considering the impact of various inputs in the module. Our system combines all the various input values of the Mamdani module to calculate a single output.

The generic output that we have defined is formally described in (13) and depicted in Figure 7-8.

$$\mu_{u_1}(x) = \begin{cases} 0 & x > \frac{1}{3} \\ 2-6x & \frac{1}{6} \le x \le \frac{1}{3} \\ 1 & x < \frac{1}{6} \end{cases}$$

for $k = 2, 3, 4$

$$\mu_{u_k}(x) = \begin{cases} 0 & x \le \frac{1}{6} \, or \, x \ge \frac{5}{6} \\ 6x+(1-k) & \frac{k-1}{6} < x \le \frac{k}{6} \\ (k+1)-6x & \frac{k}{6} < x < \frac{k+1}{6} \end{cases} \tag{13}$$

$$\mu_{u_5}(x) = \begin{cases} 0 & x < \frac{2}{3} \\ 6x-5 & \frac{2}{3} \le x \le \frac{5}{6} \\ 1 & x > \frac{5}{6} \end{cases}$$

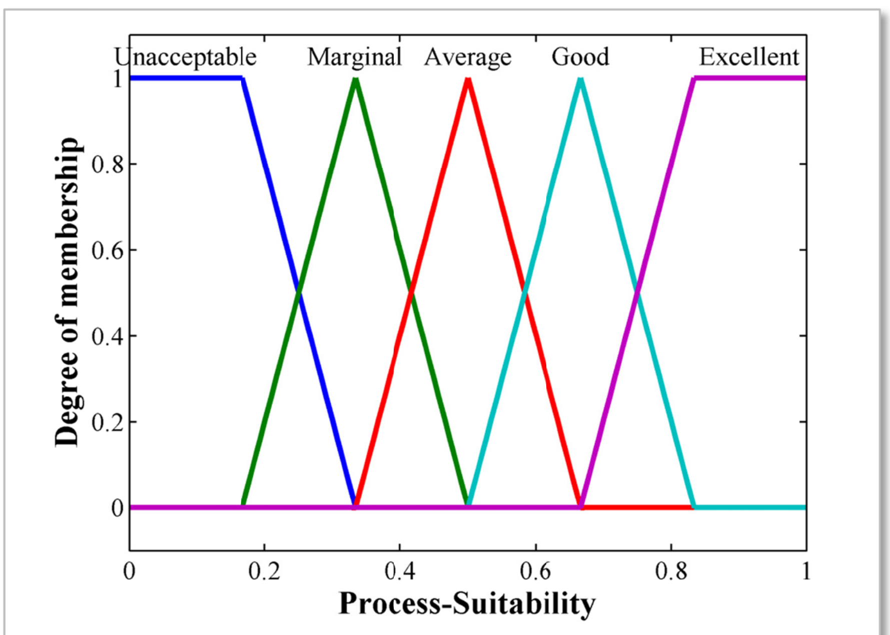


Figure 7-8: Mamdani module general output MFs

The desired performance for critical parameters in similar microsystems can be quite different from one application to another. For example, a pressure sensor based on piezoresistivity elements for a specific application may require the surface dopant concentration to be few orders of magnitude higher (or lower) than another pressure sensor for a different application. Many other functional parameters and specifications could be identical, but that specific parameter should be totally different in order for the device to work properly. Therefore, we always need to verify the criteria against a specific application functional range (i.e., a range that will provide the functionality required for the microsystem for a given application). Due the high number of possible criteria that may need to be described, a generic but comprehensive definition of linguistic terms is required. The linguistic scale adopted for the generic inputs in this module is the one defined by [188], which is formed by seven linguistic levels:

$\{\tilde{u}_1,\tilde{u}_2,\tilde{u}_3,\tilde{u}_4,\tilde{u}_5,\tilde{u}_6,\tilde{u}_7\}=\{$*Unacceptable, Poor, Marginal, Average, Good, Great, Excellent*$\}$.

Here we use the same normal triangular fuzzy numbers for the universe of discourse as the one employed by [186]. With these membership functions, it is possible to cover the entire spectrum of options for characteristics of the various inputs and still use simple triangular MFs. The formal definitions for these MFs are described by (14) and shown graphically in Figure 7-9(a).

$$\mu_{u_1}(x)=\begin{cases}0 & x<0 \; or \; x>\frac{1}{6}\\ 1-6x & 0\le x\le\frac{1}{6}\end{cases}$$

$$\mu_{u_2}(x)=\begin{cases}0 & x<0 \; or \; x>\frac{1}{3}\\ 3x+\frac{1}{2} & 0\le x\le\frac{1}{6}\\ 2-6x & \frac{1}{6}<x\le\frac{1}{3}\end{cases}$$

for k = 3, 4, 5

$$\mu_{u_k}(x)=\begin{cases}0 & x\le\frac{k-2}{6} \; or \; x\ge\frac{k}{6}\\ 6x-(k-2) & \frac{k-2}{6}<x\le\frac{k-1}{6}\\ k-6x & \frac{k-1}{6}<x<\frac{k}{6}\end{cases} \tag{14}$$

$$\mu_{u_6}(x)=\begin{cases}0 & x\le\frac{2}{3} \; or \; x>1\\ 6x-4 & \frac{2}{3}<x\le\frac{5}{6}\\ \frac{7}{2}-3x & \frac{5}{6}<x\le 1\end{cases}$$

$$\mu_{u_7}(x)=\begin{cases}0 & x\le\frac{5}{6} \; or \; x>1\\ 6x-5 & \frac{5}{6}<x\le 1\end{cases}$$

The input of seven linguistic levels was mapped to the five linguistic levels output by using the following rules:

IF (*Critical-Parameter1* is *Unacceptable*) THEN (*Process Suitability* is *Unacceptable*)

IF (*Critical-Parameter1* is *Poor*) THEN (*Process Suitability* is *Marginal*)

IF (*Critical-Parameter1* is *Marginal*) THEN (*Process Suitability* is *Marginal*) **(Weight 0.5)**

IF (*Critical-Parameter1* is *Average*) THEN (*Process Suitability* is *Average*)

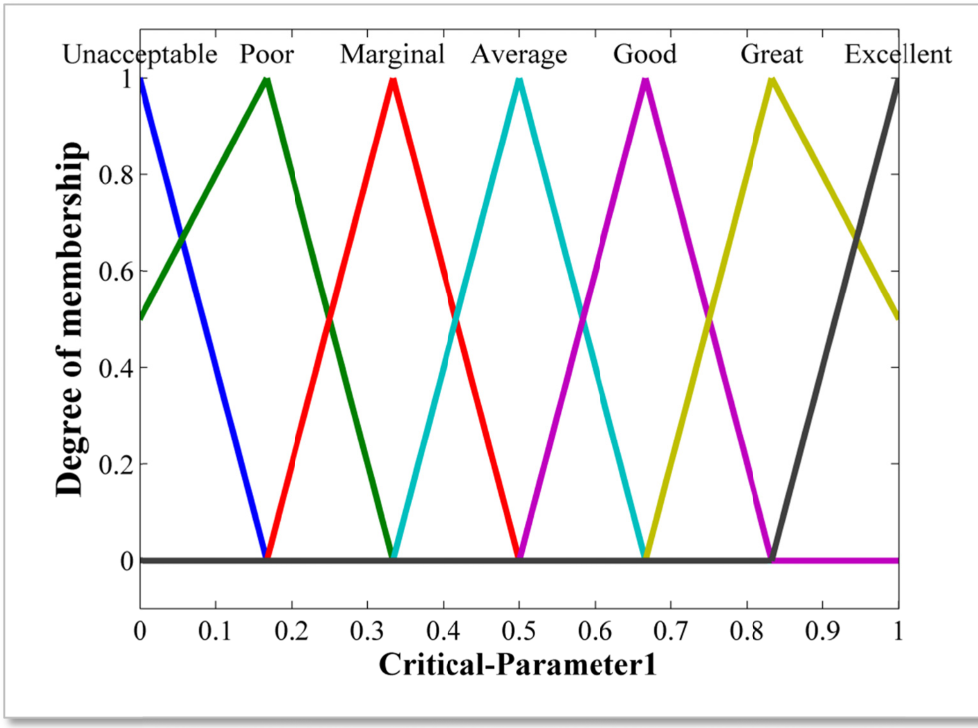
IF (*Critical-Parameter1* is *Good*) THEN (*Process Suitability* is *Good*) **(Weight 0.5)**

IF (*Critical-Parameter1* is *Great*) THEN (Process-Suitability is Good)

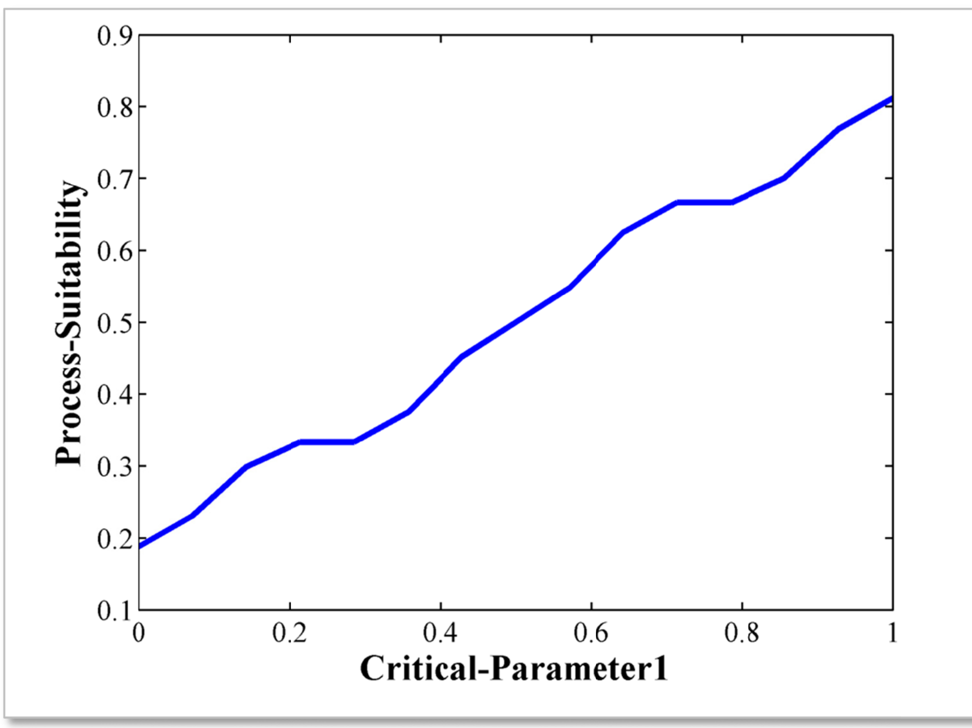
IF (*Critical-Parameter1* is *Excellent*) THEN (*Process-Suitability* is *Excellent*)

IF (*Complexity* is *Simple*) THEN (*Process-Suitability* is *Excellent*)

Note that there are two rules that have a weight value of 0.5; this is due the fact that we map our linguistic input variables using seven fuzzy numbers to a more coarse output of only five linguistic variables. By defining these weights, we can achieve the desired behaviour in the output (Figure 7-9 (b)). This will be generated and combined for each of the critical parameters to be evaluated.



(a)



(b)

Figure 7-9: Input MF for performance of critical parameters

Another important factor in defining critical parameters in evaluation of a microsystem, is the current stage of development. For instance, the degree of importance of a critical parameter during a proof of concept, or initial prototyping stage, may be different than during an up-scaling stage. During the proof of concept phase, simply proving the feasibility of experimentally implementing the various theoretical concepts will be much more important than any concerns of the various intricate details that might be required. Conversely, during an up-scaling phase, critical parameters might be controllability and repeatability, which are directly related with the complexity of the fabrication steps.

We are certain that since the inception of any design, the degree of complexity for manufacturing processes should be minimized, especially to promote design for manufacturability. The level of complexity is one of the pre-define criteria that we propose to be evaluated for every design. For instance, it is well known that the larger the total number of steps in the process the more probability of a fatal defect [189]. Our understanding of microsystems allowed us to model and to define specific behaviour for complexity for fabrication. As the complexity increases, there are some requirements to improve the fabrication success rate.

In Figure 7-10, the probability of success of a fabrication step, its relation with the complexity degree, and the characteristics required to deal with the complexity are illustrated in four different regions (R1 to R4).

