CRANFIELD UNIVERSITY

JEEVAN SAGOO

Developing Microelectromechanical Systems (MEMS)

SCHOOL OF APPLIED SCIENCES

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Developing Microelectromechanical Systems (MEMS)

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Abstract

Intellectually and technologically, the art of design is one of the oldest forms of mankind's expression of creativity. Since the early days of primitive man to now, humans have discovered needs that require functional artefacts to perform necessary operations. There are vast differences in the appearance and applications of such artefacts which have varied with time. Developing artefacts to fulfil the new and changing requirements presents a creative response to problem solving at the macro and micro scales. Developments in technology have progressed rapidly driven by the requirement to create smaller artefacts that possess a larger variety of functions.

The current developments of micro and nano scale devices have the potential of triggering a technological revolution in many fields. The healthcare industry is utilising micro and nanotechnology applications and aiming these to provide quicker and more affordable medical diagnostic equipment such as the lab on a chip. This is currently being developed to provide a point of care testing to analyse blood samples for different viruses, in a miniature blood testing laboratory which is in the space of a microchip, and providing the appropriate response in a real time environment. Some of these devices are still in the conceptual phases with the possibility for future large volume manufacturing however; the development of microelectromechanical systems or MEMS as they are more commonly known, is performed by the experts with an intuitive based approach.

In such context, this thesis proposes a theoretical model for the development of MEMS devices by examination of literature in; generic product development processes used in the engineering and manufacturing areas and capturing how MEMS are currently developed. Parallel to this, development practices currently deployed for MEMS as performed by the experts and practitioners have been illustrated in the form of an As-Is model validated by MEMS experts. The use of IDEF0 to model the existing MEMS development process has provided the necessary tool to analyse the existing process, recognise the limitations, identify the areas of improvement and implement these into a To-Be model proposed for future MEMS development validated by domain experts.

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Firstly, I would like to acknowledge the support and guidance from Dr Ashutosh Tiwari, Dr Jeffrey Alcock, and Dr Meiling Zhu, from Cranfield University, in completion of this thesis, supervision and for providing continual positive feedback. I would like to thank the research and secretarial staff members of the Manufacturing Department at Cranfield University, for their support and enthusiasm throughout the academic year. Special mention should be made to Dr Emma Carter and Nor Hayati Saad from the Micro-Engineering and Nano-Technology Research Group at the University of Birmingham, for their vital contribution into the development of the As-Is model, collaboration and taking me on a tour of the MEMS fabrication facilities.

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List of Abbreviations

AD	Axiomatic Design
ANOVA	Analysis of Variation
ASICS	Application Specific Integrated Circuits
BEA	Boundary Element Analysis
BOM	Bill of Materials
CAD	Computer Aided Design
CE	Concurrent Engineering
CFD	Computational Fluid Dynamics
CMOS	Complementary Metal Oxide Semiconductor
CMP	Chemical Mechanical Polishing
CRs	Customer Requirements
CVD	Chemical Vapour Deposition
DFA	Design for Assembly
DFD	Design for Disassembly
DFE	Design for Environment
DFLC	Design for Life Cycle
DFM	Design for Manufacture
DFMA	Design for Manufacture and Assembly
DFMt	Design for Maintainability
DFR	Design for Recyclability
DFSS	Design for Six Sigma
DFQ	Design for Quality
DFX	Design for X
DOE	Design of Experiments
DPs	Design Parameters
DPU	Defects per Unit
DRIE	Deep Reactive Ion Etching
DTUPC	Design to Unit Production Costs
EC	Evolutionary Computing

ERs	Engineering Requirements
FEA	Finite Element Analysis
FIB	Focussed Ion Beam
FRs	Functional Requirements
IC	Integrated Circuits
IDEF	Integrated Definition Methods
LCA	Life Cycle Assessment
MEMS	Microelectromechanical Systems
MS	Manufacturing Specification
NNI	National Nanotechnology Initiative
QFD	Quality Function Deployment
SOI	Silicon On Insulator
SQC	Statistical Quality Control
TSs	Technical Specifications
VLSI	Very Large Scale Integration

1. Introduction

"Nanotechnology is the art of manipulating materials on an atomic or molecular scale especially to build microscopic devices"

(Hall, 2006)

MEMS is an abbreviation of microelectromechanical systems. A MEMS device contains components of sizes that range from one micrometer (μm) to one millimetre (mm) and are developed to fulfil designated functions by electromechanical or electrochemical means (Hsu, 2008).

Microelectromechanical systems (MEMS) are a combination of mixed technologies that integrate mechanical structures, electromechanical actuators, fluidic chambers, and digital and analog electronics. MEMS are fabricated using batch processing techniques from the microelectronics domain which can sense, control and actuate at the micro scale (Mukherjee and Fedder, 1998). MEMS functionalities are usually defined by their three dimensional structures which is fundamentally different when compared to microelectronic circuits (Brück *et al*, 2006).

Innovation within the field of micro and nano technology is greatly characterised by multi-disciplinary factors. Disciplines such as physics, biology, medicine and engineering are unified in a common development process that can only take place in the presence of multi-disciplinary competences. An example of a MEMS device which incorporates the different disciplines is a sensor for the chemical analysis of fluids. The chemistry, biology and flow mechanics all influence the design of the product (microfluidic device) and thereby the fabrication of the product (Alting *et al*, 2003).

Applications of MEMS and nanotechnology in the healthcare industries are being targeted at providing cost effective medical diagnostic equipment incorporating the lab on a chip concept. This development will provide a point of care testing to analyse blood samples and provide an instant diagnosis in a real time environment (Booker and Boysen, 2005).

1.1. Product Development

At the present time, products are developed using sequential processes that transform a set of inputs into a set of outputs. The product development process is described as a "*sequence of steps or activities which an enterprise employs to conceive, design, and commercialise a product*" (Ulrich and Eppinger, 2008).

Product development is a key step in micro engineering. Product development and the designing of new products will be the core competence of companies in the future using nano and micro technology. This includes the ability to integrate into the product development phase considerations regarding the materials, processes and manufacturing technology, and the development of new design principles and methodologies which integrate the necessary and diverse disciplines. Micro engineering deals with the product development and manufacture of micro products and is not restricted to specific materials and processes (Alting *et al*, 2003).

1.2. Research Context: Developing Microelectromechanical Systems

The focus of this research is on microelectromechanical systems (MEMS) which are the smallest functional machines, also referred to as functional micro machines, which are currently being developed for various applications across many industrial sectors. The key output of the research is the identification of the process for developing MEMS devices.

The research aims to provide the MEMS experts and practitioners with a structured model for generic MEMS devices that; utilises design tools and techniques from the engineering and manufacturing areas, to identify the existing development process constraints, and consider the manufacturing of MEMS devices earlier on in the development process. There is a requirement for a structured and standardised development model for MEMS due to the decreased pace in development which is caused by; the novelty of approaches taken in the development and more importantly, the lack of standard design methodologies for the MEMS design process to support the designers in the microsystems industry (Vudathu and Laur, 2007). The motivation for this research has arisen from the following questions:

- What is the existing MEMS development process?
- Can it be standardised for generic MEMS development?
- Have design methodologies such as DFX been applied to the micro/nano domains and could they be applied?
- What are the requirements to make them applicable?

1.3. Problem Definition

The research context, described in the previous section, has highlighted that there is a requirement for a structured process for developing MEMS devices. The areas reviewed by the research include; the current MEMS development practices, development limitations and constraints, identifying the areas of improvement in existing process, and incorporation of known design tools and techniques from the design domain.

1.4. Research Aim

The research context and problem definition, as previously described, have outlined the main aim of the research which is to:

"Capture the existing MEMS design practices and propose a model for future MEMS development"

1.5. Research Collaboration

This research has been sponsored by and carried out at Cranfield University linked with the Departments of Manufacturing and Materials. The development of the As-Is model and capture of the current MEMS design practices has included experts from the Microsystems and Nanotechnology Centre and Decision Engineering Centre at Cranfield University, and the Micro-Engineering and Nano-Technology Research Group at the University of Birmingham.

In order to define and validate the research areas, experts from both the design and MEMS areas have been approached due to the multi-disciplinary nature of MEMS. This provides the necessary domain expertise to validate the model which involves design and product development principles from the engineering and manufacturing areas, and the development of complex micro devices.

1.6. Thesis Structure

The introduction chapter (chapter 1), introduces design and product development from the engineering and manufacturing domains, and nanotechnology with particular emphasis on microelectromechanical systems (MEMS). The research context is outlined including the problem definition, aim and collaboration. An illustration of the thesis structure is provided in Figure 1-1.

Chapter 2, ‘Literature Review’, examines the related literature to obtain background knowledge on the development concepts used in the engineering and manufacturing domains, and in the different MEMS areas. This chapter also identifies the current achievements in the area of MEMS and summarises some of the existing gaps in research.

Chapter 3, ‘Research Aim, Objectives and Methodology’, describes the set of actions required following the literature review process in order to define the main aim and objectives. The structured methodological approach applied by this research ensures that the stated objectives for fulfilling the research aim, have been addressed in a sequential manner that can be easily followed and validated.

Chapter 4, ‘Designing MEMS Devices’, presents the design practices currently employed when developing MEMS devices as performed by the MEMS experts and practitioners. Techniques deployed to obtain the development practices from the MEMS domain experts are detailed including, the available modelling tools and criteria for selection for representing the existing development practices in the form of a graphical As-Is model. Areas of improvement in the MEMS development process are identified and discussed.

Chapter 5, ‘Developing a Model for Future MEMS Development’, proposes a To-Be model for future MEMS development based on the analysis of the As-Is model and identification of the areas of improvement in the existing MEMS development process. Explanations are provided of how the existing MEMS development process could be improved compared to the As-Is model which identified how the MEMS development activities are currently performed.

Chapter 6, ‘Validating the Model’, covers the validation process of the proposed model for future MEMS development. The validation process confirms the generic models validity and feasibility for the MEMS community when developing future MEMS devices. Experts in the area of design and MEMS have validated the theoretical model that can be applied when physically developing MEMS devices with consideration for manufacturing.

Chapter 7, ‘Discussion, Future Research and Conclusions’, reviews the findings from the conducted research which are summarised and discussed. The conclusions cover the accomplishment of the objectives and in response to the research questions. The chapter concludes with the research contributions, limitations and areas of future research.

The following chapter in this thesis details the literature reviewed which includes a historical perspective on design, generic product development processes and design methodologies from the engineering and manufacturing areas, the multidisciplinary fields of nanotechnology and microelectromechanical systems (MEMS), and reviews the current MEMS design practices and fabrication techniques.

