DESIGN METHODS IN MEMS/NEMS

Volume 1

Cornelius T. Leondes
Editor

MEMS/NEMS Handbook

Techniques and Applications

Springer

MEMS/NEMS

Handbook Techniques and Applications

Volume 1
Design Methods

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Contents

Foreword

Over the next decade, major industrial and scientific trends that emerged during 1990s will influence not only how manufacturing will be done, but also what is manufactured. The size of many manufactured goods continues to decrease, resulting in ultra-miniature electronic devices and new hybrid technologies. It has been predicted that within the next decade at least half of the newly designed advanced materials and manufacturing processes will be built at the nanoscale. MEMS/NEMS (Micro/Nano Electro-Mechanical Systems) is a rapidly growing field building upon the existing silicon processing infrastructure and techniques to create micro/nano-scale devices or systems. MEMS/NEMS devices integrate physical, chemical, and even biological processes in micro- and millimeter-scale technology packages. MEMS/NEMS devices now are emerging as product differentiators in market areas such as automotive, aerospace, electronics instrumentation, industrial process control, appliances, biotechnology, healthcare, office equipment, and telecommunications. Unlike conventional integrated circuits, micro/nano devices can have many functions including sensing, communication, and actuation. MEMS/NEMS technology just like microelectronics will permeate our daily lives in the coming decades. On the horizon is the development of nanomanufacturing technologies that will support tailor-made products having functionally critical nanometer-scale dimensions produced using massively parallel systems or self-assembly. The trend in product miniaturization will require new techniques for design, fabrication/manufacturing, and process measurement and control that can span millimeter, micrometer, and nanometer-size scales while accounting for the associated physics that govern the device and environment interaction at each specific size scale. This will require new standardized architectures, advanced computational representations, and innovative design methods and processes that support multiple physics-based models and allow seamless transition and traversing through these various models.

MEMS/NEMS is a significant, extremely timely contribution to the MEMS and nanotechnology field. Edited by Professor Cornelius Leondes, a leading contributor to MEMS/NEMS, this set of five well-integrated volumes on the subject of MEMS and nanotechnology provides a valuable reference for researchers and practitioners. This multi-volume major reference work features contributions from more than 100 of the world's foremost MEMS/NEMS authorities in industry, government, and academia. It provides a wealth of the state-of-the-art techniques and applications in MEMS/NEMS. In contrast to ordinary academic pedagogy, where abstraction and elegance are the guiding principles, practical techniques and applications require detailed relevant examples or case studies that can be used by practitioners to successfully innovate new design, fabrication/manufacturing, and operational capabilities. The progress of the MEMS and nanotechnology depends on the flow of these innovations, which requires multi-volume major reference works with carefully selected, well-written, and well-edited examples and applications.

The two most valuable features of this major reference work are the breadth of material and the depth of the topics covered. Each volume comprehensively treats a significant and specific subject area of fundamental importance to MEMS/NEMS: design, fabrication/manufacturing, and applications. *Volume I* addresses the design methods in MEMS/NEMS. Here the reader can learn from some of the leading individuals in the field how to design an MEMS/NEMS device or system. Nine chapters comprehensively describe emerging design, analysis and simulation, synthesis techniques and how to apply them in real applications. These include electrostatics analysis, analytical simulation, synthesis and dynamic simulation, global optimal design, hierarchical design, knowledge intensive design, concurrent & collaborative design methodologies and web-enabled frameworks and systems. *Volume II* covers the fabrication techniques for MEMS/NEMS devices. In this volume the reader can see the methods and steps taken to effectively fabricate different types of micro/nano devices and structures, including micro rotors, ultrasonic transducers, thermally-based micro devices, micro fluidic devices, nano-structures, micro-mechanism joints, etc. *Volume III* describes manufacturing methods/techniques for MEMS/NEMS out of micro/nano components or parts, including micro-machine tool prototypes and micro-factories, tool-based micro-machining, rapid prototyping and rapid tooling, injection molding, laser machining, acoustic microscopy scanning, production scheduling, etc. The last two volumes provide insight into developing and deploying micro/nano devices and systems in a wide range of applications. *Volume IV* comprehensively discusses micro/nano sensors and actuators, their modeling techniques and applications in MEMS/NEMS. These include accelerometers, micro-humidity sensor, micro-pump actuator, stress measurement sensor, micro-thermal actuator. *Volume V* specifically describes medical applications of the state-of-the-art MEMS/NEMS and MOEMS (Micro Optical Mechanical Systems) devices, including: biomedical devices, actuators and sensors for glaucoma treatment, electro-thermal MEMS mirrors, endo-vascular micro-tools, optical MEMS devices, optically integrated pressure and temperature sensors, optical micro-scanners, torsion micro-mirrors, etc. Collectively, this material provides tremendous resources for emerging design, fabrication/manufacturing techniques and applications of MEMS/NEMS and MOEMS.

To understand the essence of this major reference work, we can consider/review it in the context of the evolution of MEMS/NEMS techniques and their applications. The early days were spent in somewhat of a probing fashion, where researchers looked for ways to design a micro/nano device or system that promises to have multiple functionalities using batch fabrication techniques similar to the way integrated circuits are made. Armed with an understanding of how to design and fabricate a micro/nano device or system, researchers can continuously develop new design, fabrication/manufacturing, and even control techniques and useful applications to solve real-world problems. The current research extensively covers design, analysis and simulation, synthesis, fabrication/manufacturing, and control techniques of MEMS/NEMS and their applications. In particular, the quantum controlled NEMS or nanotechnology is now the focal research area all over the world. The topics that are being explored are scaling laws and principles for NEMS, modeling of NEMS devices, materials and structures, control of NEMS, and applications of NEMS in carbon nanotubes, nanowires, and molecular electronics areas. Thus, the current effort comprises the research thrust supporting manufacturing at the atomic, molecular, and micro-millimeter (nanometer) scales and serves as the mechanism for development of relevant models, architectures, and methods for MEMS/NEMS design and manufacturing as well as control systems. However, the major challenges we are facing for developing MEMS and nanotechnology products are: lack of comprehensive, reliable material properties; difficulty in qualifying new process flows and design tools that meet the requirements of concurrent & collaborative engineering strategies; packaging differing significantly from microelectronics; lack of standards across industry; lack of maturity for design methodologies and tools. Therefore, the emerging techniques, applications, and examples of MEMS/NEMS collected by Professor Leondes in this work provide a wealth of practical ideas and methodologies designed to trigger the development of innovation. The contributors in this major reference work clearly reveal the effectiveness and great significance of the techniques available and with further development the essential role that they will play in the future.