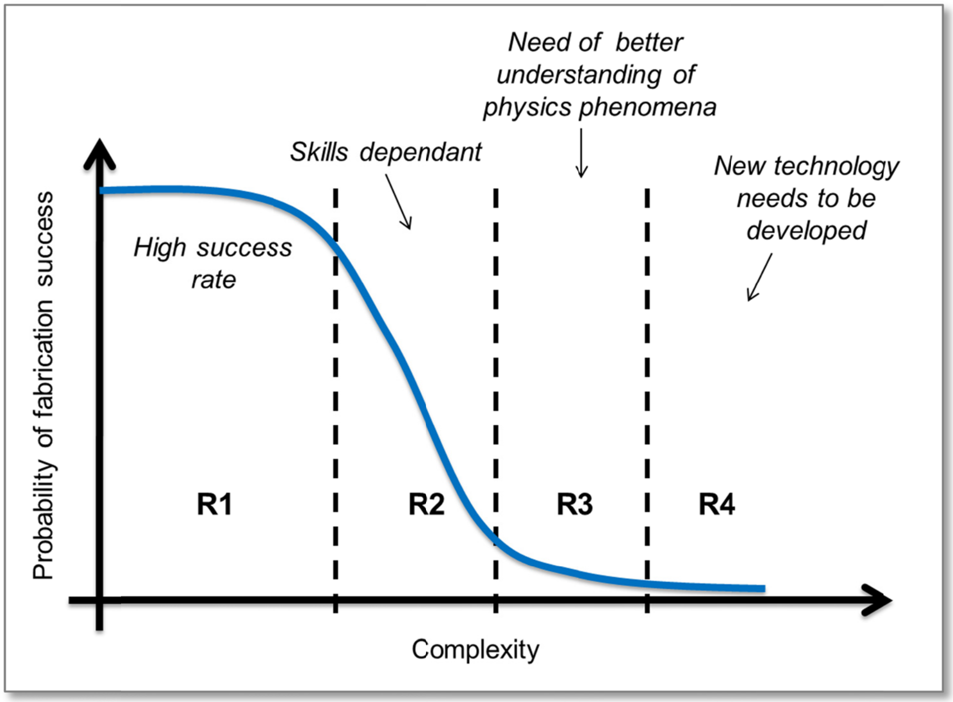
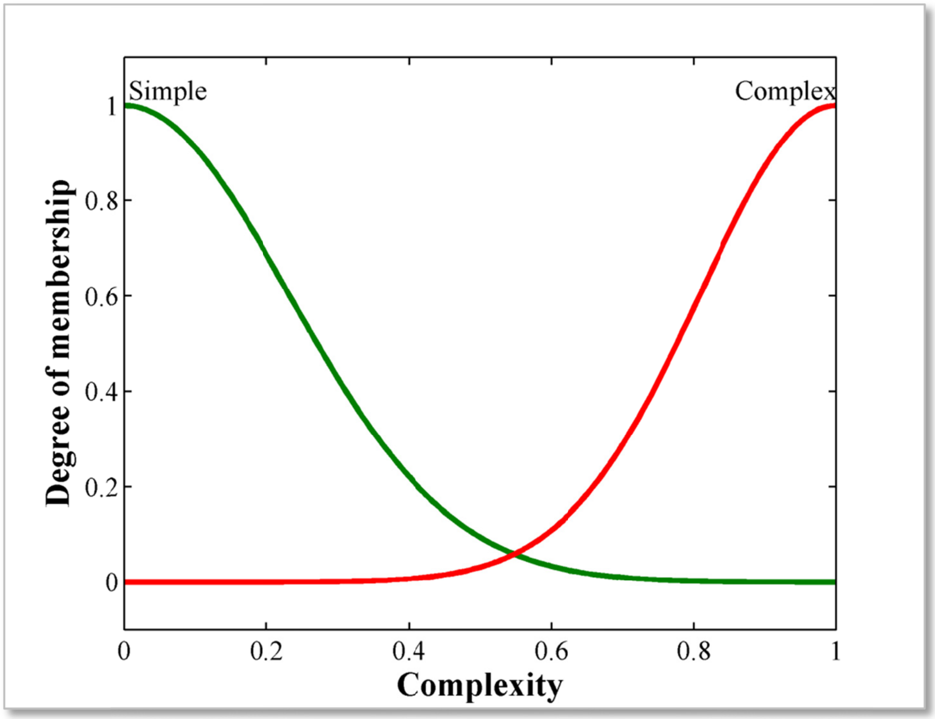


Figure 7-10: Fabrication success and complexity

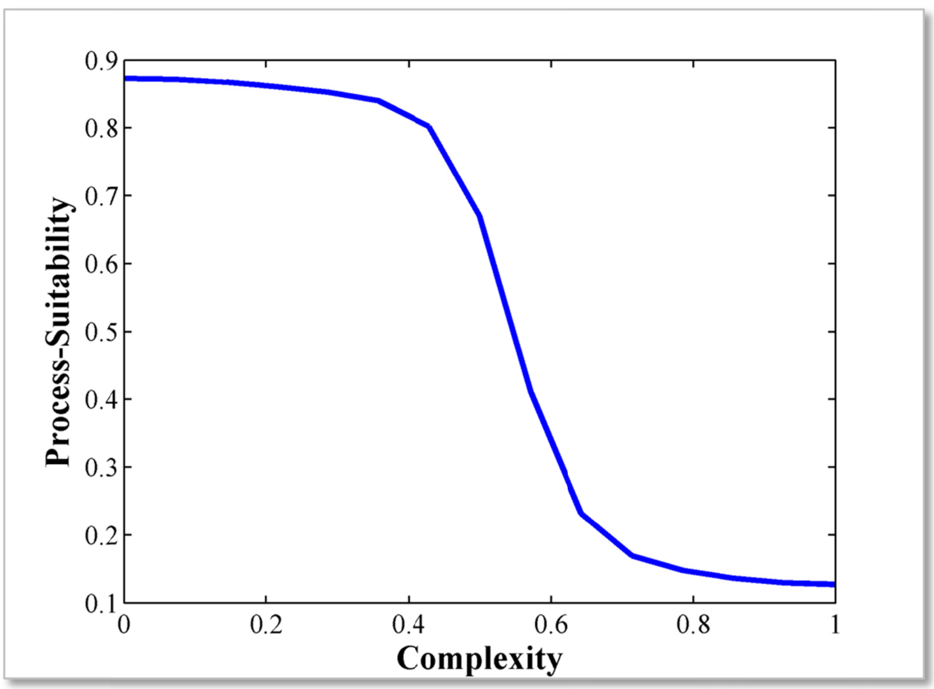
The best way to account for the behaviour of the critical parameter *Complexity* (depicted in Figure 7-10) in our fuzzy model was to define MFs using two Gaussian curves that represent the linguistic fuzzy variables $\{\tilde{u}_1,\tilde{u}_2\}$={Simple, Complex}. The formal definition of the generic Gaussian curve is shown in (15):

$$f(x;\sigma,c)=e^{\frac{-(x-c)^2}{2\sigma^2}}, \tag{15}$$

where c is the centre of the peak, and σ is the standard deviation which controls the width of the bell. Many values for c and σ were evaluated; the best values found to represent our MFs are listed in Table 7-7. The graphical representation of these Gaussian curves as MFs is shown in Figure 7-11(a).



(a)



(b)

Figure 7-11: (a) Membership functions for criterion *"Complexity"*; (b) Effect on the output for this criterion.

Table 7-7: Values for c and σ for the MFs of Complexity

MF	*c*	σ
Simple	0	0.23
Complex	1	0.19

Using the values from the table above in combination with the following rules:

IF (*Complexity* is *Simple*) then (*Process Suitability* is *Excellent*)

IF (*Complexity* is *Complex*) then (*Process Suitability* is *Unacceptable*),

we can achieve a close match to the desired behaviour in the output of the Mamdani module. The verification of this can be observed in Figure 7-11(b).

In Figure 7-12, it is possible to observe that the most suitable alternative will be the one that can be achieved with the minimum complexity and the best performance in the critical parameter being evaluated. This behaviour is extended to include *m* critical parameters.

The modules for the fuzzy inference system mentioned in sections 7.4.1 and 7.4.2 were implemented in MATLAB®. The definition files containing the various inputs and membership functions for these modules are provided in APPENDIX "B".

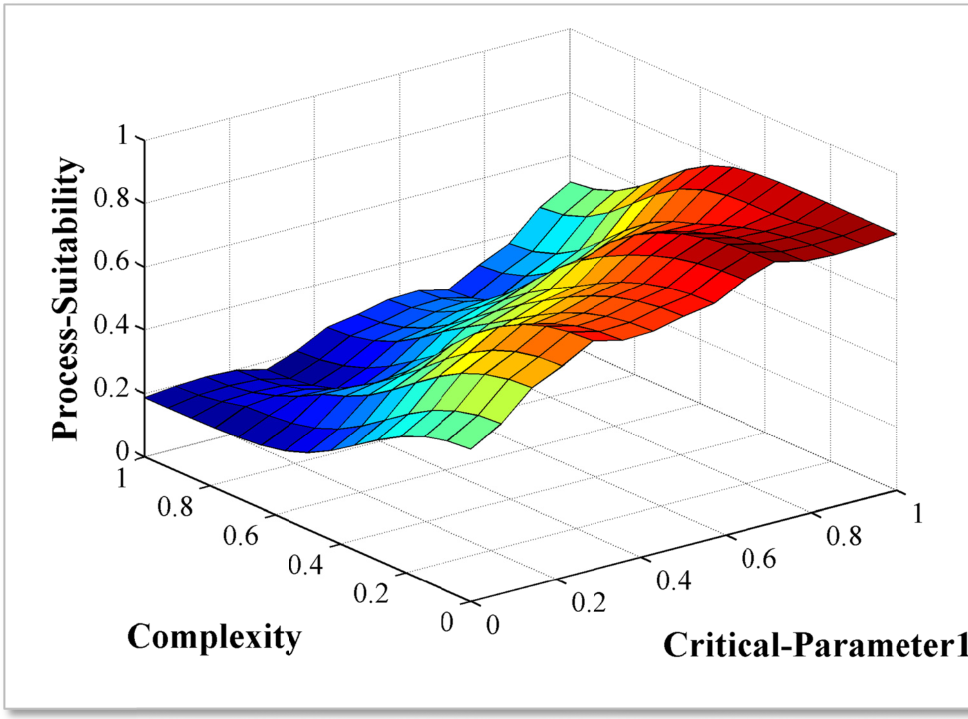


Figure 7-12: Output for the Mamdani component of the system

7.4.3. Integration Module

In Sections 7.4.1 and 7.4.2, two modules were presented where different inputs were combined. The intervals used to define the membership functions for input variables (Equations (11), (12)and (14)) were established based on the following objective: Identify the ***most generic*** and the ***simplest*** membership functions (MFs), with the granularity required to properly map the influence each input variable should have in the overall ranking process for each alternative.

In Equation (11), which represents the intervals for the *Cost* input variable of the Sugeno module, five simple triangular functions, equally spaced in the 0 to 1 range, in combination with the five output singletons, were enough to represent the desired behaviour in a reliable way, as the desired behaviour is a linear up-rising trend from 0 to 1. In Equation (12), which defines the required intervals for the *Use of Known Process* input variable of the Sugeno module, two trapezoidal membership functions (MFs 1 and 5) were needed in order to reliably represent the two extremes of the desired behavior observed in the *Commonness Process* Index (Figure 7-5). These two extremes present a small rate of change in comparison with the segments in middle of the graph. Equation (14) was designed to provide a general definition to be used when evaluating any new input variable within the Mamdani module. Based on the theory provided by [188], seven linguistic levels were defined to provide enough detail to represent the various performance levels. The simplest configuration is to use seven triangular MFs with non-symmetrical MFs 2 and 6 overlapping over MF 1 and 7, respectively.

Equation (13) defines the generic output for ALL the variables used on the Mamdani module. For this work we considered that it is extremely important that all the inputs in the Mamdani module are evaluated using the same metric (i.e., to have only one output were all the inputs are aggregated). The intervals were carefully selected in order to provide 5 linguistic intervals that are able to describe how suitable a given alternative is. These five linguistic levels should be general enough but at the same time they should provide a degree of malleability so the mapping from a new *Critical Parameter* defined by the user is easy to map in order to represent the desired behavior.

Similarly, we look for the simplest way that truthfully maps the behaviour of the Complexity variable (Figure 7-10). In order to do this, we tried various linear functions with some success. However, there was generally a need to use multiple rules and several input MFs. Then we realized that we could greatly simplify the mapping process by using only two Gaussian functions, mapped to the two trapezoidal MFs in the generic output of the Mamdani module. Doing this (and adjusting the values for c and σ (Table 7-7) to properly match the desired performance), we only needed two MFs input and two rules to represent the four regions observed in Figure 7-10.

As depicted in Figure 7-3, once all the multiple criteria have been evaluated using the two methodologies mentioned previously, we aggregate the two *Suitability Degrees* outputs from the Sugeno and Mamdani modules to generate a crisp value that can be used to rank the various alternatives. This is done by considering the total weight of the criteria evaluated by each module and combining the two normalized values of *Suitability Degrees* obtained. The final *Alternative Suitability* value which will be used to rank the different process flow options is calculated by:

$$AS = \left[\left(\sum w_S\right)(\mathrm{SD}_S)\right] + \left[\left(\sum w_M\right)(\mathrm{SD}_M)\right], \qquad (16)$$

where w_S and w_M are the weights defining user preferences in the Sugeno and Mamdani modules, respectively; and SD_S and SD_M are the suitability degrees for the Sugeno and Mamdani modules, respectively.