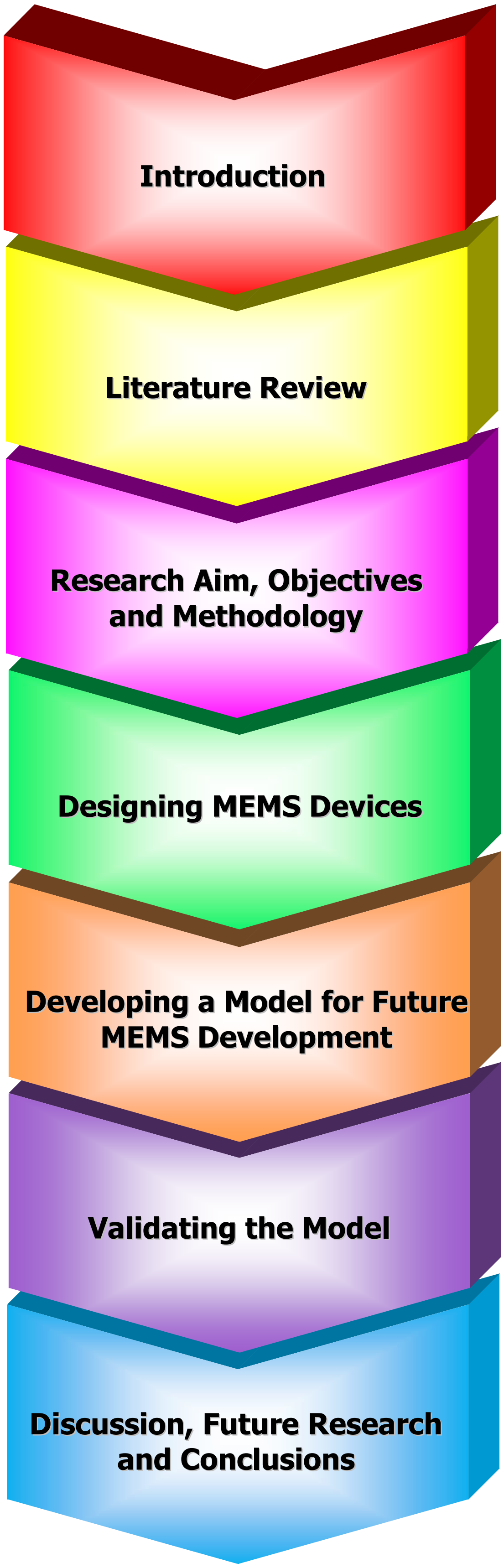
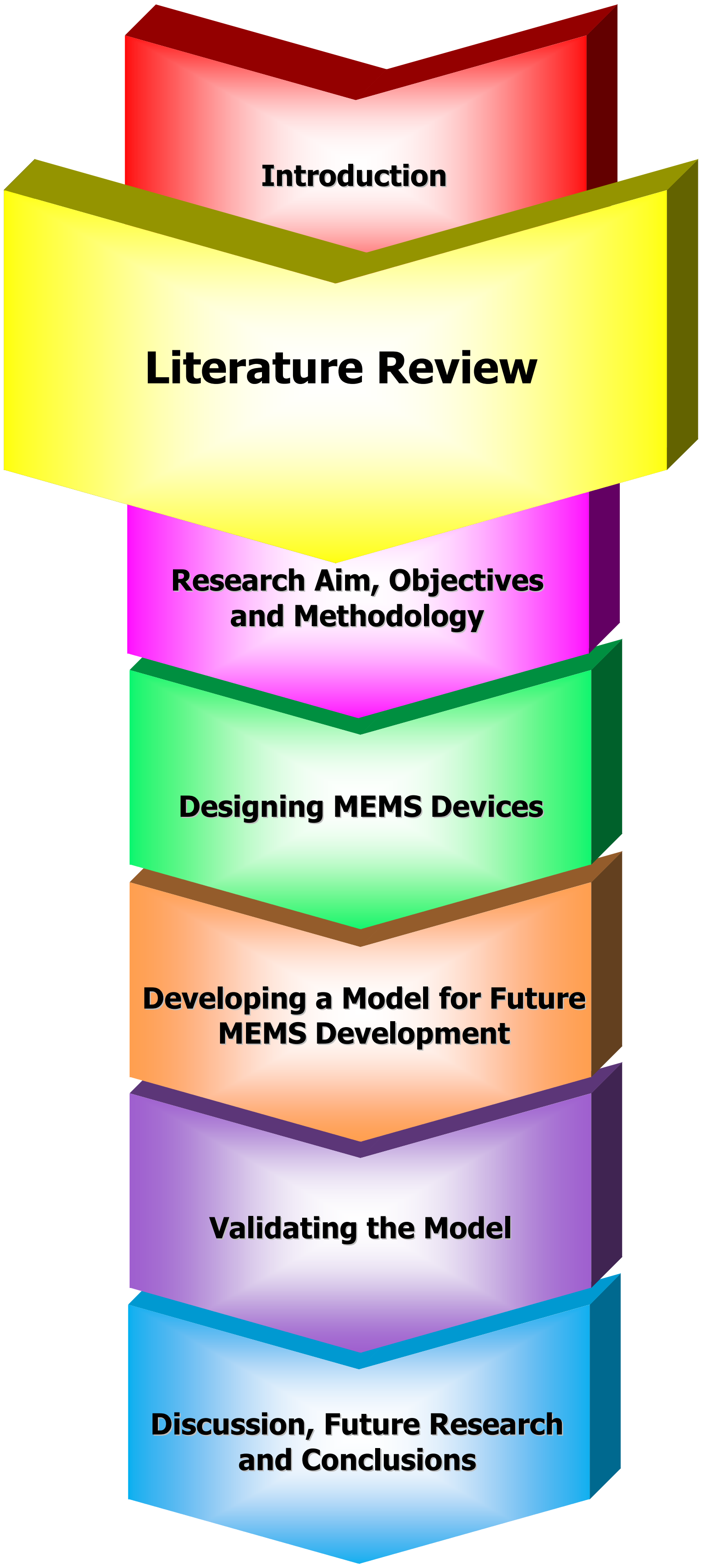


Figure 1-1: Thesis structure

Chapter 2



Introduction
Literature Review
Research Aim, Objectives and Methodology
Designing MEMS Devices
Developing a Model for Future MEMS Development
Validating the Model
Discussion, Future Research and Conclusions

2. Literature Review

The literature review identifies and examines literature that has been published in books, journals and conference papers. This assists in identifying the design methodologies used within the engineering and manufacturing domains and of the current MEMS design and development techniques.

2.1. Overview

Section 1 provides a historical perspective on design beginning with the early development of functional artefacts by primitive man to the modern times, and how the requirements and designs have varied with the available materials and technology for the different time periods, as illustrated in Figure 2-1.

Section 2 presents a generic product development process from the engineering and manufacturing areas, which use sequential steps that contribute to product and process parameters such as process planning and product improvement. The different phases that constitute the product design and development process are presented.

Section 3 describes the design methodologies utilised in the engineering and manufacturing domains for instance design for manufacturing (DFM) and design for assembly (DFA), and how the introduction of these methodologies within the mentioned domains have simplified the manufacturing and assembly of products during the early stages in the product development process.

Section 4 identifies the applications of the available design for ‘x’ (DFX) methodologies used in the engineering and manufacturing sectors and explains how the defined criteria such as; manufacturing, assembly and disassembly, recyclability, environment and reliability are denoted for the ‘X’.

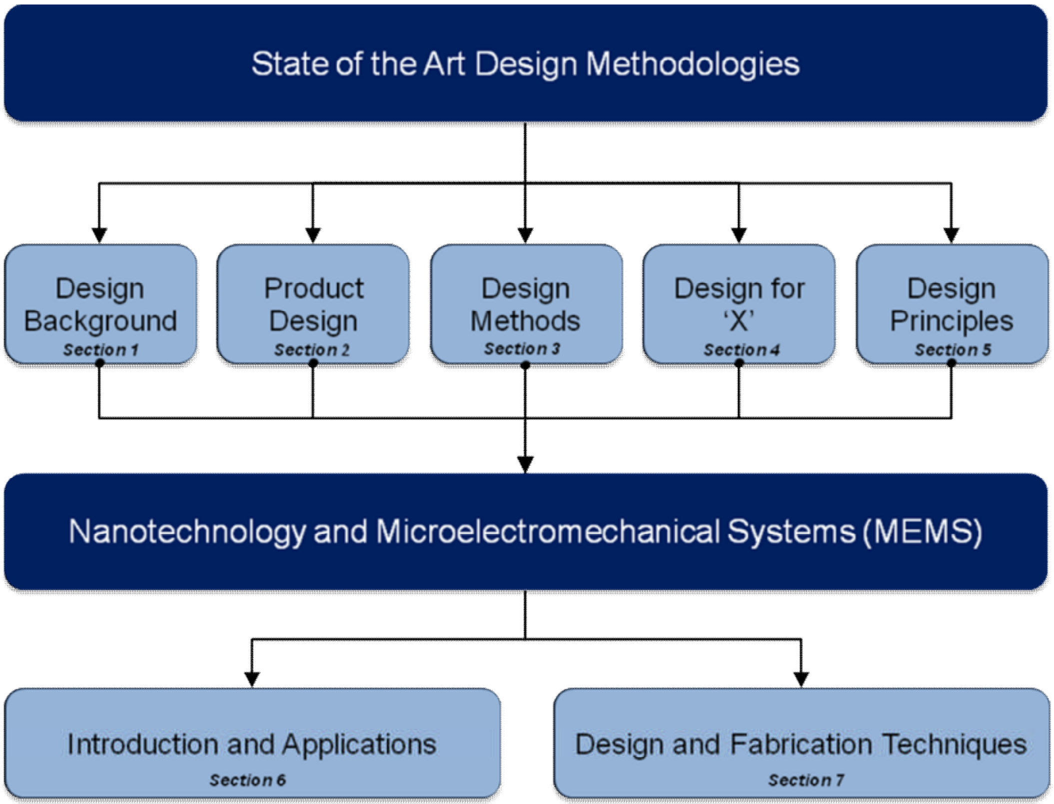


Figure 2-1: Topics evaluated in literature review

Section 5 evaluates design principles that are used independently and concurrently with the design for 'x' methodologies including; design to unit production costs (DTUPC) and design of experiments (DOE) which are both part of the design for six sigma (DFSS) methodology, quality function deployment (QFD), design for quality (DFQ) and axiomatic design (AD). An illustration of the topics reviewed in literature is presented in Figure 2-1: Topics evaluated in literature review.