Along the way there were a few individuals who published or saw the importance of publishing the accomplishments to provide guidance to advance the field of MEMS/NEMS. Among this small group I believe that Professor Leondes has made the most comprehensive and important contribution to this effort. It has taken many decades of experience and unflagging hard work for him to accumulate the wisdom and judgment reflected in the editorial stewardship of this major reference work. The latest work discussed here is his most valuable contribution to date and should be on the desk of anyone involved in the field. I believe that its publication will definitely stimulate and promote further research and development of MEMS/NEMS and speed up the application of MEMS/NEMS.

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Preface

Integrated circuit technology has brought unprecedented computational power ever closer to the point of use, revolutionizing the design of electronics products and enabling the creation of entirely new product categories. Micro Electro Mechanic Systems (MEMS) promise to do the same for Electro Mechanical Systems through miniaturization, batch fabrication, and integration with electronics, thereby enabling the development of smart products by providing the required interface between the available computational power and physical world through the perception and control capabilities of micro devices or systems (e.g., micro sensors and micro actuators). Micro mechanical devices and systems are inherently smaller, lighter and faster than their macroscopic counterparts, and in many cases are also more precise. MEMS devices are emerging as a product differentiators in numerous markets. MEMS technology is expected to have enormous opportunities in the commercial markets due to the low-cost, high functionality, and small size and weight of the devices. MEMS technology allows much more functionality to be placed within a given space than conventional technologies. Alternatively, sophisticated functionality can be placed within a given space than was possible before.

A special class of MEMS is optical MEMS technology, also referred to as MOEMS (Micro Optical Mechanical Systems). MOEMS have become increasingly important in the development of many networks, tele-communications and optical systems. Potential MOEMS applications include optical data storage, optical sensors, bead mounted displays and projection systems. State-of-the-art devices include torsional mirrors, digital micro-mirror devices, laser scanners, optical shutters, micro-optical switches, and micro-machined corner cube reflectors.

Nano Electro Mechanical Systems (NEMS) are MEMS scaled to sub-micrometer dimensions, to exploit the mechanical degree of freedom on the nanometer scale. In this size regime, it is possible to attain extremely high fundamental frequencies while simultaneously preserving high mechanical responsivity. This combination of attributes translates directly into high force sensitivity, operability at ultra-low power, and the ability to induce non-linearity with very modest control forces, leading to potential payoffs in a diverse range of fields from medicine to biotechnology.

Application areas for MOEMS have been noted above. MEMS/NEMS devices are emerging as product differentiators in market areas such as:

Aerospace	Computer Devices
Appliances	Electronics Instrumentation
Automotive	Industrial Process Control

Biotechnology	Medicine
Chemical Systems	Office Equipment
Communications	Telecommunications

This is an MRW (Major Reference Work) on MEMS/NEMS. An MRW is a broad and rather comprehensive treatment of a subject of major international significance that, because of the great breadth of the subject, requires multiple authors and a number of distinctly titled and well integrated volumes for an adequate and proper treatment. Each volume rather comprehensively treats a broadly significant and specific subject area of fundamental importance to MEMS/NEMS. The titles of the respective 5 volumes which compose this MRW are:

1. Design Methods in MEMS/NEMS
2. Fabrication Techniques for MEMS/NEMS
3. Manufacturing methods in MEMS/NEMS
4. Sensors and Actuators in MEMS/NEMS
5. Medical Applications of MEMS/NEMS in medicine and MOEMS (Micro Optical Electro Mechanical Systems)

There is a logical flow through the volumes of this MRW. Starting with design methods then continuing to fabrication techniques followed by manufacturing methods. The final two volumes comprehensively treat applications in sensors and actuators following which is a rather comprehensive treatment of MEMS/NEMS in medical applications and closing with an extensive treatment of MOEMS (Micro Optical Mechanical Systems).

As noted above each volume is self contained and stands alone for those interested in a specific volume. Collectively this 5-volume set constitutes the first comprehensive reference dedicated to the multi-discipline and greatly significant area of MEMS/NEMS on the international scene. As a result these volumes individually, or collectively, constitute an indispensable reference source by leading contributors.

There are over 100 coauthors of this notable work and they come from 19 countries. The chapters are clearly written, self contained, readable and comprehensive with helpful guides including introduction, summary, extensive figures and design examples with comprehensive reference lists. Perhaps the most valuable feature of this work is the breadth and depth of the topics covered.

This first volume of the MRW on MEMS/NEMS on "Design Methods in MEMS/NEMS" includes rather comprehensive treatments of many significant subjects including among others:

a. Web-enabled database system development for design and manufacturing of MEMS
b. Methods in concurrent and collaborative design of MEMS
c. Web-enabled knowledge-intensive support of the collaborative design of MEMS
d. Techniques in the synthesis and dynamic simulation of complex MEMS and their applications
e. Techniques in global optimal design of MEMS and their application
f. Techniques in the efficient design of MEMS sensors
g. Hierarchal design methods for micro-electro fluidic systems (MEFS)

h. Techniques in the electrostatics analysis of MEMS and their applications
i. Techniques for efficient analytical simulation methods in the prototyping of MEMS systems

The contributors to this volume clearly reveal the effectiveness and great significance of the techniques available and, with further development, the essential role that they will play in the future. I hope that practitioners, research workers, students, computer scientists, and others on the international scene will find this set of volumes to be a unique and significant reference source for years to come.

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1

Manufacturing Advisory Service System for Concurrent and Collaborative Design of MEMS Devices

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ABSTRACT

This chapter first presents a concurrent collaborative design strategy for Micro-Electro-Mechanical Systems (MEMS). Then, it presents the development of a knowledge intensive approach and system to select suitable manufacturing processes and materials for MEMS devices a concurrent collaborative design environment. Fundamental issues on concurrent collaborative design for manufacturability of MEMS and MEMS manufacturing process and material selection such as concurrent collaborative design framework, manufacturing process and material hierarchies, and selection strategy are addressed. A fuzzy decision support scheme for multi-criteria decision-making problem is proposed for estimating, ranking and selecting possible manufacturing processes, materials and their combinations. Based on the client-knowledge server architecture and framework, a web-based prototype advisory system for MEMS manufacturing process and material selection, WebMEMS-MASS, is developed to help the designer find good processes and materials for MEMS devices. The system, as one of important parts of an advanced simulation and modeling tool for MEMS design, is a concept level process and material selection tool, which can be used as a standalone application or a Java applet via the web. The running sessions of the system are inter-linked with web pages of tutorials and reference pages to explain the facets, fabrication processes and material choices, and calculations and reasoning in selection are performed using process capability and material property data from a remote web-based database and interactive knowledge base that can be maintained and updated via the Internet. The use of the developed system including operation scenario, use support, and integration with an MEMS collaborative design system is presented. Finally, an illustration example is provided.