It is important to note here that the rules used within each rule block can be combined into a more compact form. However, we decided to keep the rules independent from each other in order to account for the users' preferences by giving weights to each criterion, as mentioned in Section 7.3. For instance, when evaluating two criteria, *Critical Parameter 1* and *Critical Parameter 2*, the rule for unacceptable performance could be expressed as:

IF (*Critical-Parameter1* is *Unacceptable*) OR (*Critical Parameter 2* is *Unacceptable*) THEN (*Process Suitability* is *Unacceptable*)

This is a more compact form that combines two rules into one; however, if the user considers that *Critical Parameter 1* is more important than *Critical Parameter 2*, there is not an easy way to account for that preference. By keeping the rules for each criterion independent from one another, we can proceed with the following rules:

IF (*Critical-Parameter1* is *Unacceptable*) THEN (*Process Suitability* is *Unacceptable*) **[Weight =1]**

IF (*Critical-Parameter2* is *Unacceptable*) THEN (*Process Suitability* is *Unacceptable*) **[Weight = 0.5]**

This will account for the user's preference that *Critical Parameter 2* is only half as important as *Critical Parameter 1*, or conversely that *Critical Parameter 1* is two times more important that *Critical Parameter 2*.

If the user defines no preferences, all weights for the various criteria will be unity and the rules for the various criteria will have the same importance. If partial preferences are present (i.e., the user would like to assign different priorities of importance for the various criteria), we use Analytic Hierarchy Process (AHP), [190]–[192], to help the user identify the most appropriate weights to represent these preferences and account for them in the decision process.

7.4.4. Case Study #1 — Impurity doping for a pressure sensor (Diffusion vs. Ion implantation)

One of the key operations in fabrication of MEMS-based pressure and stress sensors is impurity doping. This operation allows inserting impurities into a semiconductor material to change its electrical properties [36]. By carrying this out in a controlled way, it is possible to use physical shape deformation to change the electrical resistivity in the material, which can be used to measure the stress causing the deformation [46]. The two most common methods to perform impurity doping are diffusion [47] and ion implantation [193]. Schematics of these two processes are shown on Figure 7-13.

To demonstrate the functionality of the methodology described in this work, we analysed a case of the development of a three-dimensional stress sensor which uses several different levels of dopant concentrations [194], [195]. After the analytical verification of the initial physical design, we select the best manufacturing impurity doping technique between the two alternatives:

a_1: diffusion using a solid phosphorous source, and

a_2: phosphorous ion implantation.

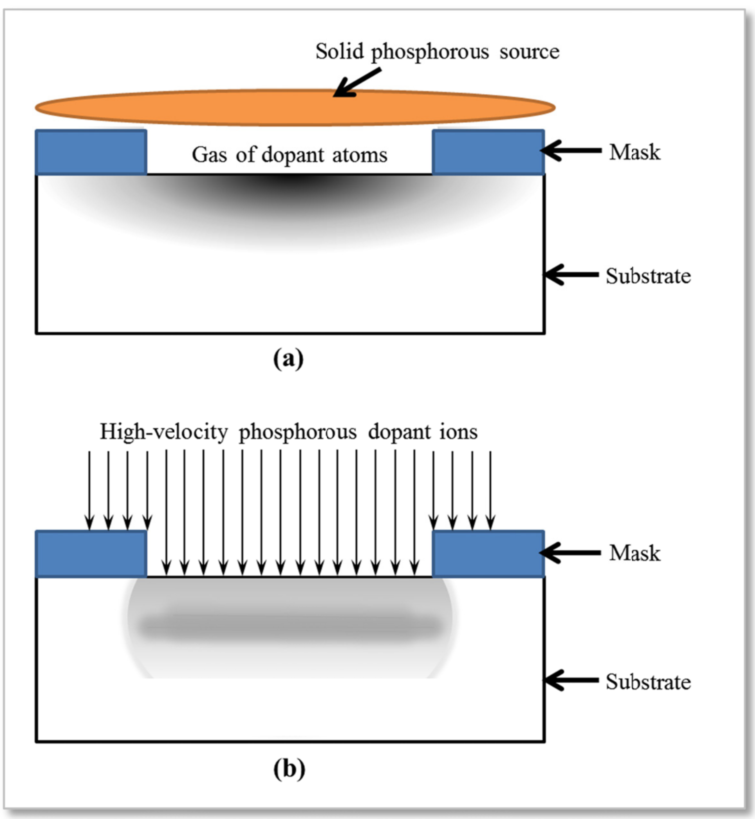


Figure 7-13: (a) Doping by diffusion and (b) ion implantation

These two alternatives were evaluated in the context of the development of the pressure sensor mentioned previously, according to pre-defined criteria as well as additional critical parameters defined by the user (and their relative importances). Our "user" was the principal sensor designer and manufacturing process developer for a MEMS-based stress sensor. The pre-defined and user-defined criteria used for this evaluation are listed in Table 7-8.

Table 7-8: Parameters being evaluated for impurity doping

Name	Type
c_1: **Cost**	*(pre-defined)*
c_2: **Use of Known Process**	*(pre-defined)*
c_3: **Accessibility of Facility**	*(pre-defined)*
c_4: **Complexity**	*(pre-defined)*
c_5: **Doping Concentration**	*(user-defined)*
c_6: **Uniformity of Dopant**	*(user-defined)*
c_7: **Reproducibility**	*(user-defined)*

As mentioned in Section 7.4.3, we used AHP to find the weights to represent the relative importance for each parameter in comparison with the others (the "Relative Importance" columns of Table 7-9). In order to make a fair comparison of all parameters, the AHP method requires calculation of normalized values (the "Normalized Values" columns of Table 7-9) to define the preference weights. The weights were obtained as the normalized eigenvector, ***W***, given in the rightmost column of Table 7-9.

Table 7-9: Weight calculation by using AHP matrices for impurity doping

	Relative Importance							Normalized Values							*weights*
c_j	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_1	c_2	c_3	c_4	c_5	c_6	c_7	$W=\{w_j\}$
c_1	1	2	1/3	1/7	1/9	1/9	1/7	0.03	0.06	0.01	0.02	0.04	0.04	0.02	**0.029**
c_2	1/2	1	1	1/7	1/9	1/9	1 1/7	0.01	0.03	0.03	0.02	0.04	0.04	0.02	**0.026**
c_3	3	1	1	1/5	1/9	1/9	1/5	0.08	0.03	0.03	0.02	0.04	0.04	0.02	**0.038**
c_4	7	7	5	1	1/3	1/3	1	0.19	0.19	0.17	0.12	0.11	0.11	0.12	**0.144**
c_5	9	9	9	3	1	1	3	0.25	0.25	0.3	0.35	0.33	0.33	0.35	**0.31**
c_6	9	9	9	3	1	1	3	0.25	0.25	0.3	0.35	0.33	0.33	0.35	**0.31**
c_7	7	7	5	1	1/3	1/3	1	0.19	0.19	0.17	0.12	0.11	0.11	0.12	**0.144**

According to our previously identified user, the most important parameters for this application are the doping concentration and the uniformity of the dopant, as the process will not function is these parameters are outside an acceptable range. Coming next in importance are the user defined reproducibility and complexity, as his objective is to take it to a mass production stage. After those criteria, the accessibility of the facility, cost, and use of a known process are at the bottom of the priority list. The calculated weights were applied to each of the rules for the fuzzy inference system.

The perceived performances of all the previously defined criteria, for this specific application, were evaluated and expressed by the user using the linguistic levels defined for each criterion, as follows:

- *Cost* (c_1), for diffusion (a_1) has been mapped to a linguistic value of *Excellent*, as the costs incurred to execute this process step are practically reduced to buying the solid phosphorous source only (at the time of this analysis the cost of a phosphorous solid source for doping was approximately $150 USD from [196]), as all the required equipment is owned by the user and the operating expenses are minimal. This solid source can be used many times, hence, the price per process run incurred by the user is extremely economical. The cost of ion implantation (a_2) is expensive for the user in comparison with the previous alternative (at the time of this analysis in the price for a run of ion implantation varies from $750 to $1,500 USD depending on the dose and energy required [197]), hence a linguistic variable of *Expensive* was used to described this criteria.
- For *Use of Known Process* (c_2), a_1 and a_2 have similar performance, as both processes are performed on regular basis and their *Commonness Process Index* is the highest possible for both alternatives.

- The *Accessibility of Facility* (c_3) is excellent for a_1 as the user owns the facilities where this process step can be performed. For a_2, the access to facilities is not as simple. The samples are required to be sent to another facility for processing, and in some cases it is not possible to accommodate immediate processing. Therefore, the perceived performance for a_2 was described using the linguistic variable of *Average.*
- Regarding *Complexity* (c_4), many more processing steps are required to achieve the three different dopant concentrations using a_1, than with those required to do the same using alternative a_2, and the level of complexity for the processing steps used by diffusion surpass those required by the ion implantation process.
- For *Doping Concentration* (c_5), the values obtained using a_1 seems to be high in comparison with the values obtained with the analytical study performed by the user [194], and performance was only marginal. The three doping concentrations of impurities for the sensing elements obtained by phosphorous diffusion with a solid source are 2×10^{20}, 1.2×10^{20}, and 7×10^{19} cm^{-3} [194]. On the other hand, the resulting peak concentrations of dopants obtained by a_2 are 7.4×10^{19}, 4.7×10^{19} and 2.9×10^{19} cm^{-3} [195]. These values worked extremely well identifying stresses in the three axes, because of this, a_2 is rated as excellent.
- For *Uniformity of Dopant* (c_6), this criterion was hard to maintain at a constant level when using a_1 and the diffused concentrations on the surface were non-uniform. This interfered when trying to calibrate the sensor. This problem does not exist using ion implantation, a_2, as the uniformity in the dopant concentration profile is quite good, allowing full calibration of the sensor [195].
- The last criterion evaluated was *Reproducibility* (c_7). The controllability of where the dopant impurities will reside after the doping process, the user felt that it is

much better using the ion implantation process, as this can be precisely controlled by regulating the velocity of the ions. When using diffusion, this parameter is not so easily controlled, hence, this process did not work very well for the application intended for the sensor.

A summary of the performance for the multiple criteria for each of the two alternatives is presented in Table 7-10.

Table 7-10: Performance of criteria using linguistic levels for impurity doping

	a_1: Diffusion		***a_2: Ion Implantation***	
c_1	Excellent	(1.00)	Expensive	(0.25)
c_2	Regular	(1.00)	Regular	(1.00)
c_3	Excellent	(1.00)	Average	(0.50)
c_4	Complex	(0.90)	Simple	(0.10)
c_5	Marginal	(0.33)	Excellent	(1.00)
c_6	Average	(0.50)	Excellent	(1.00)
c_7	Marginal	(0.33)	Great	(0.83)

We used the linguistic values for all inputs of our model to calculate the Alternative Suitability (AS) value of each alternative. In order to do this, we calculated the Suitability Degree for the Sugeno (SDS) and Mamdani (SDM) modules using (9) and (10). Then, according to (16), we aggregated these values, considering the weights defined by the user's preferences to calculate crisp values for Alternative Suitability for the first alternatives, as summarized in Table 7-11.

Table 7-11: Suitability Degrees and Alternative Suitability for impurity doping

	a_1: Diffusion	***a_2: Ion Implantation***
SD_S	0.953	0.557
SD_M	0.424	0.777
	AS_1 = 0.453	**AS_2 = 0.765**

If we compare only the S*uitability Degrees* for the two options, the values may look somehow close. However, when we aggregate the two accounting for the user's preferences and calculate the overall value for the AS_1 and AS_2, we can observe that the second alternative, doping by ion implantation, offers a better option for that particular required step.

7.4.5. Case Study #2 — Lead zirconate titanate (PZT) patterning for a micro energy harvester (Lift-off vs. Wet Etching)

As a second case study, we will consider the selection of one of two possible methods to pattern lead zirconate titanate (also known as PZT). PZT is a ceramic piezoelectric material, which generates a potential difference across two layers when these are subject to physical deformation. Depending on the application and the desired final shape of the device, there are several approaches to perform the pattering of PZT. The particular process flow step that we will consider for this case study is part of the manufacturing process flow for a micro energy harvester [198]. For this process flow, there are two main alternatives to obtain the desired PZT structure:

a_1: lift-off, and

a_2: wet etching.

The lift-off process is used to create specific structure patterns by first depositing a sacrificial layer in the inverse of the pattern desired upon which a target material is deposited over the whole surface of the substrate and any pre-existing structure (Figure 7-14(a)). Then the sacrificial layer is removed along with the exceeding target material that was deposited on top of the sacrificial layer (Figure 7-14(b)), leaving behind the desired final structure (Figure 7-14(c)). The second alternative evaluated here, wet etching, does not use a sacrificial layer. Instead, the target material is deposited on the substrate (and pre-existing structures), and a photolithography process is performed to create a mask on top of the target material (Figure 7-15(a)). Using chemical solvents as etchants, the target material is removed (Figure 7-15(b)). Finally, the mask is removed, exposing the final structure (Figure 7-15(c)).

These two techniques have been used as part of the manufacturing process flow of a micro energy harvester that uses PZT as piezoelectric material to generate electricity. By interacting with the main designer of this device, we were able to identify critical parameters for the PZT patterning step. These user-defined parameters are listed with the pre-defined parameters in Table 7-12.