Section 6 introduces the multidisciplinary fields of nanotechnology and microelectromechanical systems (MEMS) and briefly describes the background and provides examples of devices at the nanoscale range that are being developed for applications across many industrial sectors including the automotive and healthcare industries.

Finally, section 7 reviews the current MEMS design practices and fabrication techniques including the constraints and limitations encountered. The DFM approaches used in the design and manufacture of MEMS devices are presented and discussed.

2.2. Design: A Historical Perspective

Since the early days of primitive man to now, humans have discovered needs that require functional artefacts to perform necessary operations. There are huge differences in the appearance and applications of such products which have varied with time. An example of such a product is the standard kitchen knife. Kitchen knives are available in many different shapes and sizes and serve many different purposes but the requirement remains the same as when humankind first realised this necessity. Primitive man used flints carved out of stone to perform cutting operations but the requirements still exists today in order to cut however, nowadays we have designed and developed knives using much more complex processes than carving stone. Artefacts or products have evolved with the styles and requirements for the specific anthropological periods in history.

Differences in the design of products and the use of new materials is clearly visible from the stone age to the ancient Egyptian era and further more to the *Renaissance* (rebirth – industrial revolution) period. The renaissance or industrial revolution provided opportunities for the significant progress of design as it marked the transition period from the medieval to modern times.

Modern designs have been progressively developed over the past century and this maturity in product development has been implemented for human consumption. Products manufactured in our current age are produced as expressions that are aesthetically pleasing, functional, useful and expressive of their intended purpose. In any design operation, the first and foremost consideration must be of the user and their requirements which can also be expressed as the *design intent*.

A definition of design has been specified by Lindbeck (1995): "*design is the conscious, human process of planning physical things that display a new form in response to some predetermined need*". Once a product is produced, it must meet its intended functional requirements and be adequately usable.

2.3. Product Design and Development

Products are designed and developed using processes which are unique sequential steps that modify a set of inputs into a set of outputs. The product development process is the "*sequence of steps or activities which an enterprise employs to conceive, design, and commercialise a product*" (Ulrich and Eppinger, 2008). A generic product development process is useful as it contributes to the following product and process parameters:

- *Quality Assurance*
- *Coordination*
- *Planning*
- *Management*
- *Improvement*

The following six phases of the generic product development process have been defined by Ulrich and Eppinger (2008):

- **Phase 0: *Planning***
  - Referred to as phase 0, precedes project approval and launch of the product development process. Begins with corporate strategy and assessment of technology and market objectives.
- **Phase 1: *Concept Development***
  - Market and customer requirements are identified and concepts are produced and assessed. Subsequently, final concepts are selected.
- **Phase 2: *System-Level Design***
  - Definition of the product architecture and the decomposition of the product into subsystems and components. This phase usually includes the geometric arrangements of the product and final assembly schemes.
- **Phase 3: *Detail Design***
  - Detail design phase includes the complete specification of the geometry, materials, and tolerances of all unique parts. Standard components required from suppliers are also defined. The generation of the

documentation is a direct output from this phase (CAD and engineering drawings).

- **Phase 4: *Testing and Refinement***
  - Involves the construction and evaluation of multiple preproduction versions of the required product or components. These are tested against the specifications and standards, and refined accordingly to conform to the specifications.
- **Phase 5: *Production Ramp-Up***
  - This phase ensures that the product is produced using the intended production or manufacturing system. This phase in the product development process allows for the manufacturing operators or workers to be trained and assist the design and engineering teams in resolving any remaining issues.

2.4. Design Methodologies

Design methodologies, such as *design for manufacturing (DFM) and design for assembly (DFA)*, have been developed which have resulted in the simplification of products, reduction of assembly and manufacturing costs, improvement in product quality and reduced time to market. Due to the environmental impacts caused by the products and manufacturing processes, companies and organisations are increasingly acknowledging the disassembly and recycling issues during the design stages of product development (Kuo *et al*, 2001). Designing products for; assembly, manufacturing, recyclability, environment and life cycle is referred to as *Design for X.*

2.5. Applications of Design for 'X' (DFX)

Many papers have been published regarding DFX applications in the manufacturing sector (Kuo *et al*, 2001). Ulrich and Eppinger (2008), explain that many product development teams practice *design for 'X'* methodologies, where *'X'* is denoted for one of the criteria such as; manufacturability, serviceability, reliability, environmental impact and maintainability. The most commonly used criterion or methodology is design for manufacture (DFM) due to its ability to directly address the associated manufacturing costs. The following general principles have been defined which are applicable, to the methodologies as described in the subsequent sections, for successfully accomplishing any of the Xs in DFX:

- Detail design decisions can have substantial impact on product quality and cost
- Development teams face multiple, and often conflicting goals
- Important to have metrics with which to compare alternative designs
- Design improvements often require creative efforts early in the process
- A well-defined method assists the decision making process

2.5.1. Design for Manufacture (DFM)

A key determinant for the economic success of a product is the manufacturing cost. Economic success for companies depends on the gained profit margin which is the result of the number of products sold at the specified cost compared to the actual cost of manufacturing. Practicing DFM effectively will lead to lower manufacturing costs without the quality of the product being affected. DFM begins in the early stages of design such as the concept development and system-level design phase, and utilises manufacturing cost estimates to steer the and perform the required cost reductions. Five steps have been identified in the DFM process which includes: *estimate manufacturing costs, reduce component costs, reduce assembly costs, reduce supporting production costs and consider the impact of DFM decisions on other factors* (Ulrich and Eppinger, 2008).

2.5.2. Design for Assembly (DFA)

Boothroyd *et al*, (1994) explicitly state that *"design for assembly (DFA) should be considered at all stages of the design process"*. Serious considerations regarding the ease of assembly or subassemblies of the product should be taken during the production and field service. The basic principles of DFA consist of ensuring that all unnecessary parts are eliminated from the product design or if they are a necessity, they should be redesigned as multifunctional parts. Those parts that remain and require assembly should be fitted together with ease.

Direct costs are a major cost factor incurred during the products manufacture. However, even though the cost of assembling the parts together is low compared to the manufacturing costs, DFA provides significant time and cost savings due to its potential for reducing the number of product parts, reducing costs and reducing the assembly time (Lindbeck, 1995).

In order to maximise the ease of assembly, the following ideal characteristics of a part for an assembly have been defined by Ulrich and Eppinger, (2008) which have been adapted from previous work completed by Boothroyd *et al*, (1994):

- Part is inserted from the top of the assembly.
- Part is self-aligning and secured immediately upon insertion
- Part does not need to be oriented.
- Part requires only one hand for assembly.
- Part requires no tools.
- Part is assembled in a single, linear motion.

2.5.3. Design for Disassembly (DFD)

Due to the increasing complexity of new products, disassembling them at the end of their life-cycles presents an enormous challenge. The disassembly of products has been recognised in order to ensure economic recycling of used products. In past decades, machinery and products were designed to fit the purpose with manufacturing and assembly in mind, but due to new standards and legislations, designers now have to consider the efficient disassembly of products. Lambert and Gupta, (2005) elucidate how the disassembly methodology is not just confined to studying the disassembly process of products, but it also addresses other design issues. Following is a hierarchy which addresses a range of the disassembly difficulties:

1. Physical level
   - Deals with physical properties of components with emphasis on forces and deformability.
2. Surface level
   - Deals with aspects of individual components including free and mating surfaces. Detailed analyses of a disassembly operation are required.
3. Component level
   - Deals with movements of components in the course of disassembly operations and interaction with other components.
4. Modular level
   - Considers functional sub-systems of a product.
5. Product level
   - Applied if analysis of a product as a whole is required for studying relationships between disassembly operations and the sequence of those operations.
6. Batch level
   - Used if processing of multiple products has to be considered.

2.5.4. Design for Recyclability (DFR)

Since the late 1990's and more recently, a big emphasis has been placed on recycling especially in large industrial countries which is due to the quantity of used products having shorter life-cycles and being constantly discarded. Kuo *et al*, (2001) comment on how it is not possible or economic to recycle a product completely therefore, *"the aim of recycling should be to maximise the recycling resources and to minimise the mass and pollution potential of the remaining products"*. Designing products for recyclability, allows many opportunities for designers and manufacturers to work cooperatively in reducing the materials used and in turn reducing costs. Recycling materials such as aluminium can have a 95 percent saving of the energy required to produce the aluminium from the bauxite ore and making new products from recycled plastic saves 85 percent of the energy used in fabricating it from virgin resin (Lindbeck, 1995). The following general principles of DFR have been identified by Kuo *et al*, (2001) below:

- Simplify mechanical assembly
- Avoid self-contaminating combinations of materials
- Standardise materials used
- Separate high copper content items from steel items

2.5.5. Design for Environment (DFE)

Design for environment is a methodology which is concerned with the issues of the environment and product designs including the interactions of humans with the world in which we live in. The waste produced by the manufacturing of products has increased with the complexity and shear volume of production in many industrial sectors and in many countries worldwide. The waste produced in manufacturing some products, devours the natural material resources, uses energy, and creates vast amounts of rubbish which requires disposal.

Lindbeck, (1995) explains how at the end of the products life, *"a product should not contribute to the degradation of the environment"*. A practical approach taken to resolving design and environmental issues is known as *Source Reduction* which decreases the amount of generated waste at the manufacturing level. DFE has been defined by Fiksel and Wapman, (1994) as; *"the systematic consideration during new production and process development, of design issues associated with environmental safety and health over the full product life-cycle"*. DFE includes other disciplines such as; accident prevention, waste management, resource conservation, pollution prevention, ecology, environmental risk management, product safety, and occupational health and safety.

2.5.6. Design for Life-Cycle (DFLC)

DFLC concentrates towards integrating all phases of a product's life cycle in its design. The DFLC methodology has evolved from other methodologies which optimises the product's performances over their complete life cycle. An important reason for this evolution is that manufacturers can be held accountable for any accidents that may occur during the complete life cycle of a product which includes the end of life phase.

Lambert and Gupta, (2005) declare that the objectives of DFLC are to; generate a high recovery rate, a high quality of the recovered components and materials, and a minimum release of hazardous components to the environment all at minimum possible costs. This methodology is also linked to design for disassembly (DFD).

DFLC assesses the environmental impact of a product for its entire life cycle and quantifies it using the *life cycle assessment* (LCA). The life cycle assessment is a set of methods used for assessing materials, services, products, processes and technologies over the whole of the products life cycle (Kuo *et al*, 2001).