Keywords: MEMS, design for manufacturability, process and material selection, World Wide Web, concurrent design, collaborative design, simulation and modeling tool, advisory system.

1. INTRODUCTION

"Micro-Electro Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through the utilization of microfabrication technology. While the electronics are fabricated using integrated circuit (IC) process sequences, the micromechanical components are fabricated using compatible "micromachining" processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices. MEMS promises to revolutionize nearly every product category by bringing together silicon-based microelectronics with micromachining technology, thereby, making possible the realization of complete "systems-on-a-chip"." [32]

MEMS technology is truly an enabling technology that allows the development of smart products by augmenting the computational ability of microelectronics with the perception and control capabilities of microsensors and microactuators. It is also an extremely diverse and fertile technology, both in the applications and in how the devices are designed and manufactured. Strictly listing MEMS devices are extremely small, the MEMS technology is not about size, neither is about making things out of silicon, even though silicon possesses excellent materials properties making it to be an attractive choice for many high-performance mechanical applications. Instead, MEMS is a manufacturing technology, a new way of making complex electromechanical systems using batch fabrication techniques similar to the way integrated circuits are made and making these electromechanical elements along with electronics.

It is now widely accepted that the final cost of a manufactured MEMS product or device is largely determined at the design stage. When developing a product, 70% of the costs of materials, human labor, and equipment are actually set by decisions made during the conceptual design [4, 21]. MEMS designers will tend to conceive parts in terms of processes and materials with which they are familiar and may, as a consequence, exclude from considering process and material combinations that may have proven more economic [1, 4, 16]. "MEMS device design must be separated from the complexities of the fabrication sequence and packaging processes with consideration of different materials and processes" [32, 38]. MEMS device designer requires a high level of fabrication and packaging knowledge in order to embody a successful design. Further, the development of even the most common MEMS device requires a dedicated work to formulate a suitable fabrication sequence and packaging process. MEMS and microelectronic device performance analysis is rendered virtually useless if the material information used in the model is wrong. The error associated with the final simulation results will correlate one-to-one with the error associated with material property estimation.

However, most MEMS devices are currently modeled using weak analytical tools, resulting in a relatively inaccurate prediction of performance behaviors [32]. MEMS design process is usually performed in a trial-and-error fashion, which requires several iterations before the performance requirements of a given device are finally satisfied. This non-ideal design methodology combined with the length of time and high costs associated with MEMS prototyping results in a very inefficient and ineffective scenario for commercial product development. With the development of MEMS, advanced simulation and modelling tools for MEMS design are urgently needed. The design and manufacturing (fabrication and packaging) of MEMS and microelectronic devices and systems need to improve considerably from its current primitive state. The advanced simulation and modeling tools for MEMS design must provide advisory service so as to help the designer select manufacturing processes and materials for MEMS devices [50–56]. It is therefore significant to develop an efficient method and system in a computer-aided concurrent collaborative environment for designers' use at the early stages of MEMS design.

With the advent of wide-area networks and the web, it is believed that many of the largest beneficiaries of MEMS technology will be firms that have no capability or core competency in micro fabrication technology and across by these companies is critically important to the successful utilization of MEMS fabrication facilities. A mechanism or framework allowing these organizations to have responsive and affordable access to MEMS fabrication resources for prototyping and manufacturing is essential. The advisory service system can be used to help communicate the abilities of new processes to designers using the Internet and web, as advocated first by Frost & Cutkosky [18]. The availability of suitable design tools combined with computer networks to provide access to high performance workstations and local or remote supercomputer capability can radically alter this situation. The internet-based world wide web enables developers to provide intelligent knowledge services [14, 51–55]. Expert systems running on servers can support a large group of users who communicate with the system over the network, in which user interfaces based on web protocols provide access to the knowledge servers for services. Expert system technology would lead to the development of many small and medium-sized advisory systems that could help many categories of novice users in performing expert-level tasks. Therefore, it provides an opportunity for making manufacturing advisory expert system widely available via the web.

This chapter aims to develop a knowledge-based method and a web-based advisory system for selecting suitable processes and materials for MEMS devices in a concurrent collaborative design environment:

(1) to explore a new knowledge intensive intelligent methodology for estimating and ranking manufacturing processes/materials.
(2) to develop a new Client-knowledge server architecture and framework for manufacturing process/material selection.
(3) to develop a prototype advisory system for manufacturing process/material selection using Java and CORBA over the web.
(4) To integrate the developed manufacturing advisory system into a self-developed MEMS design system. The system is especially dedicated for generating process and material selection advice during embodiment design of micro-machined components.

The remaining parts of this chapter are organized as follows. The chapter begins with a review of the existing MEMS design systems for process and material selection in Section 2. Section 3 discusses the concurrent design approach and concurrent collaborative design framework for MEMS, including design for manufacturability and framework. Section 4 discusses issues on manufacturing process and material selection, including manufacturing process hierarchies for MEMS and process and material selection strategy and implementation method for such a strategy. Section 5 describes the knowledge decision support scheme for manufacturing process and material selection. Sections 6 and 7 present the development of a web-based prototype advisory service system and its use. Section 8 provides some research results, findings and observations. Section 9 summarizes the chapter and points out the future work.

2. CURRENT STATUS OF RESEARCH

In this section, the previous and current work related to manufacturing process and material selection is briefly reviewed. The focus is on an overview of the functionality of current MEMS design systems related to manufacturing process and material selection for MEMS devices.

MEMS product development is still inefficient due to both design and process related factors: lack of reliable material properties, standard processes steps and/or flows, difficulty in qualifying new process flows, design tools that meet the requirements of concurrent engineering strategies. This result in fewer products that have achieved performance and cost targets necessary to displace competing technologies and longer product development times (average in MEMS industry about 15–18 years from inception) [11, 12]. Major challenges for MEMS development: 1) Concurrent design of device and process, 2) Packaging differs significantly from microelectronics, 3) Lack of standards across industry, and 4) Design methodology and tools lack maturity.