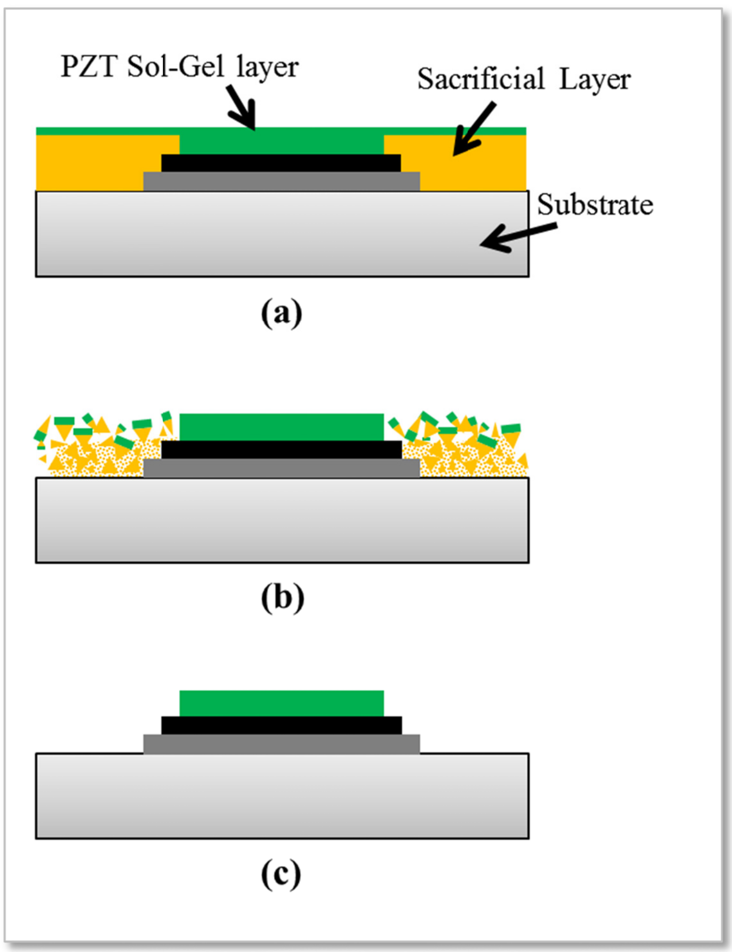


Figure 7-14: Lift-off process

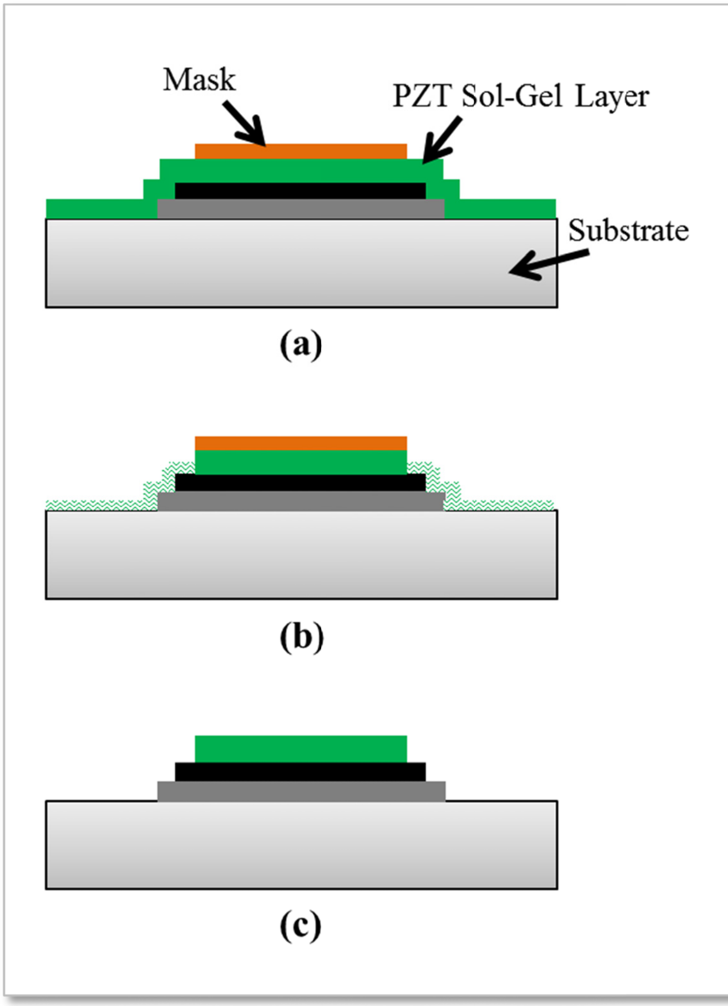


Figure 7-15: Wet etching process

Table 7-12: Parameters being evaluated for PZT patterning

Name	Type
c_1: **Cost**	*(pre-defined)*
c_2: **Use of Known Process**	*(pre-defined)*
c_3: **Accessibility of Facility**	*(pre-defined)*
c_4: **Complexity**	*(pre-defined)*
c_5: **Accuracy (alignment) in pattern**	*(user-defined)*
c_6: **Consistent PZT film**	*(user-defined)*
c_7: **PZT thickness**	*(user-defined)*

Next we used AHP to find the weights representing the relative importance for each parameter in form of a normalized eigenvector, $\boldsymbol{W}$, as shown in Table 7-13.

Table 7-13: Weight calculation by using AHP matrices for PZT pattering.

	Relative Importance							Normalized Values							weights
c_j	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_1	c_2	c_3	c_4	c_5	c_6	c_7	$W=\{w_j\}$
c_1	1	1	1/5	1/3	1/9	1/9	1/9	0.03	0.03	0.01	0.01	0.01	0.06	0.01	**0.023**
c_2	1	1	1/5	2	1/8	1/9	1/9	0.03	0.03	0.01	0.07	0.02	0.06	0.01	**0.031**
c_3	5	5	1	1/7	1/8	1/9	1/9	0.14	0.15	0.03	0.01	0.02	0.06	0.01	**0.058**
c_4	3	1/2	7	1	1/9	1/9	1/9	0.08	0.02	0.2	0.03	0.01	0.06	0.01	**0.06**
c_5	9	8	8	9	1	1/7	7	0.24	0.24	0.23	0.3	0.12	0.08	0.45	**0.237**
c_6	9	9	9	9	7	1	7	0.24	0.27	0.26	0.3	0.81	0.58	0.45	**0.416**
c_7	9	9	9	9	1/7	1/7	1	0.24	0.27	0.26	0.3	0.02	0.08	0.07	**0.176**

The perceived performances of all the previously defined criteria for this specific application were represented using the linguistic levels defined for each criterion, as follows:

- *Cost* (c_1), for lift-off (a_1) has been mapped to a linguistic value of *Convenient*, as all the steps required are available in the fabrication facility of the institution. To deposit and pattern a PZT layer using this method, the cost of equipment usage is approximately $119 CAD (information provided by the user). Wet etching's (a_2) cost is considered more expensive; the number of steps may need to be repeated several times to increase the PZT thickness, hence more steps are required at the fabrication facility, increasing the total cost. According to the user, the approximate cost for equipment usage to deposit and pattern four PZT layers is $223 CAD. The linguistic variable of *Average* was used to describe this criterion for this alternative.
- For *Use of Known Process* (c_2), both alternatives have been performed by the user, however (a_2) has an advantage over (a_1) in this case as, despite the fact that more steps are needed to complete the PZT patterning with (a_2), these steps are

more common that those used by the (a_1). We use the *User* linguistic level for (a_1) and *Regular* for (a_2).

- The *Accessibility of Facility* (c_3) is the same for both alternatives, as the equipment required for both is available in the fabrication facility of the user's institution. However, it is important to note here that they both received a low value (*Poor-Marginal*) due potential cross-contamination of the equipment (there is a diffusion of lead compounds as by-product of the process); many facilities do not offer this service or they use dedicated equipment for this process, restricting the availability.
- Regarding *Complexity* (c_4), even though there is no need of any special setup or equipment for any of these alternatives, the steps required to perform for (a_1) are more complex and attention to the detail is required to obtain an acceptable result; there is little room for error as any lack of care can result in total failure of the device. For (a_2), the required steps are simpler and there is more tolerance for potential errors. The user defined the linguistic a value of complexity for the (a_1) somewhere between *Simple* and *Complex* with a value of (0.50), and for (a_2) somehow *Complex* with a value of (0.70).
- For *Accuracy (alignment) in pattern* (c_5), the user felt that the alignment attained on a regular basis using (a_1) is *Average* as it is often difficult to get the required alignment for the sacrificial layer and the target material (i.e., PZT). For (a_2), the alignment is easier to perform on the mask alignment to cover the target material; the linguistic variable defined by the user for this is *Great*.
- For *Consistent PZT film* (c_6), (a_1) presents some problems with "pinhole" cracks across the PZT layer that can create major problems with the performance of the device. The user mentioned that a "good-enough" consistency in the PZT film is

achieved 33% of the time; hence the linguistic variable used to described this critical parameter is *Marginal*. For (a_2), the consistency is much better and another advantage of the wet etching technique is the ability to create multiple layers of PZT on top of each other, sealing any potential existing "pinhole". The linguistic variable used for this alternative is *Great.*

- The last criterion evaluated is *PZT Thickness* (c_7), another critical parameter, as more thickness on PZT may imply more energy being generated. The nature of the (a_1) technique does not allow multiple layers and the total thickness for this single layer is limited, so this critical parameter was described as *Marginal*. The other alternative, (a_2), allows depositing multiple layers on top of each other, providing the capability to increase the total thickness of the PZT layer. This alternative was qualified as *Great*.

A summary of the performance for the multiple criteria for each of the two alternatives is presented in Table 7-14.

Table 7-14: Performance of criteria using linguistic levels for PZT patterning

	a_1: Lift-off		***a_2: Wet etching***	
c_1	Convenient	(0.75)	Average	(0.50)
c_2	User	(0.70)	Regular	(1.00)
c_3	Poor-Marginal	(0.25)	Poor-Marginal	(0.25)
c_4	Simple-Complex	(0.50)	Complex	(0.70)
c_5	Average	(0.50)	Great	(0.83)
c_6	Marginal	(0.33)	Great	(0.83)
c_7	Marginal	(0.33)	Great	(0.83)

In the same way as in the previous case study, we used the linguistic values for all inputs of our model, considering the normalized weights previously obtained, to calculate the Sugeno (SD_S) and Mamdani (SD_M) modules using *Suitability Degree*. An aggregated value, the *Alternative Suitability* (AS), for each alternative was then calculated as shown in Table 7-15.

Table 7-15: Suitability Degrees and Alternative Suitability for PZT patterning

	a_1: Lift-off	***a_2: Wet etching***
SD_S	0.779	0.730
SD_M	0.430	0.626
	AS_1 = 0.449	**AS_2 = 0.632**

The S*uitability Degrees* for the Sugeno module are quite close for the two options, but slightly superior for the *lift-off* alternative. Nevertheless, when we combined these with the resultant values for the Mamdani module, for which the *wet etching* alternative presents better performance, to calculate the overall *Alternative Suitability* value for the AS_1 and AS_2, we can observe that the *wet etching* alternative is a better option to perform the PZT pattering step.

CHAPTER 8.
CLOSING DISCUSSION

8.1. Summary of Thesis

In this work, we have identified a number of challenges in MEMS/NEMS device design, manufacturing, and management tools availability. A wide diversity of systems and devices based on MEMS/NEMS components is currently in development around the world. However, many of these developments encounter problems at various points in the idea-to-market cycle, preventing them from fully developing into commercial products. By means of interaction with practitioners from industry, academia, and government, and through an extensive literature review, a multi-dimensional analysis of the current situation of the MEMS industry was performed. The current situation of the MEMS/NEMS industry was examined and important obstacles for development of this industry were identified. Many of these are technological challenges, though we also identify several that are managerial in nature. A summary of these challenges is shown in Figure 8-1.

There are frequent challenges faced in development of any new technology; these challenges are even greater in the case of disruptive technologies. MEMS have been around for more than four decades, and are only now beginning to see widespread adoption and use, with many applications and devices under development. It is evident that the development cycle for MEMS/NEMS technologies is lengthy and there is room for improvement in many areas. It is interesting to see that the problems and challenges faced by the first MEMS devices in reaching a commercial market are the same as those faced by new devices in development today. Opportunities were discussed and a methodology was proposed which can provide assistance to improve the development process time for MEMS/NEMS by acting as a virtual broker system. The lack of this type of system to evaluate the viability of a given MEMS/NEMS design and assist in selection of fabrication processes is one of the main reasons why many researchers or designers lose motivation when taking their invention to a prototype stage.