2.5.7. Design for Quality (DFQ)

In order to achieve the required product quality, beginning with the design process itself is required. In considering the quality of a product, we must understand that quality cannot be achieved through testing alone, it must built-in from the beginning of the design and maintained throughout the manufacturing processes.

Pahl and Beitz, (1999) explain that; *"quality is influenced decisively during design and development, and has to be realised during production"*. Unfortunately, not even statistical quality control (SQC) and inspection can compensate for errors caused by poor design therefore, as identified by Kuo *et al*, (2001) the objectives of DFQ are to:

1. Design a product to meet the customer requirements

2. Design a product that can minimise effects of potential manufacturing variations of the product and its environment
3. Improve product reliability, performance to exceed customers expectations

2.5.8. Design for Maintainability (DFMt)

The ultimate goal in product development is to design a product that requires little or no service or maintenance. This is known as the *optimum condition* however, if a product or its components do require maintenance, this should be accomplished simply and economically. Lindbeck, (1995) describes both maintenance and maintainability. Maintenance has been described as *"the act of keeping products in, or restoring them to, an operating condition"*. Included in the act of maintenance are both corrective and preventative actions.

Maintainability is described as; *"a design attribute that assures that maintenance can be performed with a minimum of cost, inconvenience, and effort"*. Kuo *et al*, (2001) identified; that maintainability is the *"probability that a failed system can be repaired in a specific interval of downtime"*, and that the basic objective of DFMt is to assure the maintainability of the product during its life cycle at an economical price without any complications.

2.5.9. Design for Reliability

According to Pahl and Beitz, (1999) reliability is the *"ability of a technical system to satisfy its operational requirements within the specified limits and for the required life"*. Reliability of products and individual components especially in protective systems are vital requirements for safety considerations. An associated metric of reliability is the availability of operations of a technical system. Availability is a measure of the percentage of time that a system is available for operation compared to its maximum possible time. The reliability of products is critical for their operations, environmental impact and for the operators (users) safety.

Four factors of reliability have been comprised by Kuo *et al*, (2001) which consist of:

1. Probability
2. Specified function
3. Designated environment
4. Length of time

2.5.10. Design for Six Sigma (DFSS)

The DFSS methodology; applies a statistical approach in order to achieve an almost defect free product, and encompasses the *design for manufacture and assembly* (DFMA) principles with additional statistical techniques in order to steer the design process thus reducing product defects. Scorecards are used to quantify parts, processes, performance and software capabilities or sigma level.

DFSS facilitates effective product design by assisting the selection of; suppliers, manufacturing and assembly processes, system architecture and design, and a software process minimising defects and consequently producing higher quality products in a reduced cycle time (ReVelle, 2002). The typical statistical applications in design utilised by the DFSS methodology are:

1. Tolerance Analysis
2. Process Mapping
3. Product Scorecards
4. Design to Unit Production Costs (DTUPC)
5. Design of Experiments (DOE)

2.5.11. Design for 'X' (DFX)

There are other existing DFX methodologies that have not been mentioned but are comparable to those described in the previous sections of this chapter. The *raison d'être* used to define the methodologies indentified in this section are themselves similar. Pahl and Beitz, (1999) have referred to; *Design for Safety, Design for Ergonomics, Design for Aesthetics, Design for Production, Design for Ease of Assembly, Design for Ease of Maintenance, Design for Recycling, Design for Minimum Risk, Design for Quality and Design for Minimum Cost.*

Thorpe, (2007) has used the terminology, *Design for Sustainability*, which is defined as; *"theories and practices for design that cultivate ecological, economic, and cultural conditions that will support human well-being indefinitely".*

2.6. Design Principles

Although not included in the *Design for 'X'* methodologies, there are other important design principles that are used independently and concurrently with the DFX methodologies. Design to unit production costs (DTUPC) and design of experiments (DOE) are both utilised by the design for six sigma (DFSS) methodology and DOE and quality function deployment (QFD) are both utilised by the design for quality (DFQ) methodology. Axiomatic design is an independent methodology which characterises *design axioms* (*independence axiom and information axiom*) as basic principles used for analysis and decision making to facilitate the creative process of design.

2.6.1. Design to Unit Production Costs (DTUPC)

The design to unit production costs (DTUPC) methodology applies statistical techniques to optimise the design process. Cost is the critical dependant variable and the product is designed to satisfy this requirement.

DTUPC uses six sigma analyses to facilitate cost trades and is an approach in achieving minimum production costs for a product. The use of DTUPC allows a company to understand the product's cost structure and to determine the cost of manufacturing the product. ReVelle, (2002) has recognised that DTUPC *"offers the opportunity to know* *the true cost of every unit produced"*. Seven basic manufacturing cost elements in the DTUPC methodology have been classified as:

1. Setup and assembly labour costs
2. Overhead and general administrative costs
3. Bill of material (BOM), including cost of parts
4. Inspection costs
5. Defects per unit (DPU)
6. Rework cost to correct defects
7. Warranty costs

2.6.2. Design of Experiments (DOE)

Designs of experiments (DOE) techniques are employed to reduce the amount of models required for construction which minimises the amount of experiments needed to explore the design space. Different combinations of design variables are explored by design teams to validate the technical feasibility (Ulrich and Eppinger, 2008).

One of the most useful applications of DOE is to optimise the design process which is accomplished by determining the parameters within a process which may result in the greatest effect on the response. DOE's can be analysed by use of statistical methods which provide capability analyses such as ANOVA (ANalysis Of VAriance) and regression. ANOVA is a technique which decomposes variation of the results obtained experimentally into the variance from experimental parameters including the underlying variation of the process. Regression is a technique which endeavours to fit an equation to the available data (ReVelle, 2002).

2.6.3. Quality Function Deployment (QFD)

Quality function deployment (QFD) is a technique used by the DFQ methodology which facilitates the translation of the frequent ambiguous customer requirements into requirements which are visibly formulated and quantifiable (Pahl and Beitz, 1999). In simplistic terms, it is a way to capture, organise, and deploy the *voice of the customer* including both internal and external customers (ReVelle, 2002).

QFD utilises the use of a matrix to define and represent the relationship between the needs and metrics (needs-metrics matrix). Ulrich and Eppinger, (2008) explain that *"the most useful metrics are those that reflect directly as possible the degree to which the product satisfies the customer needs, and the relationship between needs and metrics is central to the entire concept of specifications"*. The rows in the matrix represent the customer's requirements and the columns represent the metrics. Cells within the matrix that have been marked indicate that there is a relationship between customer's requirement and the associated metric. The use of this matrix is a vital element in developing the *House of Quality* which is used for graphical representation.

2.6.4. Axiomatic Design (AD)

Axiomatic design (AD) is a systems design methodology that was developed in the mid to late 1970's addressing the design and manufacture of complex systems. Axiomatic design can be applied to the design and development of systems such as; hardware, software, materials, manufacturing and organisational. Suh, (2001) defines design as the "*interplay between what we want to achieve and how we want to achieve it"*.

Understanding the customer's requirements is essential in order to transform these into a minimum set of specifications which are then defined as *functional requirements* (FRs). Design parameters (DPs) are the descriptors of how to achieve those requirements. Axiomatic design has acquired its name from the Greek word *axioma* which means 'require' and it is sometimes referred to as 'evidently true' or law. These laws or axioms for axiomatic design have been developed by Suh, (1990, 2001) to establish a scientific basis for design by providing a theoretical foundation based on logical and rational processes and tools.

The fundamental assumption deduced by the axiomatic approach to design is that an essential set of principles exist which determine good design practices. These principles or axioms have been identified by investigating the common elements present in all good designs and the actions taken which have resulted in remarkable improvements. Suh, (2001) has defined the following two axioms:

- ***Axiom 1***: The Independence Axiom
    - *Maintain the independence of the functional requirements (FRs).*
- ***Axiom 2***: The Information Axiom
    - *Minimise the information content of the design.*

2.7. Nanotechnology and Microelectromechanical Systems (MEMS)

Nanotechnology is an emerging multidisciplinary scientific field which is associated with matter at the atomic scale. *Nano* has been derived from the Greek word which means 'dwarf'. The National Nanotechnology Initiative (NNI)[1] in the U.S have defined nanotechnology as a science which involves research and the development of technology at the 1 to 100nm (*nanometre*) range, and the ability to manipulate and control the materials at the atomic scale in a useful way. The common unit of measurement used in nanoscience is a nanometre which is one billionth of a metre, or otherwise expressed as 10^{-9}m (Booker and Boysen, 2005).

Materials and devices at the nanoscale range are being developed for applications concerned with security, healthcare and resources such as energy and water. New stronger and lightweight materials are currently in development that are intended to provide superior material properties but at a fraction of the weight thus providing new alternative materials which could reduce the use of organic materials. Examples of the materials used in nanotechnology (nanomaterials) are provided in Table 2-1: Nanomaterials and applications.

[1] http://www.nano.gov

Name	*Size*	*Definition*	*Applications*
Buckyball (fullerene)	1nm	Molecule made of 64 atoms shaped as a football	• Composite reinforcement • Drug delivery
Carbon Nanotube	1.3nm	Sheet of graphite rolled into a tube	• Composite reinforcement • Conductive wire • Fuel cells • High resolution displays
Quantum Dot	5nm	Much like an atom, a semiconductor nanocrystal whose electrons show discrete energy levels	• Medical imaging • Energy efficient light bulbs
Nanoshell	100nm	Nanoparticles made of silica core surrounded in gold coating	• Medical imaging • Cancer therapy

Table 2-1: Nanomaterials and applications (Booker and Boysen, 2005)

In the healthcare industries, nanotechnology applications are being aimed at quicker and more affordable medical diagnostic equipments such as the lab on a chip, which is being developed to provide a point of care testing to analyse a patient’s specific ailment and provide an instant diagnosis. The fundamental concept of the lab-on-a-chip device is to miniaturise a blood testing laboratory in the space of a microchip analysing blood samples for different viruses and providing the appropriate response in a real time environment (Booker and Boysen, 2005).

There are two main approaches that are used in the fabrication of devices at the nanoscale range which are *top-down* and *bottom-up*. A top-down approach used in nanotechnology has been adapted from the systematic approach used in the fabrication of microprocessors whereby layers are defined then removed from the top surface.

The bottom-up manufacturing approach requires the construction of a nanoscale product one atom at a time and employs a self assembly process whereby the atoms and molecules conform to specified conditions in order to arrange themselves in to the designated product (Booker and Boysen, 2005). The combination of nanotechnology and mechanical systems has resulted in the evolution of devices that are known as microelectromechanical systems, abbreviated MEMS.