Generally, the selection of a suitable process-material pair to manufacture a component or device is not a straightforward matter [7, 8, 15, 41]. There are many factors to be considered at the design stage, for example, size of component, material to be processed and tolerance on dimensions. While all processes have slightly different capabilities, there is also a large overlap—for many components there are a large number of processes used; methods and software tools for the process selection stem from the more widespread use of computer tools to assist with material selection. Some popular commercial tools are documented for material selection [1]. Process selection tools are more rarer than the material selection tools such as Computer-aided Material and Process Selection (CAMPS) [3], Design Advisor (DA) [28], Material and Manufacturing Process Selection (MAMPS) [20, 21], Cambridge Process Selector (CPS) [15], Process Sequencing Expert Shell (PSES) [16], Manufacturing Advisory System (MAS 1.0 & 2.0) [6, 2, 41]. These systems are mainly dedicated to common (macro level) product manufacturing process and material selection. Details can be found in [41, 52–54].

For a product at the micro level (i.e. MEMS) manufacturing process and material selection, no such system is yet available although there are several commercial MEMS design systems such as MEMCAD™ (now coventorWARE™) [10], IntelliSuite™ [23], and MEMSCAP™ [31], which support integrated modeling and process. These systems have some functionality for MEMS manufacturing process and material selection or contain some embedded modules for this purpose. In what follows, an overview of the functionality of the above three MEMS design systems in manufacturing process and material selection for MEMS devices is given.

DESIGNER™ is Coventor's powerful front-end design tool for creating layouts and 3D models of manufacturable MEMS devices. From DESIGNER™ users/designers can create models for further analysis or export files for mask making and fabrication. Manufacturing processes and material properties can be added to create 3D models. Process emulator in it can emulate fabrication steps for MEMS devices and uses standard processes of deposition and etching with control of bulk and thin-film geometries and materials. Material properties database is used for proper identification of each process layer in MEMS device. Layout geometry and fabrication process information are furnished for automatic 3D model generation and visualization.

IntelliSuite™ takes a process-oriented approach to MEMS design and analysis, which starts the design process not from device geometry but from fabrication machine settings. Incorporating process templates, material data, mask layout, and device analysis, it provides a platform for the entire design team to develop manufacturable devices. It is the only CAD for MEMS™ tool to address process parameters linked with thin-film material properties. Processes can be custom-designed one step at a time, or designers/engineers can draw from a wide range of foundry-ready process templates. Users can also create their own process flows from a database of over 70 process steps or by including custom process steps. IntelliSuite's process and materials databases become a major MEMS resource. MEMaterial™, as a most comprehensive thin-film materials database with over 70 materials included, can provide a vital link between the process parameters and the device behaviors. It allows users to predict mechanical, electrical, thermal, physical, optical, and other material properties as a function of processing parameters. As the database is extensive based on measured data rather than constitutive relationships users can expand with their own proprietary data.

MEMSCAP offers two primary software MEMS design tool suites: MEMS Xplorer™, for UNIX workstations and MEMS Pro™, for PC operating systems. The two CAD software tools provide a system-level approach enabling designers to develop new MEMS designs, integrate existing designs (intellectual property or IP), and couple them with the system electronics that will drive them. The tool suites offer a comprehensive and customizable design environment for the development and test of MEMS-based products. MEMSCAP CAD tools are open-platform products that support leading electronic design automation environments used for integrated circuit development. These tools allow data sharing between system designers, IC designers, process engineers and MEMS experts, permitting earlier and consistent design checks between multidisciplinary teams. MEMSCAP also provides modular subsets of these tools for those customers not requiring full capability. Each of the tool suites has easy-to-use graphical interfaces for rapid design. MUMPStart™ is an all-in-one MEMS design kit. MEMS Pro's built-in Technology Manager permits targeting of specific process technologies.

From the review of current MEMS design systems above, we can find that the functionality of them for MEMS manufacturing process and material selection can eliminate a large amount of work during design, analysis, and simulation such as looking up table, data sharing, form filling, and process/material coding. However, they may still suffer one or more of the following drawbacks: depend heavily on the experience and knowledge of designers/users, no built-in ways for selection or decision-making knowledge representation; no mechanisms to utilize the given knowledge and guide the designer/user; difficult to modify, not easy to extend or update, and no mechanism to provide advisory services or explain the results and what-ifs. Also, they are generally specialized and stand-alone applications, and still lack of effective and efficient methods for selecting manufacturing processes and materials and their combinations. It is very difficult for designers to use them for understanding and designing the integrated distributed performances of product systems when selecting different materials and processes. Thus, they are unable to support and coordinate highly distributed and decentralized collaborative MEMS design and modeling activities.

To overcome the above drawbacks and improve the current method of selecting manufacturing processes and materials and their combinations, this chapter presents a knowledge intensive decision support methodology and a web-enabled advisory system to help designers/users collaborate and make rapid and more intelligent decisions in selecting manufacturing processes and materials for MEMS devices. The motivation and vision in this chapter share themes with the macro-level product process and material selection software system, especially MAS 2.0 [41] and WebMCSS but focus on MEMS (micro-level) with providing not only the choice but also advisory service. Details will be discussed below.

3. CONCURRENT COLLABORATIVE DESIGN METHODOLOGIES AND FRAMEWORK FOR MEMS

In this section, issues on MEMS design and manufacturing integration, concurrent design for manufacturability, concurrent and concurrent collaborative design framework are discussed.

3.1. Concurrent Design for Manufacturability of MEMS Devices

Traditional MEMS manufacturing approaches using “build and test” to design lack of standard process and adequate design tools. Concurrent engineering approach for MEMS focuses mainly on design for manufacturing and assembly of MEMS, simply design for manufacturability (DFM). The objective of design for manufacturing and assembly of MEMS is to develop the methods and associated computer tools, necessary for the concurrent engineering process of MEMS products, integrating considerations about manufacturing and assembly. Table 1 lists essential elements of MEMS product design and development methodology. The fundamental MEMS DFM principles are [4, 48, 12]:

1) Minimize the number of components—fewer masks, fabrication steps etc. can reduce material and assembly costs. This provide greater reliability in the final product, and easier automation downstream.
2) Developing modular designs—components with standard interfaces that are capable of being assembled into more complex systems. This reduces assembly time and efforts, inventory requirements, and facilitates automated assembly.
3) Use of standard components—standard fabrication steps, standard packing etc. results in reduced design efforts, fewer parts, and avoids custom engineered parts.