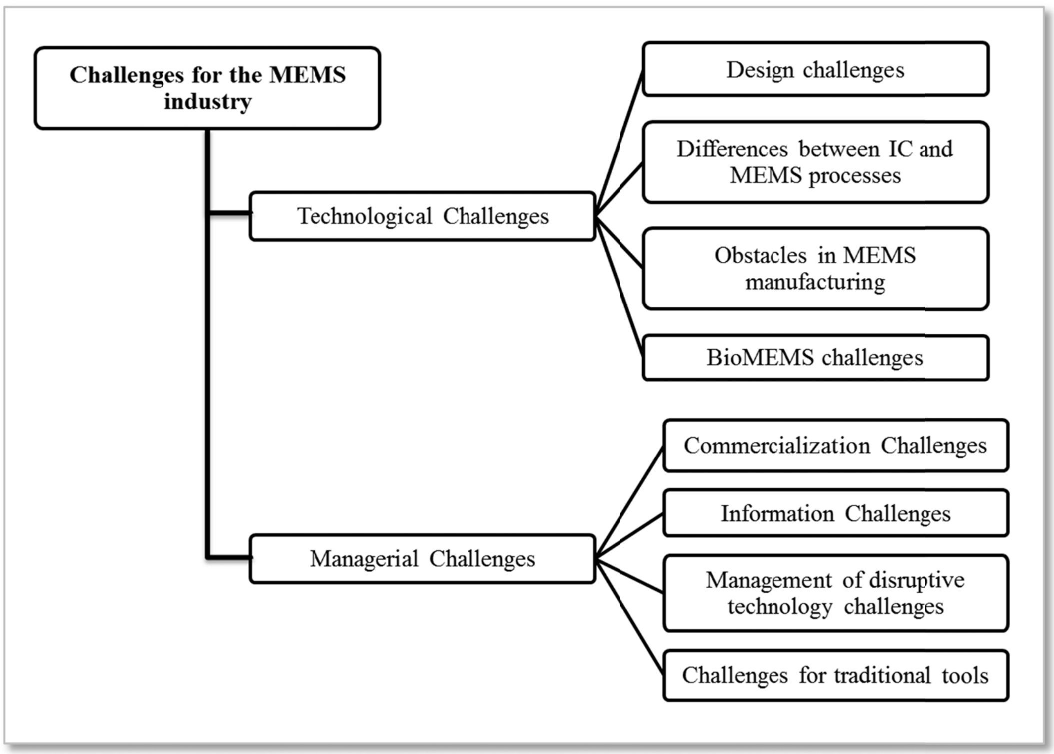


Figure 8-1: Type of challenges for the MEMS industry

Another important finding of this work is that, when dealing with disruptive technologies, there is a need to develop and adapt appropriate managerial tools to gain leverage in uncertain markets. There have been cases of systems that were driven by MEMS/NEMS technologies that are now success stories and have created worldwide businesses (e.g., digital-light-processors (DLPs), air-bag systems, ink jet heads, MEMS-based microphones, etc.). However, such cases have remained exceptions in the MEMS/NEMS industry. We feel that by providing management tools that facilitate the various managerial and technical factors that lead to successful development and commercialization of MEMS/NEMS devices we will help entrepreneurs to capitalize on their technologies. As an illustrative example, we carefully studied the DLPs' features and put them in context of our findings (Figure 4-6).

We also corroborated that a considerable degree of interaction is required for managing the activities related to product development in the MEMS field. Numerous organizations, designers, practitioners, and process experts with various backgrounds need to exchange information through the product lifecycle. In this work, we have laid a foundation for formally describing the set of activities related to manufacturing processes used by the MEMS community and their relationships. We developed our own MEMS process taxonomy (Figure 6-3), which we used to develop a new methodology using the logic definitions in the international standard ISO 18629-1. We were able to demonstrate that MEMS processes can be formally described with the existing logic expressions within the PSL standard, using core theories for generic processes, and generating extensions for more complex cases. We presented a case study, where three standard operating procedures for a common MEMS fabrication cleaning process were analyzed, finding important discrepancies among them. One of these operating procedures was selected and its structure and requirements were coded using the developed methodology. Once the code was completed, it was possible to construct a visual representation of the process structure and verify the proper composition of the process steps. An important scientific contribution of this work is that, by using our formal PSL definition for MEMS, it is possible to remove ambiguities and improve the overall clarity for MEMS manufacturing processes.

When undertaking PSL to define process steps for fabrication of microsystems, we identified additional problems that lead to the development of two additional scientific contributions of this thesis: the proposal of a formal and systematic method for representing a process flow for MEMS development and the development of a means to effectively find the best alternative, from a pool of different options, for a MEMS fabrication process step via a fuzzy inference approach. Currently, many applications are being developed using fuzzy inference systems for many applications and expert systems; we advance this work and leverage concepts to provide solution to our specific field and application. This work represents an advancement in the application of fuzzy inference systems to a new area to solve a specific problem in the MEMS field.

The steps required to use the methodology described in this thesis to formally define a process flow and to analyse various alternatives are listed below.

Step 1: ***Identify the criteria that define the functionality of the system.*** Common criteria important in the majority of MEMS developments (i.e., *Cost*, *Use of Known Process*, *Accessibility of Facility*, and *Complexity*) have already been defined and included in the system. However, additional criteria may be defined by users as additional critical parameters. The system provides a generic model to account for these additional criteria (e.g., *Performance of Critical Parameter X*) which uses seven linguistic levels providing enough definition to describe the various levels of performance that can be present on the newly defined input criteria.

Step 2: ***Define weights for the criteria based on user's preference.*** If a user has preferences for various criteria, weights can be assigned to each. Through the Analytic Hierarchy Process, these weights are defined and applied to all the individual rules dealing with each criterion in a fuzzy inference system and are used to evaluate different process step alternatives and to calculate a *Process Suitability* degree for each.

***Step 3:* Define quantifier values for each criterion.** Once the criteria have been defined and the user's preferences have been established, we need to evaluate the performance of each criterion for all alternatives in the context of the application intended. In many cases, linguistic variables are needed to properly define the level of performance. The fuzzy inference system presented here provides the opportunity to operate linguistic values, as well as ordinary quantitative values to find an alternative suitability degree as a crisp value. Such values are then used to rank, in order of importance, the multiple alternatives.

These steps were implemented in two case studies to illustrate the functionality and applicability of our system. In the first case study, similar alternatives for an impurity doping process flow step were evaluated: doping by diffusion and ion implantation. In the second case study, we evaluated two patterning techniques for lead zirconate titanate (PZT) for a micro energy harvester device. We demonstrated that our fuzzy inference system approach can be used to assist MEMS developers to objectively improve and accelerate the decision-making process to select between alternative approaches. In the first case study, we used our approach to show that ion implantation offers more advantages and is a more suitable doping technique for use in fabrication of the particular device under development. Furthermore, we provided a second case study where we used our methodology to show that wet-etching technique is more suitable than the lift-off patterning for PZT in the process flow of interest. These two examples demonstrate how our system can effectively improve the fabrication process by reducing the unnecessary use of valuable and expensive fabrication time.

When dealing with new technologies, the rapidness of the development cycle could be the difference between success or failure of a new product. The window of opportunity for new technologies can close in a very short time, during which a substitute technology can unexpectedly emerge, turning the new as-yet developed product into an obsolete technology. For products based on MEMS technology, this is especially important, as one of the main bottlenecks for the product development cycle is the early stage of manufacturing [25], [199]. By applying the methods described in this thesis, MEMS practitioners will have a new tool to improve the overall product development time by reducing the time required for initial fabrication of MEMS devices.

8.2. Main Contributions

8.2.1. Goals and Objectives Achieved.

All the research work summarised in this thesis, was performed in order to provide a greater understanding and insights into MEMS/NEMS commercialization process. As well as to present alternatives to the conventional methods and tools that are being used for this endeavour. The specific objectives established at the beginning of this thesis are:

1. To provide a formal analysis of the various obstacles the MEMS designers are facing while trying to take their designs from an idea to a commercial stage,

2. To shed some light on the multiple opportunities to develop management tools (e.g., product development management, knowledge management, R&D management) for the MEMS/NEMS industry, and

3. To offer an initial practical solution to mitigate some of the identified challenges to improve the overall time-to-market for MEMS/NEMS.

We decided to use a pragmatic approach. In order to include various perspectives and not just a single academic perspective, the author of this thesis performed a field research while working in industry as a co-op program with the Alberta Centre for Advance MNT Products (ACAMP). This allowed us to interact directly with MEMS/NEMS practitioners in industry and in government. Complementing this field research with an extensive literature review, it was possible to perform a formal analysis.

In order to provide a relevant scientific contribution, we have designed a methodology, to ultimately be expressed as a software tool. It will be implemented as a knowledge-based system to help researchers, development groups, and lead users in academia as well as in industry. The MEMS/NEMS practitioners will benefit from this research by being able to develop systems and devices more effectively and efficiently. This will allow to reduce time-to-market for these technologies. A clear manifestation of these benefits and a tangible proof of a factual time reduction in the overall development was observed while working on the case studies for the fuzzy inference system (i.e., Case Study #1 — Impurity doping for a pressure sensor (Diffusion vs. Ion implantation) and Case Study #2 — Lead zirconate titanate (PZT) patterning for a micro energy harvester (Lift-off vs. Wet Etching)). The total time required for explaining the system functionality to the user, ask the user to define the critical parameters, and have the user provide the relative performance of the parameters was less than two hours in total. If we compare this time with the normal time of executing each of the two alternatives, which can take up to few weeks or more to complete, the benefits and savings on time are evident. This time reduction will lead to more systems reaching commercial markets faster, passing the advantages of these new technologies to society in a timely and cost effective fashion. The specific scientific contributions to the Engineering Management field of this work are presented next.

8.2.2. Scientific Contributions

The scientific contributions emanated from this work are result of two main research approaches: descriptive and prescriptive research. The most notable scientific contributions from the research work performed for this thesis are:

- **Identification and corroboration of specific technological and commercialization related challenges, and opportunities for MNT products.**
- **Implementation of a methodology to capture tacit and explicit knowledge pertinent to MEMS/NEMS fabrication.**
- **Development of a new taxonomic classification for MEMS/NEMS fabrication processes, which allows practitioners to systematically locate and use existing processes and easily add new processes.**
- **Generation of a standard representation of MEMS/NEMS manufacturing processes, based on the standard ISO-18629.**
- **Proposal of a formal and systematic method for representing a process flow for MEMS development.**
- **Development of a means to effectively find the best alternative from a pool of different options for a MEMS/NEMS fabrication process step via a fuzzy inference approach.**

8.3. Other Contributions of Ph.D. Work

The main contributions of this work have been summarized in four peer-reviewed publications ([119], [162], [199], [200]), three of which have been accepted for publication and one that is still under review. In addition to these publications, several other notable contributions to the MEMS/NEMS ecosystem were made (e.g., technical reports, presentations). Furthermore, due the nature of my research work, I was fortunate to be invited to several meetings, workshops and conferences where I held an active role providing input and contributing to generate guidelines, evaluate performance of micro and nanotechnology programs, and to suggest course of action for the triple helix (i.e., industry, academia and government) involved with micro and nanosystems development. The following subsections present lists of the various contributions produced during my Ph.D. program.

8.3.1. Peer-reviewed journal papers:

- Nakashima-Paniagua, T., Doucette, J., & Moussa, W. (2014). "Fabrication Process Suitability Ranking for Micro-Electro-Mechanical Systems Using a Fuzzy Inference System", *Expert Systems with Applications*, vol. 41, no. 9, pp. 4123–4138, July 2014.

- Nakashima-Paniagua, T., Doucette, J., & Moussa, W. (2014). "Virtual Broker System to Manage Research and Development for Micro Electro Mechanical Systems", *Journal of High Technology Management Research*, vol. 25, no. 1, pp. 54–67, 2014.

- Nakashima-Paniagua, T., Doucette, J., & Moussa, W. (2014). "Process Specification Language for Management of MEMS Device Development - A Step towards Standardization" (Periodical Style — in press, accepted for publication March 16, 2014). *International Journal of Manufacturing Technology and Management*.