2.7.1. MEMS: Introduction and Fundamentals

"What are the possibilities of small but moveable machines? They may or may not be useful, but they surely would be fun to make".

(Feynman, 1961)

Microelectromechanical systems (MEMS) are devices that commonly have characteristic lengths of less than 1mm but not more than 1µm (*micron*) usually expressed as 10^{-6}m which is equal to one millionth of a metre. MEMS devices combine mechanical and electrical components including; electrostatic, magnetic, electromagnetic, pneumatic, and thermal actuators, motors, valves, gears, cantilevers, and diaphragms. Various combinations of the mentioned electrical and mechanical components have been used as sensors for pressure, temperature, velocity, mass flow, and chemical composition, and also as singular components for complex systems such as the lab-on-a-chip, robots, micro-heat-engines and micro heat pumps (Gad-el-Hak, 2006a).

Hsu, (2008) explains that MEMS are; constructed to accomplish certain engineering functions by the use of electromechanical or an electrochemical approach depending on the device and its application, and the core element in MEMS is composed of two principle components which are a sensing and/or an actuating element and a signal transduction unit.

Microsystems are miniature engineering systems that contain MEMS components which have been designed to perform the required engineering functions as illustrated in Figure 2-2: Essential components of a microsystem. A physical application of a microsystem (Figure 2-2) is to convert the signals received by the sensor in a microsystem into compatible forms with the actuator through the signal transduction and processing unit. The deployment of an airbag system in an automobile uses this principle in a collision as the micro-inertia sensor, which is based on the principle of the microaccelerometer, is triggered at the point of impact and sends a signal to the actuator therefore deploying the airbag for both the drivers and passengers safety (Hsu, 2008).

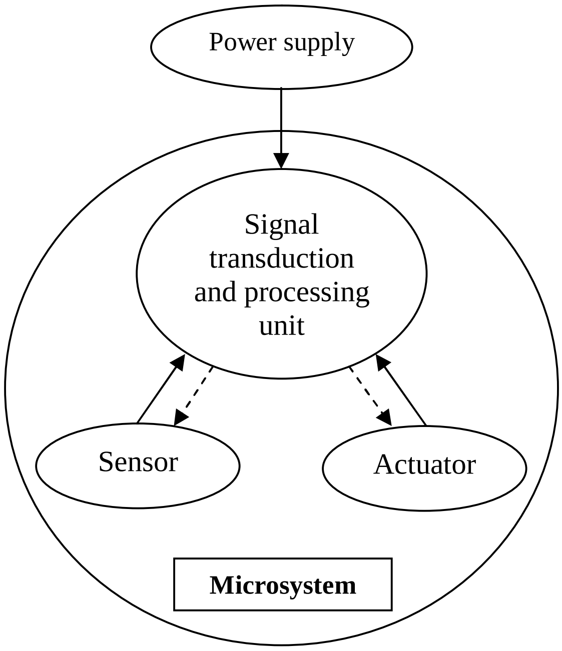


Figure 2-2: Essential components of a microsystem (Hsu, 2008)

2.7.2. Applications of Microsystems and MEMS Components

Many microsystems are built on the lab-on-a-chip concept where the entire unit can be contained in the form of a silicon chip which is less than 0.5^2mm (Hsu, 2008). Bao, (2005) substantiates that devices referred to as MEMS are based on the micro mechanical and microelectronics technology and that micro mechanical sensors, actuators and electronic circuits can be amalgamated into a functional system that is on a single chip.

Booker and Boysen, (2005) also confirm that it is now possible to have a MEMS device on a microchip that includes an information processing component including certain mechanical components for instance gears, motors, levers and bearings. The following list, compiled by Hsu (2008), presents some of the recent MEMS devices and components:

- Microactuators
- Microaccelerometer
- Microgripper
- Microgyroscope

- Microgears
- Micromirrors
- Micromotors
- Micropumps
- Microturbines
- Microtweezers
- Microvalves
- Microsensors
- Micro-Pressure Sensors
- Micro-Heat Pipes
- Micro-Inertia Sensors
- Micro-Optical Components

Functional MEMS devices are currently used in the information technology industries which involve the production of inkjet printer heads and read/write devices in data storage, the health care industry, and aerospace industry and in the automotive industry where applications of MEMS and microsystems in vehicles have been categorised into the following four main areas (Hsu, 2008):

1. ***Safety:***
   - Airbag deployment system which uses microaccelerometers or micro-inertia sensors
   - Antilock braking system using position sensors
   - Suspension systems using displacement, position and pressure sensors
   - Object avoidance using pressure and displacement sensors
   - Automatic navigation system using microgyroscope and GPS

2. ***Engine and Power Train:***
   - Manifold control with pressure sensors
   - Airflow control
   - Exhaust gas analysis and control
   - Crankshaft position

- Fuel pump pressure and fuel injection control
- Transmission force and pressure control

3. ***Comfort and Convenience:***
   - Seat control using displacement sensors and microvalves
   - Rider comfort using sensors to control air flow, temperature and humidity
   - Security
   - Sensors for defogging windshields
   - Satellite navigation sensors

4. ***Vehicle Diagnostics and Health Monitoring:***
   - Engine coolant temperature and quality
   - Engine oil pressure, level and quality
   - Tyre pressure and brake oil pressure

2.8. Design and Fabrication of MEMS Devices

Mukherjee and Fedder, (1998) describe that MEMS based designs either involve a solitary micromechanical sense element surrounded by traditional electronic signal conditioning or that they contain arrays of identical micromechanical devices whereby the focus is typically at the device level. MEMS devices have a tendency to encompass a large number of design specifications together with the large variations for each specification.

Microelectromechanical systems (MEMS) are a combination of mixed technologies that integrate mechanical structures, electromechanical actuators, fluidic chambers, and digital and analog electronics. Since the emergence of MEMS in the early 1980's, research was primarily focussed on the development of new process technologies in order to support the specific applications (Mukherjee and Fedder, 1997). MEMS are fabricated using batch processing techniques from the microelectronics domain which can sense, control and actuate at the micro scale (Mukherjee and Fedder, 1998).

Mukherjee, (2003) has explicitly stated that in order to satisfy the requirement of designing low volume custom MEMS, an integrated MEMS design methodology must:

- Support a wide class of MEMS designs
- Be extensible to handling new MEMS design concepts
- Support a wide variety of MEMS fabrication techniques
- Fit into existing VLSI (Very Large Scale Integration) design flows
- Have the capability to evaluate integrated system designs

2.8.1. Existing Tools and Techniques

Mukherjee and Fedder, (1997) have explained that MEMS engineers typically begin the design phase of new components with a rough sketch and very basic mathematical equations to ensure feasibility. Once this is complete, the engineers proceed directly to the physical layout of the device, as shown in Figure 2-3, which is then sent to fabrication with little verification which frequently results in non-functional devices. Some of the existing tools used by the MEMS engineers to perform analyses are; mechanical finite element analysis (FEA) based on numerical simulations coupled with boundary element analysis (BEA), and behavioural simulation which requires specific MEMS device expertise.

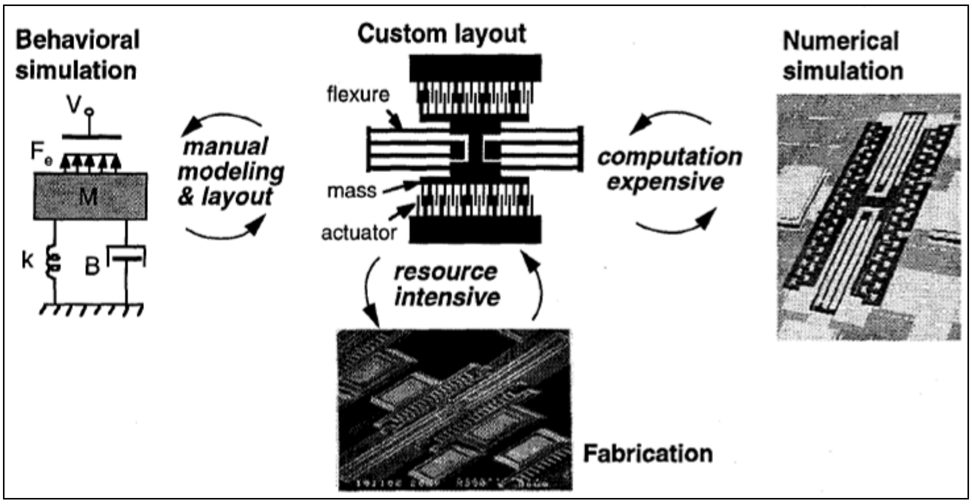


Figure 2-3: Schematic of current MEMS design for a micromechanical resonator (Mukherjee and Fedder, 1997)

The development of MEMS has been based on the existing manufacturing technologies from the microelectronics domain and yet it is not fully developed. Standard methods are used extensively in the microelectronics domain where their presence has provided huge benefits. There has been interest recently in standardising the design practices in the MEMS domain however, they have provided a general outline and targeted a nominal design strategy for MEMS devices but there are no methodologies that define the design flow to achieve unambiguous design targets (Vudathu and Laur, 2007).

A design flow which is commonly followed for MEMS that has a relationship between the electronics and micromechanical components has been identified by Fedder, (1999) and is illustrated in Figure 2-4. The shaded boxes in the design flow (Figure 2-4) indicate the portion of the flow exclusive to micromechanics.

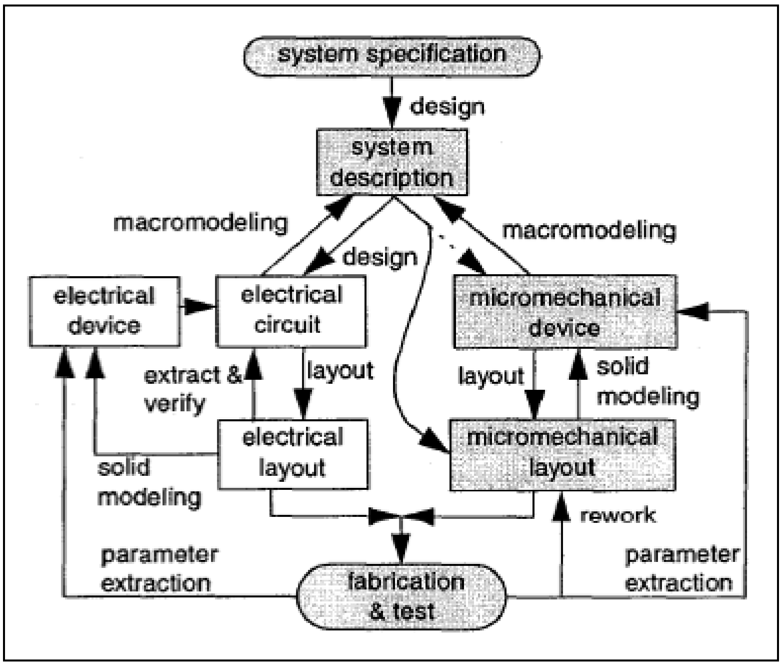


Figure 2-4: Commonly used MEMS design flow (Fedder, 1999)

As illustrated in Figure 2-4, the top level specification is provided in the form of a written datasheet specifying the functional requirements then the design concepts are embodied into a high level abstract system description. The current MEMS design manipulates two principal representations, which are the physical geometry and the device macromodel. The design tends to take a direct path to the physical layout of the device from the systems description (Fedder, 1999).