TABLE 1. MEMS Product design and development methodology (Source: [12])

MEMS Product Design and Development Methodology (PDDM)
I Implement a uniform PDDM through out Organization
II Essential Elements of the PDDM
1 Specification Development—begins with a clear determination of the needs of the customer
2 Conceptual Design Phase–many design concepts are developed and evaluated simultaneously so as to offer enough choices for a successful product
1) Many design concepts are developed to satisfy ER (engineering requirement)
2) Use techniques such as brainstorming, Unified Structured Inventive Thinking (USIT), analogies (i.e. muscle as an actuator)
3) Evaluate the concepts to select the best concept(s) into the Detailed Design Phase
▪ Absolute Methods: Go/No-Go, Technological Evaluation
▪ Relative Methods: Decision Matrices (Pugh Matrices)
3 Detailed (Verification) Design Phase–variety of analysis methods such as analytical, FEM, BEM or macro-modeling to verify the design; Perform detailed engineering analysis of the selected design concepts
1) Apply Design of Experiments (DOE) to define the experimental simulation space
2) Simulation and Analysis
▪ Analytical, FEM, BEM, MM, System Dynamics
▪ Optimization
▪ Tolerance Design
▪ Probabilistic Design
▪ Design rules and guidelines
Package Design
1) Identify Product-Package requirements
2) Identify the critical properties (hermeticity, cost, technology (Ceramic, Plastic, QFP, CSP, BGA, etc))
3) Co-Design MEMS-Package
▪ Selection of die attach and molding compounds
▪ Selection of wafer level encapsulation methods
Package-Device Co-Design
1) Identify critical properties: hermeticity, cost, technology (ceramic, plastic, QFP, CSP, BGA)
2) Co-design MEMS-package
▪ Selection of die attach and molding compounds and wafer level encapsulation methods
▪ Package-die-MEMS thermo-mechanical behavior
4 MEMS Standard Manufacturing Process:
1) Develop process requirements
▪ Identify product requirements
▪ Identify critical process characteristics
2) Identify and evaluate existing processes
▪ Identify and benchmark fabrication vendors
▪ Use existing process, improve existing process, develop a new process
• Standard MUMPS Process: Design rules, material properties, process capability, multi-user cost advantage
• Modified MUMPS Process: Similar or violated design rules, some material properties, some process development, customer bears cost of full wafer lot
• New Process: Develop design rules, verify material properties, determine process capability, significant cost to customer
5 Material Property Characterization
1) Identify Product-Process requirements
2) Identify the critical material properties
▪ Young's modulus, fracture strength
▪ Electrical resistivity, dielectric constant
▪ Thermal conductivity,
3) Develop test structures to assess critical material properties
4) Develop extraction models
5) Determine material properties

4) Designing parts for multi-use—standard process flows for example could be used for multiple MEMS products. This has enormous potential to cut costs and save time.
5) Design for ease of manufacturing—employing existing materials, processes etc. implies using standard process steps wherever possible, and simplifying part geometry.

The key points of the concurrent design for manufacturability (DFM) methodology can be summarized as follows:

1) definition of systematic, concurrent design principles
2) utilization of CAD framework for evaluation of product designs and process flow: integrated process, MEMS element, electronics and packaging design
3) rapid process and design qualification through systematic parametric modeling and testing from initial development to specifications for volume manufacturing

Traditional CAD systems allow users to create 2D or 3D models of products without support for manufacturing and assembly. These tools are also used relatively late in the design process (in general during the detailed design phase). These imply [48]: (i) that the designers have no CAD support during the early design phase (conceptual design phase) (ii) that manufacturing and assembly are considered very late in the design process, (iii) that the modifications implied by these considerations are done when their economical consequences are worst. To avoid these inconveniences we propose a computer-aided approach covering the entire design process from conceptual design to detailed design and considering as early as possible in the process the different lifecycle phases (manufacturing, assembly, use, end-of-life). Concurrent MEMS design system focusing on the MEMS design and manufacturing integration offers the designer at each step of the design process: (i) methodologies (QFD, Case Based Reasoning), (ii) analysis and evaluation tools based on constraint graphs, (iii) representation tools, and (iv) expertise in the domains of manufacturing and assembly. The criteria for manufacturability and assemblability usually used in concurrent engineering are adapted to the particular nature of MEMS products (size, tolerances, and manufacturing technologies).

3.2. Concurrent Collaborative MEMS Design Framework

A wide range of design problems are included in MEMS devices or systems development, such as conceptual design, configuration design, process simulation, solid body geometric renderings from photo-masks and process descriptions, optimization of geometry and process sequence, micro assembly design, planning and simulation, and design of full systems. There are generally two rather different types of CAD requirements [39]: conceptual design phase and product-level phase. The first conceptual phase of a new device is to assist in finding practical configurations; the second product-level phase is to enable careful attention to physical behavior and parasitic phenomena. There is a great benefit if the actual device masks and process description can be used as input to the simulations. The rendering of three-dimensional solid models from mask and process data, both to permit checking of geometries and as input to physical simulation, assures that the device being simulated is also the one being built. MEMS CAD can be categorized into the work at the following levels: system, device, physical/behavioral, and process level, in which lumped networks,

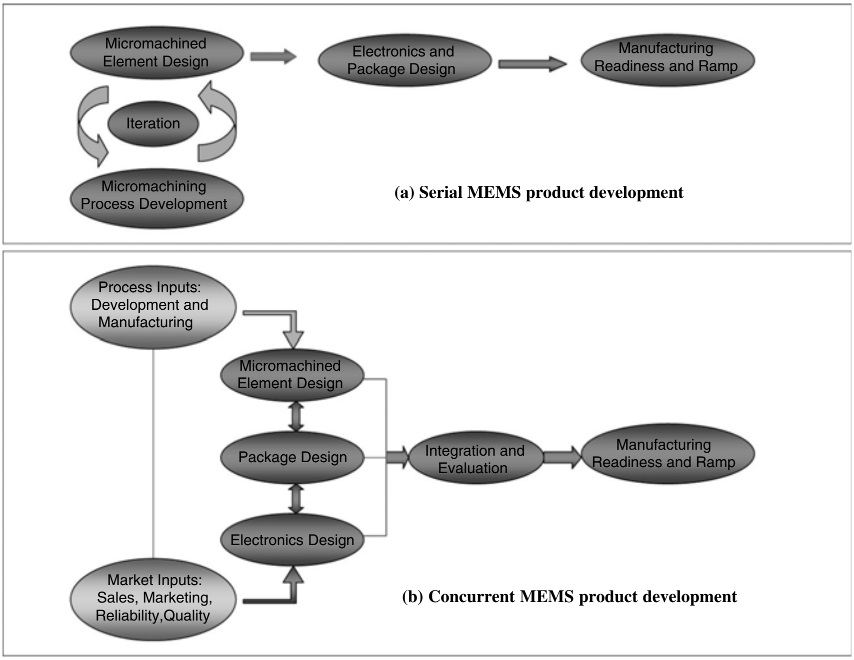

FIGURE 1. Serial and concurrent engineering approaches for MEMS development (Source: [12])

energy-based macro-models, 3D simulation, and TCAD are included respectively [39]. The host of modeling and simulation requirements for a MEMS CAD system at these levels can be identified and described as follows:

(1) process modeling tools for all process steps;
(2) process optimization tools to achieve a desired device geometry (e.g., topology optimization);
(3) physical simulation in multiple coupled energy domain;
(4) construction of designer-useful behavioral models from simulation (micro models);
(5) device optimization tools to achieve desired device behavior;
(6) insertion of behavioral device models into system-level simulation tools;
(7) behavioral model optimization for desired system performance

In an ideal MEMS design environment, the user will first simulate the fabrication process steps to generate the 3D geometrical model including fabrication dependent material properties and initial conditions (e.g. fabrication induced stresses). The input to this simulation step is the mask layouts (e.g. in CIF or GDS II format) and a process description file (e.g. PFR). To compute fabrication dependent initial fields, the initial geometry model will be meshed and physics based process models (deposition, etching, milling, bonding, annealing, etc) will create a simulation-ready virtual model with complete definition of material properties, boundary and volume conditions, and physical/numerical parameters for field solvers. All model parameters should be specified directly "on geometry" rather than on mesh to allow multi resolution (grid independence) and solution-based mesh adaptation. The ultimate goal, of course, is that the device and the associated system are fabricated, and

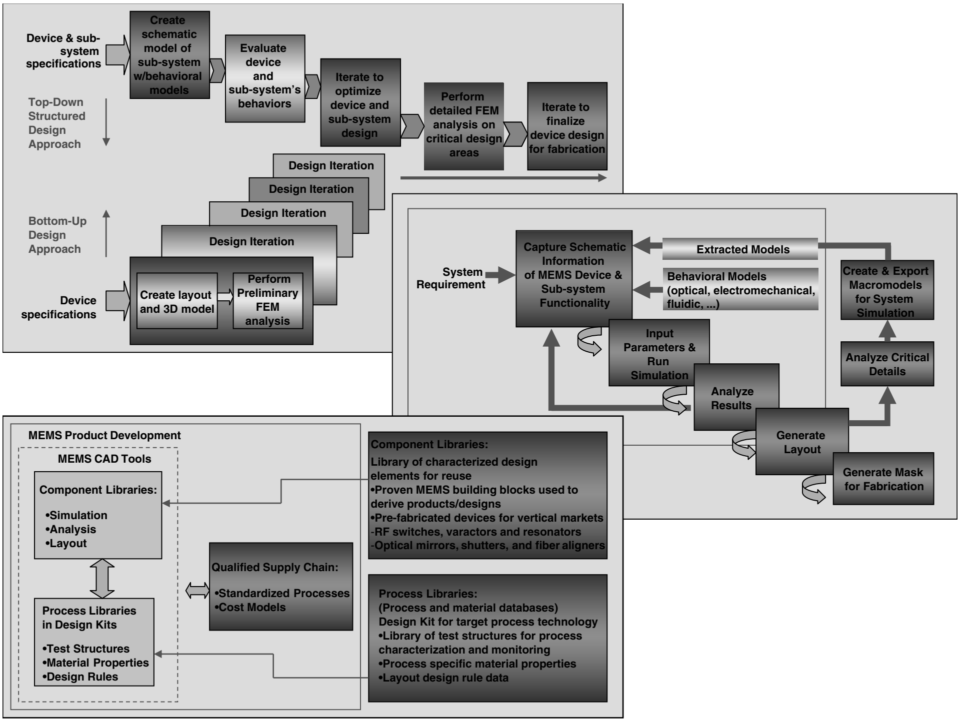

FIGURE 2. Top-down or bottom up design flexibility, 3D micro device CAD flow, and MEMS DFM environment (source: [12])

the system performance is as desired. To the extent that issues can be anticipated through simulation and modeling, also called computational prototyping, costly fabrication experiments can be reduced in number and increased in effectiveness. Figure 2 shows top-down or bottom up design flexibility, 3D micro device CAD flow, and CAD tools for MEMS design and manufacturing integration.

As stated above, one of the challenges of MEMS technology is that MEMS devices or systems design must be separated from the complexities of the fabrication sequence and packaging processes with consideration of different materials and processes. In our previous work [50, 56], a knowledge intensive methodology for design and simulation of MEMS devices was developed, and a web-based knowledge intensive support framework was built up to support concurrent collaborative design of MEMS. In this concurrent collaborative design framework, an interface is designed to separate design from fabrication/packaging processes, which allows the designer to use process-independent design tools and methodologies [32]. It enables more manufacturable designs, done correct the first time or with fewer iterations to become routine so that the amount of time and effort required to realize MEMS devices can be reduced. Since extensive knowledge of fabrication is no longer a prerequisite before starting design activities, more designers are able to participate in design activities, and these will result in increased levels of innovation and creativity. Further, the interface separating design from fabrication enables higher levels of integration without