8.3.2. Peer reviewed archived conference papers:

- T. Nakashima-Paniagua, T. Heidrick, and W. Moussa "Multi-stage collaborative system for microelectromechanical systems manufacturing", *Proceedings of the Portland International Center for Management of Engineering and Technology - Management of Converging Technologies*, 05 August 2007

8.3.3. Other publications and presentations:

- T. Nakashima-Panaigua, “Fuzzy Inference System to Evaluate Process Alternatives for MEMS Fabrication.”, – *Presentation at MEMS/NEMS Advanced Design Laboratory*, University of Alberta, 02-Julio-2013

- T. Nakashima-Paniagua, “Technical report: Commercialization development activities for the project: In-Situ Tuneable Micro Energy Harvester” (*Technical Report for nanoBridge Project RES0010293*). University of Alberta, Edmonton, Alberta, Canada, 03 September 2012

- T. Nakashima-Panaigua, “An approach to verify process availability/cost for MEMS in real time”, – *Presentation at MEMS/NEMS Advanced Design Laboratory*, University of Alberta, 12-March-2012

- T. Nakashima-Paniagua, T. Heidrick, and J. Kramers, “Literature Review of Job Creation” (*Report for Alberta Innovates – Technology Futures*), Owl Ventures Inc., Edmonton, Alberta, Canada, 30 November 2011

- T. Nakashima-Panaigua, “Process Specification Language for MEMS”, – *Presentation at MEMS/NEMS Advanced Design Laboratory*, University of Alberta, 08-Agust-2011

- T. Nakashima-Panaigua, “Formalizing Process Specification Language for MEMS: A Step towards Standardization”, – *Presentation at MEMS/NEMS Advanced Design Laboratory*, University of Alberta, 26-Abril-2011

- T. Nakashima-Paniagua, J. Doucette, and W. Moussa, “Adaptive MEMS/NEMS Broker tool for Idea to Market-Ready Prototype”, *Report of Invention*, submitted to TEC Edmonton, Edmonton, Alberta, Canada, 13 April 2011

- T. Nakashima-Panaigua, “Design Methodology”, – *Presentation at Noetic Engineering*, Edmonton, Alberta, Canada, 01 November 2010

- T. Nakashima-Paniagua, E. Inda-Camacho, T. Heidrick, and J. Kramers, “A Literature Review on Performance Metrics and Measurement Systems” (*Report for Alberta Innovates – Technology Futures*), Owl Ventures Inc., Edmonton, Alberta, Canada, 05 October 2010

- T. Nakashima-Paniagua, “Introduction to Axiomatic Design (AD)” – *Presentation at MEMS/NEMS Advanced Design Laboratory*, University of Alberta, 13-July-2010

- T. Nakashima-Paniagua, J. Doucette, W. Moussa, “System to Improve Manufacturing Process Generation for MEMS/NEMS Development” -*Presentation at University of Alberta Faculty of Engineering Graduate Research Symposium 2010*, Edmonton, AB, Canada, 17 Jun 2010

- T. Nakashima-Panaigua, “Evaluation of the pathway Solar Energy for Electricity” (*Document for the Canadian Academy of Engineering – Energy Pathways Project*), Edmonton, Alberta, Canada, 01 November 2006

8.3.4. Meetings, Workshops and Conferences.

- "Meeting to evaluate the performance for the nanoAlberta initiative", *Alberta Innovates – Technology Futures*, Edmonton, Alberta, Canada, 05 December 2011
- "Wave 2011, Taking Micro & Nanotechnology Enabled Products to Market", *Alberta Centre for Advance MNT Products Conference*, Lake Louise, Alberta, Canada, 22 August 2011
- "Alberta Nanotech Showcase 2.0", *nanoAlberta Workshop/Conference*. Calgary, Alberta, Canada, 22-23 March 2011
- "69ª Jornada Informativa del IME: Red de Talentos Mexicanos en el Exterior, Sector: Nanotecnología y Nuevos Materiales" (69th Meeting of the Network of Mexican Talents in Foreign Countries, Section: Nanotechnology and New Materials), Mexico City, 13th and 14th August 2009
- "Mexico – Alberta NanoTech Partnering Mission", Workshop, *University of Alberta*, 27-29 October 2008
- "Commercialization of Micro and Nano Systems Conference 2008 (COMS'08)", *Micro, Nano, and Emerging Technologies Commercialization and Education Foundation (MANCEF) Conference*, Puerto Vallarta, Mexico, 30 August – 04 September 2008
- "Commercialization of Micro and Nano Systems Conference 2006 (COMS'06)", *Micro, Nano, and Emerging Technologies Commercialization and Education Foundation (MANCEF) Conference*, St. Petersburg, Florida, USA, 27 August – 31 August 2006

8.4. Limitations and Future work

In this section we would like to provide further clarification and additional considerations pertinent to the limitations of the research work performed in this thesis, as well as interesting lines of research that can be pursued as follow-up of the contributions of this thesis.

As mentioned in Section 1.2, the starting point for the methods implemented here is a fabrication process flow for MEMS/NEMS developments; we are not trying to validate physical designs or functionality for the devices that will result after the executions of the process flows provided.

Although many theoretical fabrication principles for MEMS and NEMS are the same, in practice, there are some substantial differences when manufacturing devices with dimensions in the order of several micrometres (i.e., MEMS) in comparison with devices with dimensions in the order of few hundred nanometres (i.e., NEMS). The level of control for process variables required for NEMS fabrication could be considerably more stringent that those used for MEMS. This brings additional challenges for the equipment used for fabrication of NEMS devices. This work is not aiming, and has no means, to improve the yield of specific fabrication processes for neither MEMS nor NEMS.

One of the main challenges for any knowledge management system is the obsolescence of the knowledge stored within. Implementing tracking and monitoring systems to keep the contents of the knowledgebase current and with valid information is no exception for the system developed in this work.

Additional lines of research can be spawned based on the research work that we have done. The system developed in this thesis is intended to be used to share information among MEMS/NEMS practitioners, however, many developments based on these technologies have a solid commercial potential which creates a tendency to hoard knowledge between competitors. It would be really interesting to investigate ways to minimize this problem and forecast open innovation [201] in the MEMS/NEMS industry.

Also, we focused this research primarily on evaluating the manufacturing processes used to build MEMS and NEMS devices, as those were the main identified bottlenecks, however a more in-depth analysis regarding an additional social aspect of the idea-to-market process, the development of markets for these technologies, would be really interesting.

Another interesting follow up for the research work presented here, would be a comprehensive usability study from the users' perspective. Perhaps, the system can be evaluated using the Technology Acceptance Model (TAM) [202] to evaluate the acceptance and adoption of our system.

Additionally, the fuzzy inference system developed in this work is based on two basic and common methods for inference systems using fuzzy logic (i.e., the Sugeno and the Mamdani methods). Our algorithm described herein uses a set of input variables, some of which are embedded in the model and some of which are entered by the user. Implementing intelligence in the system so as to detect and correct in cases where users are entering incorrect parameters would be interesting. At the same time, although the user should be the most qualified subject to provide a fair judgment of the behaviour and expected performance of these criteria, there is a degree of subjectivity inherent in the system. That was the basis for the use of fuzzy inference systems. However, there exist more advanced and/or novel techniques that may offer significant advantages over the one used here. For instance, neuro-fuzzy systems (neural networks used in combination with fuzzy systems) have been used successfully in many recent applications [180], [203]–[207]. As a forthcoming line of research for this work we would like to investigate the use of this methodology to evaluate various alternatives of process steps within a MEMS manufacturing flow. We would be particularly interested in the methods developed in those prior works for a proper training of a neuro-fuzzy system in order to be fully applicable for our application where time may be an issue.

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APPENDIX "A".
PARTIAL LIST OF MEMS PROCESSES

Subcategory Name	Subcategory ID	Process Name
Anodic bonding	1	Anodic bonding
	1	Anodic bonding (air, with alignment)
	1	Anodic bonding (air, without alignment)
	1	Anodic bonding (vacuum, with alignment)
	1	Anodic bonding (vacuum, without alignment)
	1	Anodic bonding (without alignment)
	1	Wafer Bond Pre-Align
	1	Aligned fusion bonding
Fusion bonding	2	Aligned fusion prebond
	2	Wafer Bond Pre-Align
	2	Glass frit bonding
Glass frit bonding	3	Glass frit bonding (vacuum)
	3	Adhesive bonding
Miscellaneous bonding	4	Aluminum microwave bonding
	4	Copper microwave bonding
	4	Epoxy bonding (air, with alignment)
	4	Eutectic bonding
	4	Gold microwave bonding
	4	Low-temperature glass bonding
	4	Microwave bonding
	4	Nanogetter packaging
	4	Nickel microwave bonding
	4	Resist bonding
	4	Resist bonding (Shipley 1827)
	4	Solder bonding
	4	Solder bonding (vacuum, with alignment)
	4	Thermocompression Bonding
	4	4:1 Sulfuric/peroxide bath
Cleaning Generic	5	50:1 HF dip
	5	9:1 Sulfuric/peroxide bath

	5	BOE/BHF clean
	5	Clean
	5	Clean (metal)
	5	HCl bath
	5	HF clean
	5	HF dip
	5	Ionic clean
	5	KOH decontamination clean
	5	Organic clean
	5	Organic NMP-clean
	5	Photoresist wet strip (acetone)
	5	Photoresist wet strip (PRS 3000)
	5	Piranha Clean
	5	Piranha/HF clean
	5	Pre-diffusion clean
	5	Pre-furnace clean
	5	Pre-furnace clean (for metallized wafers with DUV photoresist)
	5	Pre-furnace clean (for metallized wafers)
	5	Pre-LPCVD clean
	5	RCA clean
	5	RCA clean with HF dip
	5	RCA clean with HF Dip (Pre-furnace clean)
	5	RCA1 clean
	5	RCA2 clean
	5	Rinse/dry
	5	Solvent clean (acetone +IPA)
	5	Spin/rinse/dry
	5	Spin-Rinse-Dry (SemiTool)
	5	Supercritical CO2 Dry
	5	Supercritical dry
	5	Ultrasonic clean
Evaporation	6	Chromium E-beam evaporation
	6	Copper E-beam evaporation
	6	E-beam evaporation
	6	E-beam Evaporation (Au)
	6	E-beam evaporation (CHA)
	6	E-beam Evaporation (Cr)

	6	E-beam Evaporation (Pt)
	6	E-beam Evaporation (Ti)
	6	E-beam metal evaporation (Temescal)
	6	Evaporation
	6	Evaporation (Evatek -Batch dome)
	6	Germanium E-beam evaporation
	6	Gold E-beam evaporation
	6	Gold Evaporation with Adhesion Layer
	6	Nickel E-beam evaporation
	6	Parylene C deposition
	6	Platinum Evaporation with Adhesion Layer
	6	Resistive evaporation
	6	RF-induction evaporation
	6	Titanium E-beam evaporation
	6	Titanium Oxide (Ti3O5) E-beam Evaporation
LPCVD	7	Amorphous silicon LPCVD
	7	Amorphous silicon LPCVD (Glass-safe)
	7	Doped poly-SiC LPCVD
	7	High temperature silicon dioxide (HTO) LPCVD
	7	HTO on silicon nitride
	7	HTO on SiN on HTO LPCVD
	7	Low stress polysilicon LPCVD II (300 MPa)
	7	Low-stress polysilicon LPCVD
	7	Low-stress polysilicon LPCVD I (100MPa)
	7	LTO LPCVD
	7	LTO LPCVD (single side)
	7	Multipoly Recipe #1
	7	Multipoly Recipe #2
	7	P-doped polysilicon LPCVD
	7	Phosphorus-doped polysilicon LPCVD
	7	Poly-Silicon-Germanium LPCVD
	7	PSG LPCVD
	7	P-type polygermanium LPCVD
	7	Silicon dioxide (TEOS) LPCVD
	7	Silicon nitride LPCVD

	7	Silicon nitride on HTO
	7	SiN on HTO on SiN LPCVD
	7	Stoichiometric silicon nitride LPCVD
	7	Super low stress silicon nitride LPCVD (50 MPa)
	7	TEOS LPCVD
	7	Undoped amorphous silicon LPCVD
	7	Undoped polygermanium LPCVD
	7	Undoped polysilicon LPCVD
Low-stress SiN deposition	8	Low Stress silicon nitride LPCVD (<300 MPa)
	8	Low Stress silicon nitride LPCVD (200 MPa)
	8	Low Stress silicon nitride LPCVD (300 MPa)
	8	Low-stress silicon nitride LPCVD (<100 MPa)
	8	Low-stress silicon nitride LPCVD (<120 MPa)
	8	Low-stress silicon nitride LPCVD (<200 MPa)
	8	Low-stress silicon nitride LPCVD (<350 MPa)
	8	Low-stress silicon nitride LPCVD (<50 MPa)
	8	Silicon nitride (stress controlled) PECVD
	8	Silicon Nitride PECVD (STS)
	8	Super low stress silicon nitride LPCVD (50 MPa)
Miscellaneous deposition	9	Alumina (Al2O3) Atomic Layer Deposition (ALD)
	9	Alumina/ Zinc Oxide (Al2O3/ZnO) alloy Atomic Layer Deposition (ALD)
	9	Anti-stiction coating (Alkylhalosilanes)
	9	APCVD
	9	Atomic Layer Deposition (ALD)
	9	Cool grease bonding
	9	Copper electroplating
	9	CVD

	9	CVD epitaxy
	9	DC electrodeposition
	9	Dehydration & vapor prime
	9	Deposition
	9	Development #1 - LaNiO3 (LNO) Deposition
	9	Development #2 - PZT on LaNiO3 (LNO)
	9	Diamond CVD (smooth)
	9	Diamond CVD (standard)
	9	Electrodeposition
	9	Electroless deposition
	9	Electroplating
	9	Epitaxy
	9	Gold electroplating
	9	Hafnium dioxide (HfO2) ALD
	9	Molecular beam epitaxy
	9	MVD of Anti-Stiction Coating (DDMS)
	9	MVD of Anti-stiction coating (FOTS)
	9	Nickel electroplating (sulfamate)
	9	Parylene C deposition
	9	Parylene N deposition
	9	Photoresist Spray Coat
	9	Physical deposition
	9	Polyimide deposition and curing (Durimide)
	9	Polyimide deposition and pattern
	9	Polyimide deposition, patterning and curing (Durimide 7520)
	9	PTFE Deposition
	9	Pulsed electrodeposition
	9	PZT on LaNiO3 (LNO) Deposition
	9	Reactive Evaporation - Optical film coating (Leybold APS 1104)
	9	Resist bonding
	9	Selective epitaxy
	9	Solid phase epitaxy
	9	Spin casting (Durimide 7520)
	9	Spin casting (Durimide)
	9	Spin casting Programmable Spinner