Antonsson, (1996) has identified that the design cycle for a MEMS device consists of several phases where the first phase involves identifying the required structural element followed by hand calculations and the second phase is creating a realistic process flow.

Developing new sensors and actuators for MEMS that are fabricated by silicon micromachining techniques requires the development of many prototypes and much experimentation (Hubbard and Antonsson, 1996). The electronic components in MEMS devices are fabricated using IC (*integrated circuits*) process sequences however, the micromechanical components are fabricated using compatible 'micromachining' processes that selectively etch away designated parts of the silicon wafer or add new structural layers to form the mechanical and/or electromechanical devices (Zha and Du, 2003).

Garcia *et al*, (2007) verify that MEMS take advantage of the technologies developed by the semiconductor industry whereby in the majority of cases, the fabrication processes imply the deposition or removal of layers of the material where a planar layout is directly involved by the use of a photolithographic process. MEMS functionalities are usually defined by their three dimensional structures which is fundamentally different when compared to microelectronic circuits where each device is characterised by a fixed vertical sequence of layers so that the design is mainly concerned with arranging device instances in an optimum manner in a two dimensional area (Brück *et al*, 2006).

A hierarchy of the MEMS manufacturing processes is presented by Zha and Du, (2003) in which the top level of the hierarchy includes deposition, etch, pattern transfer (photolithography), mask making, CMP (chemical mechanical polishing) and ion implantation. These are then subdivided into high level nodes such as the deposition process is sub divided into CVD (chemical vapour deposition), epitaxy and other physical depositions. The hierarchy provides benefits to help new MEMS designers to familiarise themselves with the semiconductor fabrication processes including the associated technologies and terminologies, and to provide the experienced designers with a reference point to describe the scope of the available processes and terminology for description.

2.8.2. Design Limitations

Fedder, (1999) describes that a major constraint in the time to product yield for commercial MEMS is due to the requirement of simultaneous design iterations in process, devices and systems which occur with fabrication in the cycle. This is inherent from the design phase as the design of commercial MEMS has remained an art form requiring a team of skilled engineers from the various related disciplines.

Replacing simulation with the actual fabrication of MEMS prototypes during design iterations can be very expensive as the fabricated prototypes do not often meet the required performance specifications and sometimes they are non-functional. To perform the full verification of the design requires time and effort and also proposes difficulty in the design optimisation. This inhibits the growth within the field of MEMS particularly when developing devices for low cost applications (Mukherjee and Fedder, 1997).

It is critical to have accurate and efficient simulators of MEMS fabrication processes to reduce the number of design iteration cycles and consequently reduce the number of prototypes fabricated thus reducing the cost of MEMS development. Complex systems require proficient design and simulation tools to accurately model both the fabrication and performance of the MEMS devices (Hubbard and Antonsson, 1996).

Vudathu and Laur, (2007) comment on how the success of the evolution of MEMS and microsystems is evidently slower than expected due to various obstacles involved in their design processes. The decreased pace in the MEMS development process is caused by; problems encountered with the interaction and integration of the multi-physics, the novelty of approaches and more importantly, the lack of standard design methodologies for the MEMS design process to support the designers in the microsystems industry as the MEMS domain is not renowned for the standardisation of successful design practices, and there are not many design methodologies or tools available for the MEMS community that consider process effects and efficiently modify their designs to counteract the negative effects due to the process variations.

Zha and Du, (2003) explain that the MEMS design process is generally performed in a trial-and-error fashion which requires several iterations before the performance requirements of a dedicated device are fulfilled. This is described as a non ideal design methodology which is time consuming, highly costly, and very ineffective and inefficient for commercial MEMS product development. Selecting a material and fabrication process to manufacture a MEMS component or device is a difficult task due to the number of possible alternatives available.

Xin *et al*, (2007) declare that technologies for fabricating MEMS devices have developed rapidly and design tools which allow engineers to design quickly and optimise the micro machines are critical to the future and the growth of the MEMS market. The design of the process flow and layout of the device is especially important to ensure the desired device can be actually fabricated through the available micromachining techniques after the system-level and physical-level simulations. The introduction of an established VLSI fabrication technology that is compatible with MEMS has initiated the development of increasingly complex and integrated MEMS based systems (Mukherjee and Fedder, 1998).

Fedder, (1999) expresses that the introduction of MEMS to the commercial market a low cost has been justified in markets that require large quantities of parts such as automotive accelerometers and gyroscopes, pressure sensors and ink-jet print heads. However, the introductions of practical methodologies are required to design and fabricate MEMS *application-specific integrated circuits* (ASICS) at an equivalent cost to digital ASICS. This will provide enormous advances in the commercialisation of MEMS in various application areas but in order do so; the following items are required for commercialising MEMS ASICS and to ease the design limitations:

- ♦ inexpensive access to microstructural processes, preferably integrated with electronics,
- ♦ computer aided design tools to handle complexity,
- ♦ materials and process characterisation encoded in design and technology files,
- ♦ improved testing methods, equipment, and packaging methods.

Calis and Desmulliez, (2006) and Fan *et* al, (2008) also confirm that the current MEMS technology is still based on older design tools and is fabricated on a trial and error approach. It becomes difficult to separate the device design from the increasing complexity of fabrication because MEMS are highly integrated devices and require a high level of manufacturing and fabrication knowledge.

MEMS are intrinsically multi-domain systems where designers require a uniformed representation of MEMS to be able to shift among the different levels of design abstractions and also move around the design partitions in physical domains without difficulty (Fan *et al*, 2008). Xin *et al*, (2007) explain how the general approach to designing a process flow and corresponding device layout relies on purely MEMS experts' experience and prior knowledge of similar devices. Designing a MEMS device is a difficult and challenging task since the desired MEMS structures are geometrically complicated, electromechanically coupled and inherently three dimensional.

Quintessentially, MEMS is an interdisciplinary field of electronics which combines studies in mechanical engineering, electrical engineering, electronics, fluid mechanics, optics, chemistry and chemical engineering with a vast spectrum of application areas. Due to the infancy of MEMS and partly because it involves a large number of disciplines, there is not yet a developed science of design for MEMS. A fundamental objective is to establish a set of methodologies for the design of MEMS that begins from the specification of the desired function and leads to an optimised fabrication of a MEMS system (Antonsson, 1996).

2.8.3. Utilising DFX Methodologies to Develop MEMS

Design for manufacture (DFM) strategies have been applied by Da Silva *et al*, (2002) and on two MEMS fabrication processes, including SOI (silicon on insulator) and CMOS (complementary metal oxide semiconductor) compatible metal-nitride surface micromachining, by Schröpfer *et al*, (2004). These link the design and process groups by establishing systematic design principles through a common CAD framework. Da Silva *et al*, (2002) present a methodology for MEMS DFM that focuses on rapid process and design qualification through systematic parametric modelling and testing, from initial development of specifications to volume manufacturing. An average product development cycle for MEMS devices is between 4 to 10 years from the concept to final volume production and finally market insertion. The adoption of traditional manufacturing approaches taken to develop MEMS devices, as illustrated in Figure 2-5, takes longer for MEMS products to achieve volume manufacturing due to novelty of the MEMS technology, lack of standard process flows and design tools (Da Silva *et al*, 2002).

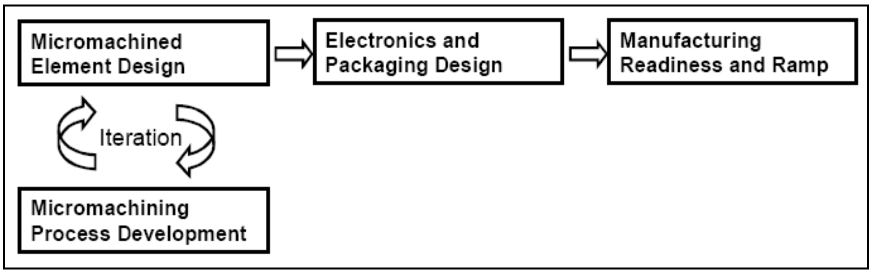


Figure 2-5: Traditional MEMS product development cycle (Da Silva *et al*, 2002)

The DFM strategy introduced for MEMS by Da Silva *et al*, (2002) primarily focuses on a top-down design tool that uses concurrent engineering (CE) practices for both the design and process engineering groups; from the initial concept to final volume production. The MEMS product development cycle using a concurrent engineering approach is presented in Figure 2-6.

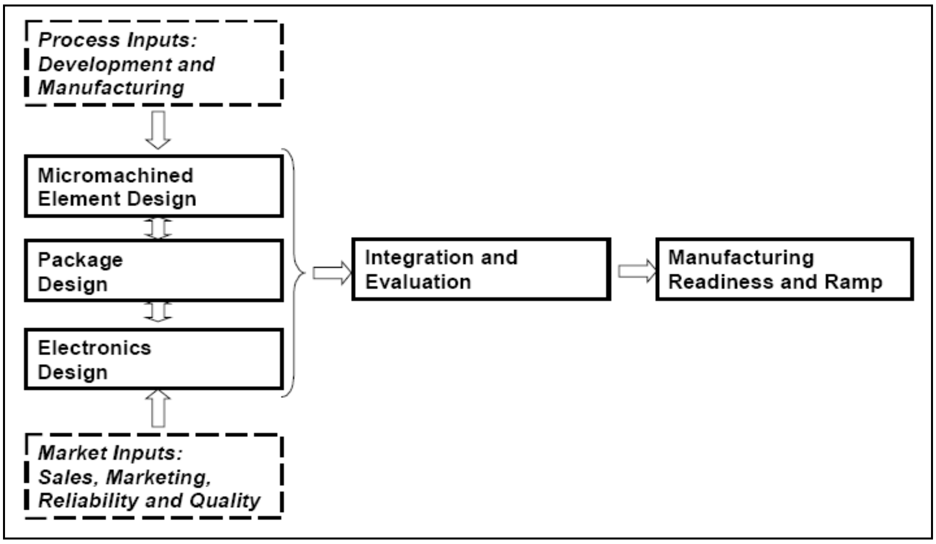


Figure 2-6: MEMS product development using CE (Da Silva *et al*, 2002)

Da Silva *et al*, (2002) have adopted several of the DFM principles and guidelines and applied the MEMS considerations as follows:

(i) **Minimise the number of components**: fewer masks and fabrication processes, reduce material and assembly costs; provide greater reliability in the final product, and easier automation downstream.