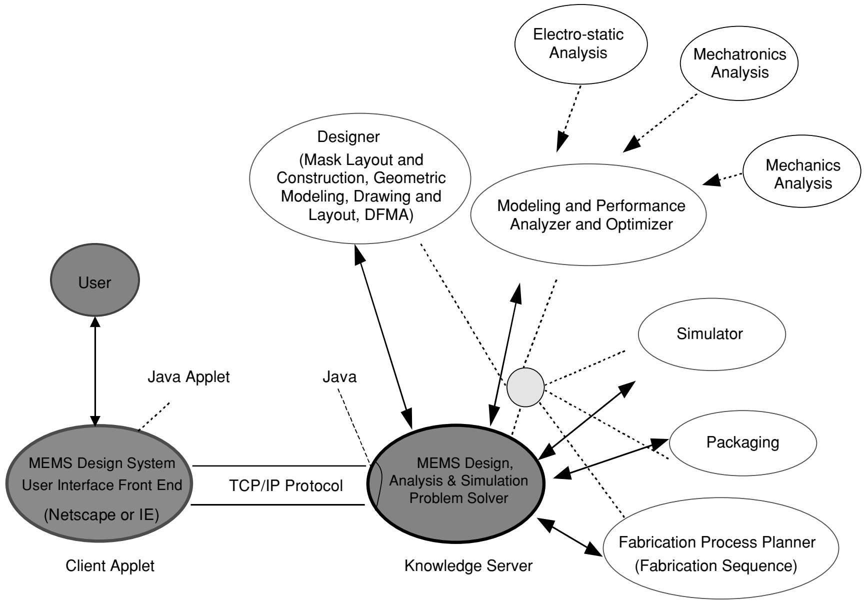

FIGURE 3. KS-WebDMME architecture for MEMS design, analysis and simulation

increasing development time or costs. To be of most utility, the interface allows designers to have ability and know the manufacturing implications of their designs at design time and fabrication specialists to be able to provide the needed functions to aid designers.

Based on the design and development process of MEMS, the KS-DMME architecture for distributed collaborative MEMS design can be illustrated as shown in Figure 3. Under this framework, the requirements for the Web-based MEMS development tool can range from complex intelligent design, modeling, and simulation capabilities to more narrowly defined requirements. Its capabilities should be built into selectable or configurable, and knowledge-intensive modules that are packaged together to meet the requirements of a desired development flow.

4. STRATEGY FOR MEMS MANUFACTURING PROCESS AND MATERIAL SELECTION

4.1. MEMS Manufacturing Process Hierarchy

While the electronics are fabricated using integrated circuit (IC) process sequences, the micromechanical components are fabricated using compatible “micromachining” processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and/or electromechanical devices. To divide the universe of all-possible semiconductor fabrication processes into increasingly specialized domains, a process hierarchy, as shown in Figure 4, is established into which all-possible steps in the fabrication of MEMS devices, including metrology and testing, will fit [32]. This kind of hierarchical

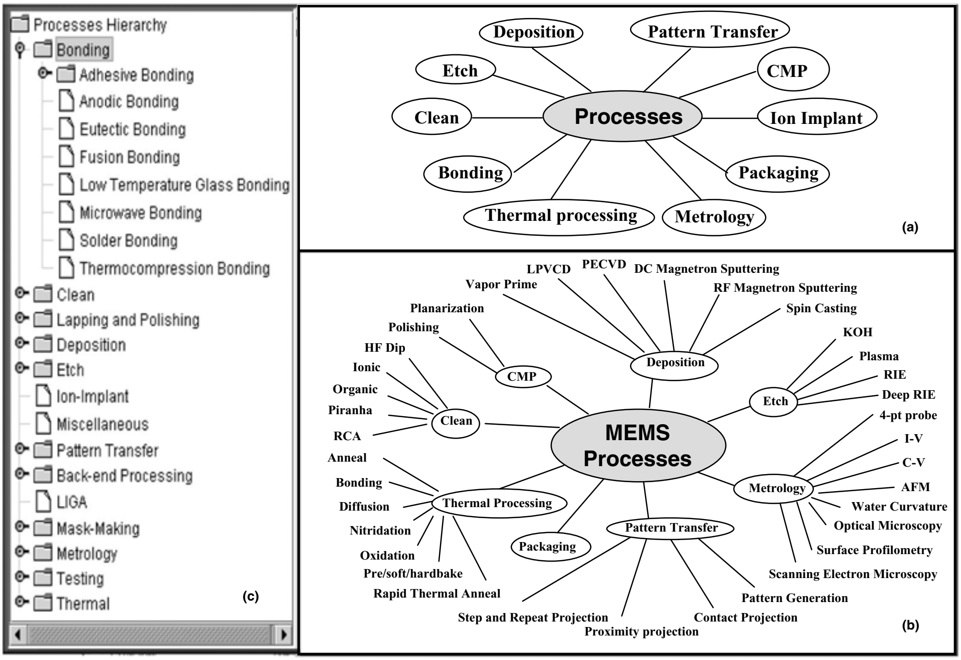

FIGURE 4. Hierarchies of MEMS manufacturing processes and their implementation

process structure can be used to visualize and organize the process capability database containing information about the component processes, materials, and vendors, etc. It can bring two major benefits: 1) helps familiarize newcomers to semiconductor fabrication with the technology and terminology; and 2) gives experienced users a reference point to describe the scope of (potentially) available processes and the terminology for description.

As shown in Figure 4, the top level of the hierarchy includes deposition, etch, and pattern transfer, mask making, and other broad, high-level terms. Descending a layer, the deposition sub-divides into CVD (chemical vapor deposition), epitaxy, andphysical deposition; the other high-level nodes in the hierarchy (or generic processes) divide similarly. As such, the designers or manufacturers allow expanding branches of the hierarchy and view a set of actual processes under each branch. Through the open web database of process capabilities below, users/designers can search along different dimensions such as material deposited or etched. Thus, designers/users can also select processes from the database of process capabilities to construct a process sequence through a process sequence builder.

4.2. MEMS Manufacturing Process and Material Selection

As stated above, the selection of a suitable process-material pair to manufacture an MEMS component or device is not a straightforward matter. There are many factors to be considered, for example: size of component, material to be processed and tolerance on dimensions. Usually at the beginning of the conceptual design stage, designers are given functional requirements and relevant production requirements such as time-to-market,

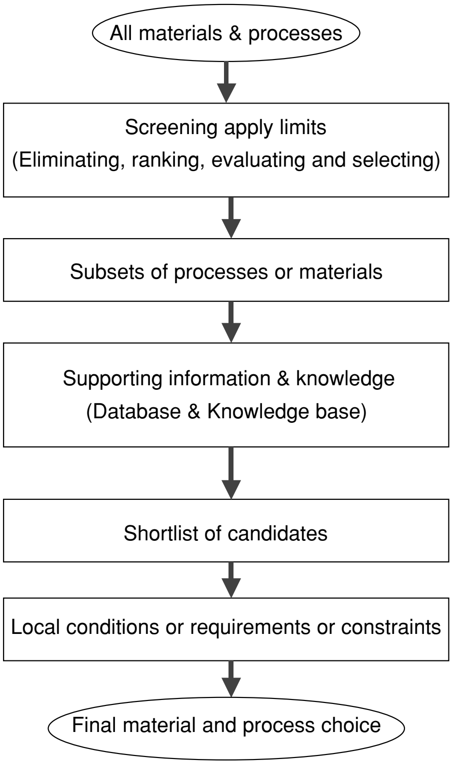

FIGURE 5. The strategy for process and material selection

likely production volume, and total production quantity. During the conceptual design stage, designers identify critical design requirements such as envelope size, material requirements, gross shape, form features, tolerances, surface finish requirements etc. At this stage there exists sufficient information to start preliminary process planning, e.g., material and process selection. The main tasks of the process and material selection are to consider alternative process sequences and compatible materials that can meet the critical design requirements and to select the process sequence that can meet the requirements with the minimum cost. Figure 5 shows a general strategy for the process and material selection.