	9	Spray casting
	9	STS polymer deposition
	9	ZnO Atomic Layer Deposition (ALD)
Oxidation	10	Dry oxidation
	10	Dry oxidation - Chlorinated
	10	Dry oxidation - Standard
	10	Dry oxidation (metal)
	10	Dry oxidation (non-metal)
	10	Dry/wet/dry oxidation
	10	Dry/wet/dry TCA oxidation
	10	Rapid thermal oxidation
	10	Wet oxidation
	10	Wet oxidation (metal)
	10	Wet oxidation (non-metal)
	10	Wet TCA oxidation
PECVD	11	Amorphous Silicon Carbide (SiC) PECVD
	11	Amorphous silicon PECVD
	11	Low-stress silicon nitride PECVD
	11	PECVD
	11	Silicon carbide PECVD
	11	Silicon dioxide low temp PECVD
	11	Silicon dioxide PECVD
	11	Silicon dioxide PECVD (PlasmaTherm 790)
	11	Silicon dioxide PECVD (STS)
	11	Silicon dioxide PECVD (TEOS)
	11	Silicon dioxide PECVD (Unaxis VLR 700)
	11	Silicon Dioxide PECVD PlasmaTherm 790
	11	Silicon dioxide VLR700 PECVD
	11	Silicon nitride (stress controlled) PECVD
	11	Silicon nitride low temp PECVD
	11	Silicon nitride PECVD
	11	Silicon nitride PECVD (PlasmaTherm 790)
	11	Silicon Nitride PECVD (STS)
	11	Silicon nitride PECVD (Unaxis VLR 700)

	11	Silicon Nitride PECVD PlasmaTherm 790
	11	Silicon oxy-nitride PECVD
	11	TEOS PECVD
	11	TEOS PECVD (STS)
Spin casting	12	Backside protect (AZ P4400)
	12	Backside protect (NR1-6000PY)
	12	Cool grease bonding
	12	G-line BCB coat (BCB 4000)
	12	G-line photoresist coat (AZ4000)
	12	Hard baked resist coat (OiR 897 10i)
	12	Photoresist coat (495 PMMA 6 A in anisole)
	12	Photoresist coat (950 PMMA 2 A in anisole)
	12	Photoresist coat (950 PMMA 4 A in anisole)
	12	Photoresist coat (950 PMMA 9 A in anisole)
	12	Photoresist coat (automated)
	12	Photoresist coat (manual)
	12	Photoresist coat (Shipley 220)
	12	Photoresist coat (Shipley 3612)
	12	Photoresist coat with softbake (AZ 9260)
	12	Photoresist coat with softbake (Shipley 1813)
	12	Photoresist Spin Coat ACS200 (AZ 9245)
	12	Prime
	12	Protective coating for KOH etch (ProTEK)
	12	Resist bonding
	12	Spin casting
	12	Spin casting (Durimide 7520)
	12	Spin casting (Durimide)
	12	Spin casting Programmable Spinner
Sputtering	13	Al sputtering (Metron)
	13	Al, Al.5%Cu, Cu Single Layer Sputter
	13	Al/2% Si DC-magnetron sputtering

	13	Aluminum DC magnetron sputtering
	13	Aluminum DC-magnetron sputtering (high power)
	13	Aluminum DC-magnetron sputtering (low power)
	13	Aluminum Nitride (AlN) Sputter Deposition
	13	Aluminum Nitride AC magnetron reactive sputtering
	13	Aluminum/silicon DC-magnetron sputtering
	13	Aluminum/silicon/copper DC-magnetron sputtering (high power)
	13	Aluminum/silicon/copper DC-magnetron sputtering (low power)
	13	Chromium DC sputtering
	13	Chromium DC-magnetron sputtering (high power)
	13	Chromium DC-magnetron sputtering (low power)
	13	Copper DC magnetron sputtering
	13	Copper DC sputtering
	13	Copper DC-magnetron sputter
	13	Cr, Ti Single Layer Sputter
	13	DC sputtering
	13	DC-magnetron sputtering
	13	Gold DC sputtering
	13	Gold static DC-magnetron sputter
	13	Indium Tin Oxide (ITO) DC-magnetron sputtering
	13	Iridium DC-magnetron sputter
	13	Metal sputter deposition (Veeco)
	13	Nichrome DC-magnetron sputtering (high power)
	13	Nichrome DC-magnetron sputtering (low power)
	13	Nickel DC sputtering
	13	Nickel DC-magnetron sputtering (high power)

	13	Nickel DC-magnetron sputtering (low power)
	13	Nickel/chromium DC-magnetron sputtering (high power)
	13	Nickel/chromium DC-magnetron sputtering (low power)
	13	Palladium DC-magnetron sputtering
	13	Platinum DC sputtering
	13	Platinum DC-magnetron sputtering (high power)
	13	Platinum DC-magnetron sputtering (low power)
	13	RF sputtering
	13	RF-magnetron sputtering
	13	Silver DC-magnetron sputter
	13	Sputter deposition (CVC)
	13	Sputter deposition (Varian)
	13	Sputtered Metal Film
	13	Sputtering
	13	Tantalum DC Magnetron Sputtering
	13	Titanium DC sputtering
	13	Titanium DC-magnetron sputtering
	13	Titanium DC-magnetron sputtering (high power)
	13	Titanium DC-magnetron sputtering (low power)
	13	Titanium/nickel DC-magnetron sputter
	13	Titanium/nickel DC-magnetron sputtering
	13	Tungsten DC-magnetron sputtering
	13	Tungsten DC-magnetron sputtering (high power)
	13	Tungsten DC-magnetron sputtering (low power)
	13	Zinc oxide (ZnO) RF-magnetron sputtering
Diffusion	14	Boron diffusion
	14	Boron diffusion and anneal
	14	Boron pre-deposition
	14	Boron pre-diffusion

	14	Deep boron diffusion
	14	Deep boron diffusion (Double-sided)
	14	Deep boron diffusion (Single sided)
	14	Deep boron diffusion with drive-in
	14	Phosphorus diffusion
	14	Phosphorus diffusion (POCl3)
	14	Phosphorus diffusion and anneal
	14	Phosphorus diffusion with drive-in
	14	Phosphorus pre-deposition
	14	POCl diffusion
Ion implantation	15	Ion implant
Anisotropic etch	16	Advanced oxide etch
	16	Advanced Oxide Etch (STS-AOE)
	16	Advanced silicon dioxide etch (AOE) with photolithography
	16	Aluminum (1% silicon) plasma etch
	16	Aluminum Nitride ICP Etch
	16	Aluminum plasma etch
	16	Aluminum RIE
	16	Anisotropic dry etch
	16	Anisotropic etch
	16	Anisotropic plasma etch
	16	Anisotropic wet etch
	16	Deep oxide etch - High aspect ratio
	16	Deep oxide etch - Microlens recipe
	16	Deep oxide etch - Standard recipe
	16	Deep oxide etch - Ultra smooth sidewall
	16	Deep RIE
	16	Deep RIE (Bosch process)
	16	Deep RIE (Bosch process) with photolithography
	16	EDP Etch
	16	EDP silicon etch
	16	Gallium Nitride (GaN), ICP Etch (Versaline)
	16	Gallium-Arsenide, ICP Etch (Versaline)
	16	Ion Milling
	16	KOH etch
	16	KOH silicon etch

	16	KOH Silicon Etch I
	16	KOH Silicon Etch I (Single side etching)
	16	KOH Silicon Etch II
	16	KOH Silicon Etch II (Single side etching)
	16	Photoresist Strip (Plasmalab)
	16	Poly-Ge RIE
	16	Poly-SiGe RIE
	16	Polysilicon plasma etch (anisotropic, MOS clean)
	16	Polysilicon plasma etch (gold contaminated)
	16	Polysilicon RIE
	16	Polysilicon RIE (clean)
	16	Polysilicon RIE (non-clean)
	16	Polysilicon RIE (thick)
	16	RIE
	16	SiC RIE (AOE)
	16	Silicon Carbide ICP Etch
	16	Silicon deep RIE
	16	Silicon Dioxide ICP Etch
	16	Silicon dioxide plasma etch
	16	Silicon dioxide plasma etch (anisotropic)
	16	Silicon dioxide plasma etch (anisotropic, MOS clean)
	16	Silicon dioxide RIE
	16	Silicon Dioxide RIE (clean)
	16	Silicon Dioxide RIE (non-clean)
	16	Silicon dioxide RIE (Plasmalab)
	16	Silicon DRIE
	16	Silicon DRIE (Bosch Process)
	16	Silicon DRIE (Bosch Process) Plasma Therm 770
	16	Silicon DRIE II
	16	Silicon DRIE with anti-footing SOI
	16	Silicon DRIE with anti-footing SOI option
	16	Silicon DRIE with photolithography (PlasmaTherm 770)

	16	Silicon DRIE with photolithography (Unaxis VLR 700)
	16	Silicon ICP Etch
	16	Silicon Nitride ICP Etch
	16	Silicon nitride plasma etch
	16	Silicon nitride plasma etch (gold contaminated)
	16	Silicon nitride RIE
	16	Silicon Nitride RIE (clean)
	16	Silicon Nitride RIE (non-clean)
	16	Silicon nitride RIE (PlasmaLab)
	16	Silicon oxide dry etch
	16	Silicon RIE (smooth sidewalls)
	16	Silicon wet etch (KOH)
	16	Silicon wet etch (TMAH)
	16	Titanium plasma etch
	16	Titanium/tungsten plasma etch
	16	TMAH silicon etch
	16	Tungsten plasma etch
Deep RIE	17	Advanced oxide etch
	17	Advanced Oxide Etch (STS-AOE)
	17	Advanced silicon dioxide etch (AOE) with photolithography
	17	Deep oxide etch - High aspect ratio
	17	Deep oxide etch - Microlens recipe
	17	Deep oxide etch - Standard recipe
	17	Deep oxide etch - Ultra smooth sidewall
	17	Deep RIE (Bosch process)
	17	Deep RIE (Bosch process) with photolithography
	17	Pocket wafer
	17	SiC RIE (AOE)
	17	Silicon DRIE
	17	Silicon DRIE - No Lag (Etch rate independent of feature size)
	17	Silicon DRIE (Bosch Process)
	17	Silicon DRIE (Bosch Process) Plasma Therm 770
	17	Silicon DRIE II

	17	Silicon DRIE with anti-footing SOI
	17	Silicon DRIE with photolithography (PlasmaTherm 770)
	17	Silicon DRIE with photolithography (Unaxis VLR 700)
	17	Silicon oxide dry etch
	17	Silicon RIE (smooth sidewalls)
Isotropic etch	18	Aluminum (1% silicon) wet etch
	18	Aluminum etch
	18	Aluminum wet etch
	18	Aluminum wet etch (High power deposition)
	18	Aluminum wet etch (Low power deposition)
	18	Ashing
	18	BCB Dry Etch
	18	BOE Etch
	18	Buffered HF etch
	18	Buffered Oxide Etch (BOE)
	18	Chromium wet etch
	18	Chromium wet etch (Low and High Power Depositions)
	18	Copper wet etch
	18	Down Stream Plasma Ashing / Stripping
	18	Down Stream Plasma Descum
	18	Gold etch
	18	Gold wet etch
	18	HF 10:1 Batch Etch
	18	HF dip
	18	HF etch
	18	HF etch (10:1)
	18	HF etch (10:1) Single Wafer
	18	HF release & Supercritical dry
	18	HF release etch
	18	HF Vapor Etch
	18	HF Vapor Phase Etch
	18	Isotropic dry etch
	18	Isotropic etch
	18	Isotropic plasma etch

	18	Isotropic wet etch
	18	Nickel wet etch (High Power Deposition)
	18	Nickel wet etch (Low Power Deposition)
	18	Nickel/Copper wet etch
	18	Phosphoric acid etch
	18	Photoresist ashing
	18	Photoresist ashing (non-clean -March)
	18	Photoresist ashing (non-clean)
	18	Photoresist ashing I (metal allowed)
	18	Photoresist ashing II (metal allowed)
	18	Photoresist descum
	18	Photoresist Descum (Metroline)
	18	Photoresist strip (metal)
	18	Photoresist strip (non-metal)
	18	Photoresist Stripping (Metroline)
	18	Photoresist wet strip
	18	Photoresist wet strip (acetone)
	18	Photoresist wet strip (PRS 3000)
	18	Polysilicon plasma etch (isotropic)
	18	Polysilicon wet etch
	18	Post-implant photoresist strip (non-metal)
	18	Post-plasma etch photoresist strip (metal)
	18	Release etch
	18	Resist ash
	18	Resist strip
	18	Titanium wet etch
	18	Wafer thinning
	18	Xenon difluoride (XeF2) Isotropic Si etch
	18	Xenon difluoride (XeF2) Isotropic Si Etch (Xactix)
	18	Zinc Oxide wet etch
Miscellaneous etch	19	Cool grease removal
	19	De-mounting handle wafer
	19	Develop
	19	Down Stream Plasma Descum
	19	G-line BCB develop (BCB4000)