(ii) **Developing modular designs**: components with standard interfaces that are capable of being assembled into more complex systems. This potentially reduces assembly time and efforts, inventory requirements, and facilitates automated assembly.

(iii) **Use of standard components**: standard fabrication steps and standard packaging which results in fewer parts and avoids custom engineered parts.

(iv) **Designing parts for multi-use**: standard process flows that could be used for multiple MEMS products. This has enormous potential to cut costs and save time.

(v) **Design for ease of manufacturing**: employ existing materials and processes. Use standard process steps wherever possible and simplify part geometry.

Fundamental components of the MEMS DFM design methodology has been divided into the design and manufacturing activities by Da Silva *et al,* (2002) which consider several overlapping phases listed and described below:

1. Technical Specifications Development:
   - Determine the needs of the customer and translate these needs into a *Customer Requirements* (CRs) document. The following step is to convert the CRs into Engineering Requirements (ERs) and Technical Specifications (TSs). Quality Function Deployment (QFD) is the tool used for the conversion, although such tools are not widely available for MEMS products.
2. Conceptual Design Phase:
   - Conceptual design phase begins once the TSs is available. Many design concepts are developed and evaluated simultaneously. For MEMS

devices, this translates to making libraries available for parameterised component elements to create more complex designs which adhere to the DFM principle - (iii) Use of standard components. Each conceptual design can be hierarchically contained within a schematic of the entire system that is available to the designer. The conceptual design phase proceeds once few concepts are available for evaluation during the detailed design phase.

3. Detailed Design Phase:
   - A detailed engineering analysis of the selected concepts is performed requiring the application of Design of Experiments (DOE) to define the simulation space. Analytical methods such as FEA, BEA or macro modelling are used to perform *optimisation studies, tolerance design*, and *statistical design* including the incorporation of design rules and guidelines to create manufacturable designs.
4. Manufacturing Phase:
   - The manufacturing phase is divided into three major activities, a) process short loops, b) prototype and demonstrator parts and c) pre and volume production. Continuous improvement and refinement must occur to reduce variability and cost. Concurrently with the design team, the process group begin to create a Manufacturing Specification (MS). The development of the MS is critical and contains three major components: *develop process requirements, identify and evaluate existing processes, and packaging requirements.* Packaging of MEMS must be considered in a systematic way as MEMS package design is not straightforward. Package design must be considered early in the design process to avoid re-design of the device and where possible, standard packages should be used.

Schröpfer *et al*, (2004) present case studies conducted on designed, simulated, fabricated and characterised test structures which demonstrate the methodology and benefits of using a DFM approach to the CMOS and SOI MEMS fabrication processes. Included is the extraction of material properties and process capabilities which enable the prediction of fabricated device performance distribution. In order to develop a robust MEMS DFM strategy, enabling the following three capabilities into a concurrent engineering framework for MEMS devices is presented:

i. Test structures with corresponding models and measurement setups that allow the extraction of material properties and determine process capabilities
ii. Software capable of incorporating these materials and process specific variables and statistical data into the design and simulation stream
iii. Stable processes proven for various common classes of MEMS devices supported by test structures that are dedicated to manufacturing analysis and yield improvement

Schröpfer *et al*, (2004) explicitly state that manufacturability should be embedded in a MEMS CAD framework to consider the manufacturing constraints in the manufacturing phase, as described by Da Silva *et al*, (2002), during the conceptual and detailed design phases. The availability of different kinds of physics solvers to simulate electrostatics, mechanics, coupled electromechanics, magnetic, electro-thermal effects, fluidic and fluid structure coupling effects is described as a vital part of the CAD framework required for successful completion of the detailed design phase.

In conclusion to the work performed by Schröpfer *et al*, (2004) which is based on the approach defined by Da Silva *et al*, (2002), the success of any DFM approach for MEMS is measured by the ability to select the correct design option quickly and accurately during the conceptual design phase. This will result in higher yield, and the time taken to ramp up to volume production is reduced than traditionally seen in the MEMS industry.

2.8.4. Optimisation of MEMS Design

The capability for measurement, device modelling and manufacture of micro/nanoscale devices has progressed at a much faster pace compared to the growth in systematic design optimisation capability for these devices (Whatmore *et al*, 2003; Zhu and Kirby, 2006). There has been some progress in the area of MEMS design optimisation in recent years (Li and Antonsson, 1998). Unlike traditional optimisation techniques, evolutionary computing (EC) can handle complex search spaces and nonlinearities in optimisation problems. This has motivated its application to a wide range of optimisation problems in the macroscale domain (Deb, 2001).

Multi-objective EC-based design optimisation for MEMS was first introduced by Zhou *et al*, (2001), associated with the Berkeley School of MEMS Design (University of California). Given a high-level description of the device's desired behaviour, Zhou *et al*, (2001) generate both the topology (physical configuration) and sizing. The topology includes the number and types of basic building blocks and their connectivity. The sizing of the designs entails assigning numerical values to parameterised building blocks.

Due to the miniaturisation of micro/nanoscale devices, even small variations in their designs can have a significant effect on the device behaviour. Nanoscale devices can offer very high sensitivities e.g. force sensitivities at the attonewton level and mass sensitivities at a single molecule or even a single atom level (Chen and Mukherjee, 2006). Therefore, it is essential to consider precision and uncertainties. There have been considerable efforts in recent years to establish firm foundations for the understanding of precision, error and uncertainty in modelling (Roache, 1998). Probabilistic methods are popular in literature for dealing with uncertainties (Gurav *et al*, 2005). However, these methods require an abundance of experimental data and are sensitive to data inaccuracies, making them unsuitable for micro/nanoscale devices.

The challenge is to develop a methodology to quantify epistemic uncertainty or model form error. Such errors represent potential deficiencies in the analysis that occur due to incomplete information or a lack of knowledge of some characteristic of the system or the environment.

2.9. Summary and Gap Analysis

This chapter has reviewed the various design and *Design for 'X'* methodologies on the topic of product development with particular emphasis on engineering and manufacturing. The DFX approach has accentuated the consideration of the new and evolving design targets. Products are longer designed just to fit the purpose; as was the case from a historical and anthropological perspective, but now with increasing customer requirements (CRs), new scientific approaches to design are being taken. Design methodologies such as; DTUPC allow a company to know the true cost of every product produced, and the practice of DFM effectively will lead to lower manufacturing costs without the quality of the product being affected.

The development of methodologies, such as DFD, DFR, DFE, and DFLC have been created to address the growing issues surrounding the environmental impacts caused by product designs including the generated waste and use of natural resources. The main objective of DFE is to consider the design issues associated with environmental safety and health throughout the whole of the products life cycle during new product and process development. DFX approaches taken in the engineering and manufacturing sectors have showed great advantages for companies by assisting them to be able to meet the customer's requirements better, reduction in the time to market for products, and reduced total life cycle cost.

Future trends show that the use of DFX applications will increase and become cutting edge technology however; there are methodologies that could be considered which have not been identified in literature. Many of the DFX applications have arisen due to the need from mechanical engineering and manufacturing sectors. Some work has been performed in electronic applications but methodologies which address electrical integration (hardware, software and mechanical) and the design of MEMS (microelectromechanical systems) devices do not exist. Nanotechnology and, in particular the conjunction with the context of the research, the field of MEMS has been introduced identifying the various devices and applications. The review of literature has identified the current tools, practices and methodologies used when designing MEMS devices and that MEMS are fabricated using batch processing techniques developed from the microelectronics domain.

Limitations in the design process of MEMS have been commented on by the different authors highlighting the urgent requirement of a structured design methodology for the MEMS community. Vudathu and Laur, (2007) described that the decreased pace in the MEMS development process is caused by; the interaction and integration of the multi-physics, the novelty of approaches taken and more importantly, the lack of standard design methodologies for MEMS product development.

The simultaneous design iterations in the process, devices and systems which occur with the fabrication cycle have also effected the time to product yield for commercial MEMS. Zha and Du, (2003) explained that the MEMS design process is generally performed with a trial and error approach which requires several iterations that is time consuming and costly, and this was stated as a non ideal design methodology that is ineffective and inefficient for commercial MEMS product development.

Calis and Desmulliez, (2006), Xin *et al*, (2007) and Fan *et* al, (2008) confirmed that the current MEMS technology is based on older design tools borrowed from the microelectronics domain and fabricated on a trial and error approach, and that designing a process flow and corresponding device layout for MEMS devices relies on MEMS experts' experience and prior knowledge gained from similar devices. Antonsson, (1996) explained there is not a developed science of design for MEMS and that the fundamental objective was to establish a set of methodologies for the design of MEMS.

Using the more common design for 'x' (DFX) methodology; DFM, Da Silva *et al*, (2002) and Schröpfer *et al*, (2004) introduced a generic framework and applied the DFM principles using case studies on two MEMS devices and fabrication processes, which include CMOS and SOI. Utilising the DFM approach in MEMS can result in a higher yield and the time taken to ramp up to volume production is significantly reduced. An important factor in enabling the effective design and maximising the probability of first pass success, while reducing the development time and cost of

MEMS, is to have the materials properties and process information available early on in the design process.

The literature review has identified the following gaps in knowledge which are summarised below:

- There are no available methodologies that define the design flow to achieve the unambiguous design targets
- There are not many design methodologies or tools available for the MEMS community that consider process effects and modify the design accordingly
- There is an urgent requirement for a structured design methodology for the MEMS community
  - A standard methodology for the design of MEMS devices does not exist
- There is not a developed science of design for MEMS and that the fundamental objective is to establish a set of methodologies for designing MEMS devices
- MEMS technology is based on older design tools taken from microelectronics domain which require novel design approaches
  - New tools and techniques are required, that are bespoke to the MEMS domain, to assist the MEMS designers in developing the multi-disciplinary devices
- DFX approaches, such as DFM, have been applied to two MEMS devices and corresponding processes; CMOS compatible metal nitride surface micromachining for a variable capacitor, and a DRIE (deep reactive ion etching) based SOI micromachining process for a comb drive resonator
  - Other DFX methodologies could be considered in the in the MEMS product development process, such as DFR, DFQ, DFSS, DFD and DFE

Chapter 3

Introduction
Literature Review
Research Aim, Objectives and Methodology
Designing MEMS Devices
Developing a Model for Future MEMS Development
Validating the Model
Discussion, Future Research and Conclusions

3. Research Aim, Objectives and Methodology

The previous chapter has presented a review of literature in the areas of engineering and manufacturing product design and development including the DFX methodologies. It also introduced nanotechnology and the current development techniques used to develop microelectromechanical systems (MEMS) devices.