Before discussing the material and process selection at the conceptual design stage two definitions are needed [41]: requirement and option. A requirement is something needed by the emerging design, which may be a material requirement (i.e. hardness), or a process requirement (i.e. production rate, part geometries, size and shape); while an option is one of the possible processes (or materials) that the designer is trying to select. Specifically, the design requirements are given as follows [9]:

(1) Material Requirements: These requirements are stated in terms of required ranges of yield strength, density, hardness, corrosion resistance, magnetic properties, thermal conductivity, operating temperatures, etc.

(2) Form Requirements: These requirements are stated in terms of envelope size, desired gross shape, likely form feature types (for example, under-cuts, overhangs, holes, and tapers), number of form features, tolerances, surface finish, etc.
(3) Production Requirements: These requirements are stated in terms of ranges on required lead-time, production rate, and overall production quantity.

It can be seen that the process requirements can also be classified into form requirements and production requirements. Based on the above design requirements, designers are interested in finding (evaluating and selecting) a process sequence that can meet the design requirements with some criteria and metrics, e.g., the minimum total production cost. The method used in this research is based on the ranking techniques for evaluating and selecting possible process/ material combinations for a particular component part in terms of the total production costs. The total production cost C for a sequence S is defined as:

$$C(S) = \sum_{i=1}^{n} C_{P_i} + C_M + \sum_{i=1}^{n} C_{T_i} + \sum_{i=1}^{n} C_{S_i} \tag{1}$$

where, C_M is material cost, C_{P_i} is the processing cost associated with the i^{th} process in the sequence (it includes both labor and capital cost), C_{T_i} is the tooling cost with the i^{th} process in the sequence, and C_{S_i} is the setup cost with i^{th} process in the sequence. If there is any imprecision in design requirements, then the total production cost is defined by the cost interval used for describing the minimum and maximum costs associated with a sequence due to imprecision in design parameters.

Accounting for the complexity of manufacturing process and selection, a variety of methods should be used to rank the appropriateness of an option with the value of a requirement. When selecting MEMS manufacturing processes and materials, a reasonable number of possible alternatives are available. The procedure of selecting manufacturing processes and materials for MEMS devices is to examine the alternatives against econo-technical criteria. It is actually a multi-criteria decision-making problem. Thus, the problem of MEMS manufacturing process and material selection can be defined as: given a set of alternatives, evaluate and select an alternative that can satisfy customer needs, meet design requirements and fit the technical capabilities of a company. In this research, a comprehensive knowledge intensive method is adopted, which is constructed using various decision-making methods to rank the options with requirement values and support knowledge. Due to the uncertainty and fuzziness of design specifications and technical requirements in the early conceptual design stage, it is difficult to assess the process and material performance in this stage. The kernel of the knowledge intensive method is a fuzzy ranking algorithm for multi-criteria decision-making problems. Details will be discussed in the next section.

5. KNOWLEDGE SUPPORT FOR MEMS MANUFACTURING PROCESS AND MATERIAL SELECTION

In this section, a knowledge-based method is constructed using a variety of methods to rank the appropriateness of an option with the value of a requirement. The focus is on the fuzzy ranking algorithm for fuzzy multi-criteria decision-making problems. Details about the ranking methods and the knowledge decision support scheme for manufacturing process and material selection are described below.

5.1. Ranking Methods and Knowledge Support Scheme

The method used in this research is based on ranking techniques [35] to evaluate and select possible process/ material combinations for a particular component part in terms of total part costs. The basic ranking scheme used in the process and material selection is described as follows. The user enters design specifications for one or more requirements (R). Each possible process/material can then be assigned a requirement rank, R_{req}, based upon the requirement's value, V_{req}. To obtain the ranking for a process, each of its requirement ranks contributes to a weighting function. The output of this weighting function, the figure of merit, is used as the final option rank, R_O. The system repeats this for every option (O) each time a requirement value is changed. Figure 6 illustrates this process. Each requirement has a method for calculating the Rank[R]. The method's parameters are process dependent. A brief description of the methods used in obtaining the requirement ranks was discussed in [41]:

(1) Trapezoidal fuzzy numbers: Generates a rank for a requirement based upon the design specification and a trapezoidal membership function. This is actually a simplified mode from the fuzzy rank method (see Section 5.2 below)
(2) Boolean list membership: The option has a list of things it can do. Anything not on the list is impossible for the process to do.
(3) Table lookup: For the more complex case of determining material/manufacturing process compatibility, a two-dimensional array is used to look up a compatibility factor.
(4) Integer programming: For qualitative requirements that have value ranges or orders of magnitude, such as production setup time's "hours" or "months." A single integer is used to represent the requirement's value.

The key elements of a process and material selection tool are composed of database and decision support systems/ modules. The database support system communicates to the

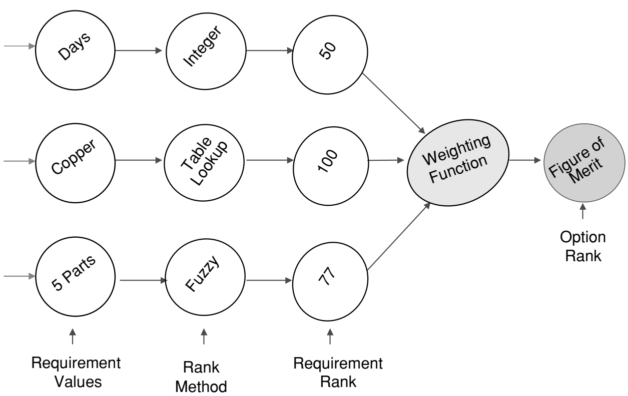

FIGURE 6. Ranking methods