	19	HF Vapor Phase Etch
	19	Pocket wafer
Strip	20	De-mounting handle wafer
	20	Down Stream Plasma Ashing / Stripping
	20	Lift-off etch (1112A)
	20	Lift-off etch (acetone)
	20	Photoresist ashing
	20	Photoresist ashing (non-clean -March)
	20	Photoresist ashing (non-clean)
	20	Photoresist ashing I (metal allowed)
	20	Photoresist ashing II (metal allowed)
	20	Photoresist Descum (Metroline)
	20	Photoresist Removal (for metallized wafers, no gold)
	20	Photoresist Strip
	20	Photoresist strip (metal)
	20	Photoresist strip (non-metal)
	20	Photoresist strip (O2 plasma)
	20	Photoresist Strip (Plasmalab)
	20	Photoresist strip (SU-8)
	20	Photoresist Stripping (Metroline)
	20	Photoresist wet strip
	20	Photoresist wet strip (acetone)
	20	Photoresist wet strip (PRS 3000)
	20	Resist strip
	20	Silicon dioxide RIE (Plasmalab)
	20	Silicon nitride RIE (PlasmaLab)
Contact mask lithography	21	BCB Contact mask align and exposure
	21	Contact G-line photolithography (front-back align, OCG 825 35CS)
	21	Contact G-line photolithography (front-front align, OCG 825 35CS)
	21	Contact I-line photolithography (AZ 5214 - MA6) -Image Reversal-
	21	Contact I-line photolithography (AZ 5214 - MA6) -Standard-
	21	Contact I-line photolithography (AZ 5214 - MJB3) -Image Reversal-

	21	Contact I-line photolithography (AZ 5214 - MJB3) -Standard-
	21	Contact I-line photolithography (front-back align, OiR 897 10i)
	21	Contact I-line photolithography (front-front align, OiR 897 10i)
	21	Contact I-line photolithography (Shipley 1818 - MA6)
	21	Contact I-line photolithography (Shipley 1818 - MJB3)
	21	Contact I-line photolithography with back protected (front-back align, OiR 897 10i)
	21	Contact I-line photolithography with back protected (front-front align, OiR 897 10i)
	21	Contact lithography (Image reversal)
	21	Contact mask align and exposure
	21	Contact photolithography
	21	Contact photolithography (Automated)
	21	Contact photolithography (AZ P4400 / AZ 1518)
	21	Contact photolithography (front-back align) (AZ 9260)
	21	Contact photolithography (front-back align) (Shipley 1813)
	21	Contact photolithography (front-front align)
	21	Contact photolithography (front-front align) (AZ 9260)
	21	Contact photolithography (front-front align) (Shipley 1813)
	21	Contact photolithography (front-front align) (Shipley 1813)
	21	Contact photolithography (front-front align) (SU-8)
	21	Contact photolithography (Image reversal)
	21	Contact photolithography (Manual - Negative)
	21	Contact photolithography (Manual)

	21	Contact photolithography (NR1-6000PY)
	21	Contact photolithography (Shipley 1813)
	21	Contact photolithography (Shipley 1827)
	21	Contact photolithography (Shipley 220)
	21	Contact photolithography (Spray coat)
	21	Contact photolithography (SU-8)
	21	Contact/proximity printing
	21	G-Line BCB process
	21	G-line contact photolithography (Shipley 220)
	21	G-line contact photolithography (Shipley 3612)
Maskless lithography	22	Maskless photolithography (align/expose only)
	22	Maskless photolithography (front-front align) (Rogers R/Flex 8080)
	22	Maskless photolithography (front-front align) (Shipley 1827)
	22	Maskless photolithography (front-front align) (Shipley 220)
	22	Maskless printing
Miscellaneous lithography	23	E-beam Lithography
	23	Hot embossing
	23	Injection molding
	23	Ion beam lithography
	23	Molding
	23	Pattern transfer
	23	Polyimide deposition and pattern
	23	Post-exposure bake (automated)
	23	Stamping
	23	X-ray lithography
Projection mask lithography	24	10X G-line photolithography (OCG 825 35CS)
	24	10X G-line photolithography (Shipley SPR 220-7)
	24	1X LPG maskmaking (CD=1.5um)
	24	1X LPG maskmaking (CD=3.0um)
	24	1X maskmaking (Pattern Generation)

	24	4X DUV (193nm) photolithography
	24	4X DUV photolithography (SVGL Micrascan III)
	24	4X Projection photolithography
	24	5X DUV photolithography
	24	5X DUV photolithography (with BARC)
	24	5X i-line photolithography (Automated)
	24	5X i-line photolithography (image reversal)
	24	5X I-line photolithography (OiR 897 10i)
	24	5x i-line step & expose
	24	5x i-line stepper photolithography
	24	5X reticle making (Pattern Generator)
	24	E-beam mask-making
	24	Laser-writing
	24	Step/repeat projection
Anneal	25	Forming gas anneal (N2/H2)
	25	Furnace anneal (Nitrogen)
	25	Nitrogen anneal
	25	Nitrogen anneal (non-MOS-clean)
	25	Oven anneal
	25	Rapid thermal anneal
	25	Rapid thermal anneal (argon)
	25	Rapid thermal anneal (hydrogen/nitrogen)
	25	Rapid thermal anneal (nitrogen)
	25	Rapid thermal anneal (oxygen)
	25	Rapid Thermal Anneal III-V Materials (air, nitrogen)
	25	Rapid Thermal Anneal Oxide, Nitride (air, oxygen, nitrogen)
	25	Rapid Thermal Anneal PZT (air, nitrogen)
Bake	26	Bake
	26	Dehydration bake
	26	G-line BCB cure
	26	G-line photoresist bake (AZ4000)
	26	G-line photoresist hardbake (AZ4000)
	26	Hardbake

	26	Photoresist Blue M Pre- & Post-Bake
	26	Photoresist hardbake (hotplate @105C)
	26	Post-exposure bake
	26	Post-exposure bake (automated)
	26	Sinter
	26	Softbake
Chemical-mechanical polishing	27	Silicon dioxide CMP
Lapping	28	Standard Lapping
Miscellaneous polishing	29	Mechanical polishing
	29	Selective polishing

APPENDIX "B".
MATLAB® DEFINITIONS FOR THE FUZZY INFERENCE SYSTEM

- **Sugeno Module Definition**

```
[System]
Name='SugenoModule'
Type='sugeno'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=10
AndMethod='prod'
OrMethod='probor'
ImpMethod='prod'
AggMethod='sum'
DefuzzMethod='wtaver'

[Input1]
Name='Cost'
Range=[0 1]
NumMFs=5
MF1='Unacceptable':'trimf',[-0.25 0 0.25]
MF2='Expensive':'trimf',[0 0.25 0.5]
MF3='Average':'trimf',[0.25 0.5 0.75]
MF4='Convenient':'trimf',[0.5 0.75 1]
MF5='Excellent':'trimf',[0.75 1 1.25]

[Input2]
Name='Known-Process'
Range=[0 1]
NumMFs=5
MF1='New':'trapmf',[0 0 0.1 0.3]
MF2='Literature':'trimf',[0.1 0.3 0.5]
MF3='Facility':'trimf',[0.3 0.5 0.7]
MF4='User':'trimf',[0.5 0.7 0.9]
MF5='Regular':'trapmf',[0.7 0.9 1 1]

[Output1]
Name='Process-Suitability'
Range=[0 1]
NumMFs=10
MF1='CPI1':'constant',[0.1]
MF2='CPI2':'constant',[0.2]
MF3='CPI3':'constant',[0.4]
MF4='CPI4':'constant',[0.8]
```

```
MF5='CPI5':'constant',[0.9]
MF6='Unacceptable':'constant',[0]
MF7='Marginal':'constant',[0.25]
MF8='Average':'constant',[0.5]
MF9='Good':'constant',[0.75]
MF10='Excellent':'constant',[1]

[Rules]
1 0, 6 (1) : 1
2 0, 7 (1) : 1
3 0, 8 (1) : 1
4 0, 9 (1) : 1
5 0, 10 (1) : 1
0 1, 1 (1) : 1
0 2, 2 (1) : 1
0 3, 3 (1) : 1
0 4, 4 (1) : 1
0 5, 5 (1) : 1
```

- **Mamdani Module Definition**

```
[System]
Name='MamdaniModule'
Type='mamdani'
Version=2.0
NumInputs=5
NumOutputs=1
NumRules=30
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Input1]
Name='Accessibility'
Range=[0 1]
NumMFs=7
MF1='Unacceptable':'trimf',[-0.1667 0 0.1667]
MF2='Poor':'trimf',[-0.1667 0.1667 0.3333]
MF3='Marginal':'trimf',[0.1667 0.3333 0.5]
MF4='Average':'trimf',[0.3333 0.5 0.6667]
MF5='Good':'trimf',[0.5 0.6667 0.8333]
MF6='Great':'trimf',[0.6667 0.8333 1.1667]
MF7='Excellent':'trimf',[0.8333 1 1.167]

[Input2]
Name='Complexity'
Range=[0 1]
```

```
NumMFs=2
MF1='Simple':'gaussmf',[0.23 0]
MF2='Complex':'gaussmf',[0.19 1]

[Input3]
Name='CriticalParam1'
Range=[0 1]
NumMFs=7
MF1='Unacceptable':'trimf',[-0.1667 0 0.1667]
MF2='Poor':'trimf',[-0.1667 0.1667 0.3333]
MF3='Marginal':'trimf',[0.1667 0.3333 0.5]
MF4='Average':'trimf',[0.3333 0.5 0.6667]
MF5='Good':'trimf',[0.5 0.6667 0.8333]
MF6='Great':'trimf',[0.6667 0.8333 1.1667]
MF7='Excellent':'trimf',[0.8333 1 1.167]

[Input4]
Name='CriticalParam2'
Range=[0 1]
NumMFs=7
MF1='Unacceptable':'trimf',[-0.1667 0 0.1667]
MF2='Poor':'trimf',[-0.1667 0.1667 0.3333]
MF3='Marginal':'trimf',[0.1667 0.3333 0.5]
MF4='Average':'trimf',[0.3333 0.5 0.6667]
MF5='Good':'trimf',[0.5 0.6667 0.8333]
MF6='Great':'trimf',[0.6667 0.8333 1.1667]
MF7='Excellent':'trimf',[0.8333 1 1.167]

[Input5]
Name='CriticalParam3'
Range=[0 1]
NumMFs=7
MF1='Unacceptable':'trimf',[-0.1667 0 0.1667]
MF2='Poor':'trimf',[-0.1667 0.1667 0.3333]
MF3='Marginal':'trimf',[0.1667 0.3333 0.5]
MF4='Average':'trimf',[0.3333 0.5 0.6667]
MF5='Good':'trimf',[0.5 0.6667 0.8333]
MF6='Great':'trimf',[0.6667 0.8333 1.1667]
MF7='Excellent':'trimf',[0.8333 1 1.167]

[Output1]
Name='Process-Suitability'
Range=[0 1]
NumMFs=5
MF1='Unacceptable':'trapmf',[0 0 0.1667 0.3333]
MF2='Marginal':'trimf',[0.1667 0.3333 0.5]
MF3='Average':'trimf',[0.3333 0.5 0.6667]
MF4='Good':'trimf',[0.5 0.6667 0.8333]
MF5='Excellent':'trapmf',[0.6667 0.8333 1 1]

[Rules]
```

```
1 0 0 0 0, 1 (1) : 1
2 0 0 0 0, 2 (1) : 1
3 0 0 0 0, 2 (0.5) : 1
4 0 0 0 0, 3 (1) : 1
5 0 0 0 0, 4 (0.5) : 1
6 0 0 0 0, 4 (1) : 1
7 0 0 0 0, 5 (1) : 1
0 1 0 0 0, 5 (1) : 1
0 2 0 0 0, 1 (1) : 1
0 0 1 0 0, 1 (1) : 1
0 0 2 0 0, 2 (1) : 1
0 0 3 0 0, 2 (0.5) : 1
0 0 4 0 0, 3 (1) : 1
0 0 5 0 0, 4 (0.5) : 1
0 0 6 0 0, 4 (1) : 1
0 0 7 0 0, 5 (1) : 1
0 0 0 1 0, 1 (1) : 1
0 0 0 2 0, 2 (1) : 1
0 0 0 3 0, 2 (0.5) : 1
0 0 0 4 0, 3 (1) : 1
0 0 0 5 0, 4 (0.5) : 1
0 0 0 6 0, 4 (1) : 1
0 0 0 7 0, 5 (1) : 1
0 0 0 0 1, 1 (1) : 1
0 0 0 0 2, 2 (1) : 1
0 0 0 0 3, 2 (0.5) : 1
0 0 0 0 4, 3 (1) : 1
0 0 0 0 5, 4 (0.5) : 1
0 0 0 0 6, 4 (1) : 1
0 0 0 0 7, 5 (1) : 1
```