Various design for 'x' (DFX) methodologies used in the engineering and manufacturing domains were primarily identified in order to evaluate the current methods used when designing products for commercial use. Literature was reviewed in the area of MEMS including the applications and existing design practices to help identify the areas where the engineering and manufacturing design methodologies could be incorporated into MEMS design. Finally, the literature review has been used to identify gaps in the existing research.

This chapter describes the research aim, objectives and methodology following the literature review process. The deliverables are stated as part of the outcome of the research corresponding with the research methodology.

3.1. Aim

The motivation for the research has assisted in defining the main research aim which is to:

"Capture the existing MEMS design practices and propose a model for future MEMS development"

The key output of this research is to identify the applicability of the current design tools on MEMS devices. In order to accomplish the research aim, the following research questions are to be addressed as illustrated in Figure 3-1:

1. What are the current design methodologies applied in generic product design and development with emphasis on engineering and manufacturing?
2. Are the MEMS community aware of these methodologies used in the field of design?
3. What are the current design tools and fabrication techniques used to develop MEMS devices?
4. Are design methodologies such as DFX utilised when designing MEMS devices?
5. Can the DFX methodological approach be adapted and applied to the designing and manufacturing of MEMS devices?

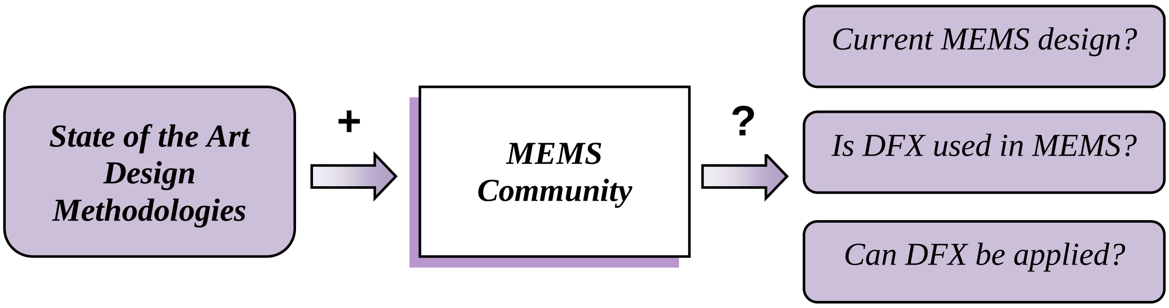


Figure 3-1: Illustration of research questions

3.2. Objectives

To fulfil the main research aim; "Capture the existing MEMS design practices and propose a model for future MEMS development", it is necessary to divide the main aim into the following set of actions associated with the objectives which are given in *italics*:

- Identify design methods for generic product development processes including DFX methodologies used in the engineering and manufacturing domains
  - *Identify from literature review*
- Capture the current MEMS design practices (As-Is model) including tools and techniques
  - *Identify from literature review*

    - *Semi structured interviews with MEMS experts and practitioners from industry*
- Recognise the constraints and limitations of the current MEMS design methods
    - *Identify from literature review*
    - *Semi structured interviews with MEMS experts and practitioners from industry*
- Propose a 'To-Be' model for future MEMS development
- Validate the research conducted with experts in the area of MEMS

3.3. Deliverables

The concluding deliverables as part of the outcome of this research, and those illustrated in the methodology, are stated below:

1. Report on the design methodologies used in the engineering and manufacturing domains including the current DFX methodologies
2. Identify existing MEMS design practices (As-Is model) and constraints
3. Perform analysis identifying areas of improvement in MEMS design process
4. To-Be model for future MEMS development validated by MEMS experts

The main focal points of the research are; the identification of existing design tools and methodologies that have been utilised in the engineering and manufacturing domains and to examine if these can or have been applied in the design and fabrication of MEMS devices, and to perform an analysis which will identify the constraints encountered in MEMS design thus recognising the areas for improvement. A model for future MEMS development will be proposed to the MEMS community validated by the collaborating MEMS experts. Finally, it is intended to publish the results of the research in a journal paper where the thesis is introduced as developing microelectromechanical systems detailing the findings from the research and highlighting the areas of improvement for future MEMS design practices.

3.4. Research Methodology

The methodology to be followed by this research is illustrated in Figure 3-2: Research methodology. The initial research context for this study has been defined including the main research aim. A structured methodological approach has been taken to ensure that the stated objectives for fulfilling the research aim have been addressed in a sequential manner. Literature is reviewed (published books, journal and conference papers) identifying some of the previous and current works performed in the areas of; design, product development with emphasis on engineering and manufacturing, and MEMS design and development techniques. The review of literature and collaboration with MEMS experts and practitioners has provided the necessary background knowledge required to identify the areas for improvement, and to develop and propose a model which is then validated by experts in the area of MEMS.

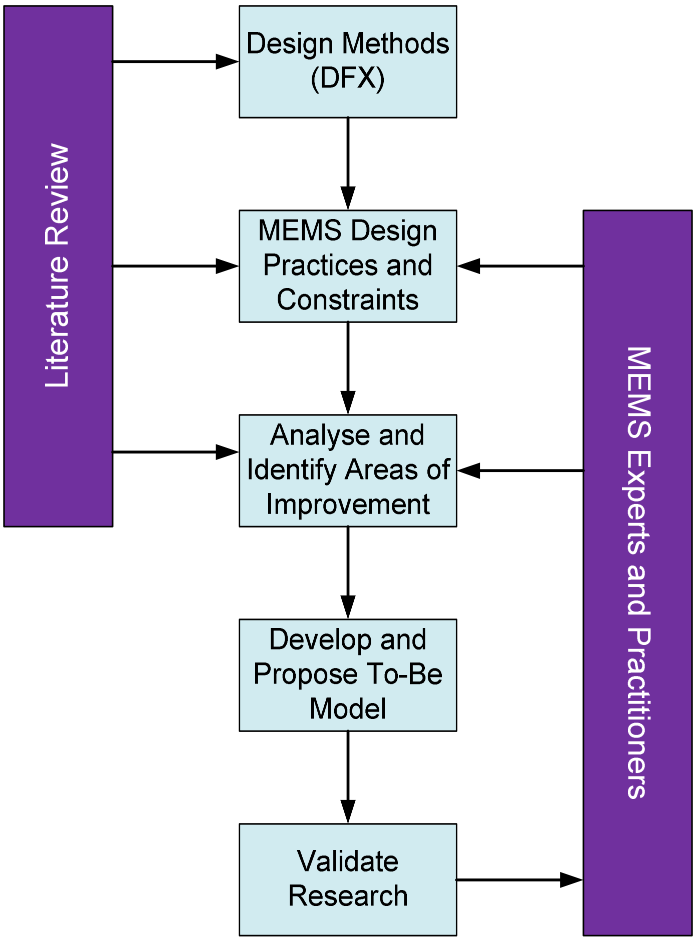


Figure 3-2: Research methodology

The research methodology (Figure 3-2) has been divided into the following five main activities which correspond in achieving the defined objectives as stated in section 3.2:

- Identify Design Methodologies Used for Product Development.
- Capture MEMS Development Practices (As-Is model).
- Identify MEMS Development Constraints.
- Identify Areas of Improvement and Propose To-Be model.
- Validate the Research.

Each of the five activities commence with an explanation of the approach taken. This approach provides support by focussing on the intentions and objectives that require accomplishing. The activities as presented in the methodology offer a defined sequential framework.

The five main activities are described in the following sections as illustrated in Figure 3-2: Research methodology.

3.5. Identify Design Methods Used for Product Development

The literature review provides the existing design methodologies used in the engineering and manufacturing domains. Design for ‘X’ (DFX), and generic product development methodologies have been identified as the existing applicable design tools available in the area of design. Past and current literature has been sourced from published books, relevant journal and conference papers providing the background information and knowledge of the current development practices.

The existing design methodologies will be analysed with the current MEMS development techniques to evaluate their possible applicability in order to develop and propose a model which incorporates the DFX methods in the MEMS development process.

3.6. Capture Current MEMS Design Practices

Literature has been reviewed in the area of MEMS to understand the background of MEMS design, to capture the current design practices and to discover if design methodologies such as DFX have been applied to the micro/nano domain. Literature has also identified the current manufacturing techniques for MEMS including the design limitations encountered. This will be evaluated with the tools and methods utilised by MEMS practitioners.

Collaboration with the practitioners and MEMS experts, via semi structured interviews, will offer practical knowledge of the MEMS design practices and recognition of the development constraints and limitations. The information captured from the experts and practitioners will also serve as a foundation when identifying the areas of improvement within the MEMS development process.

3.7. Identify Areas of Improvement

Identifying the areas of improvements includes; recognising the design constraints and limitations encountered throughout the MEMS development process from the literature reviewed and expertise acquired from the MEMS experts. Capturing the current MEMS development process in the form of an 'As-Is' model, using the IDEF0 process modelling tool, will identify the process; inputs, outputs, mechanisms and controls (constraints) associated with the development of MEMS devices.

Identification of the MEMS development process constraints from the 'As-Is' model will provide visualisation and assist in developing a 'To-Be' model for future MEMS development. Explanations of the required improvements are provided, taking into account the process constraints and development limitations, which are also linked directly with the development of a model (To-Be) for future MEMS design.

3.8. Propose 'To-Be' Model for Future MEMS Design

The information obtained from the literature and that acquired from the experts and practitioners in the area of MEMS, including the identification of the constraints and areas of improvement, will be used to develop a model which will integrate the applicable design methodologies with the current MEMS development process.

The To-Be model will be proposed to the MEMS community for future MEMS development taking into consideration the current MEMS design process and constraints, and by adapting the appropriate and applicable design methodology used in the engineering and manufacturing domains. The objective of the 'To-Be' model is to provide a new structured framework, for supporting the MEMS experts and practitioners when designing and manufacturing MEMS devices, incorporating design methods widely used in the engineering and manufacturing domains for product development.

3.9. Validate Research

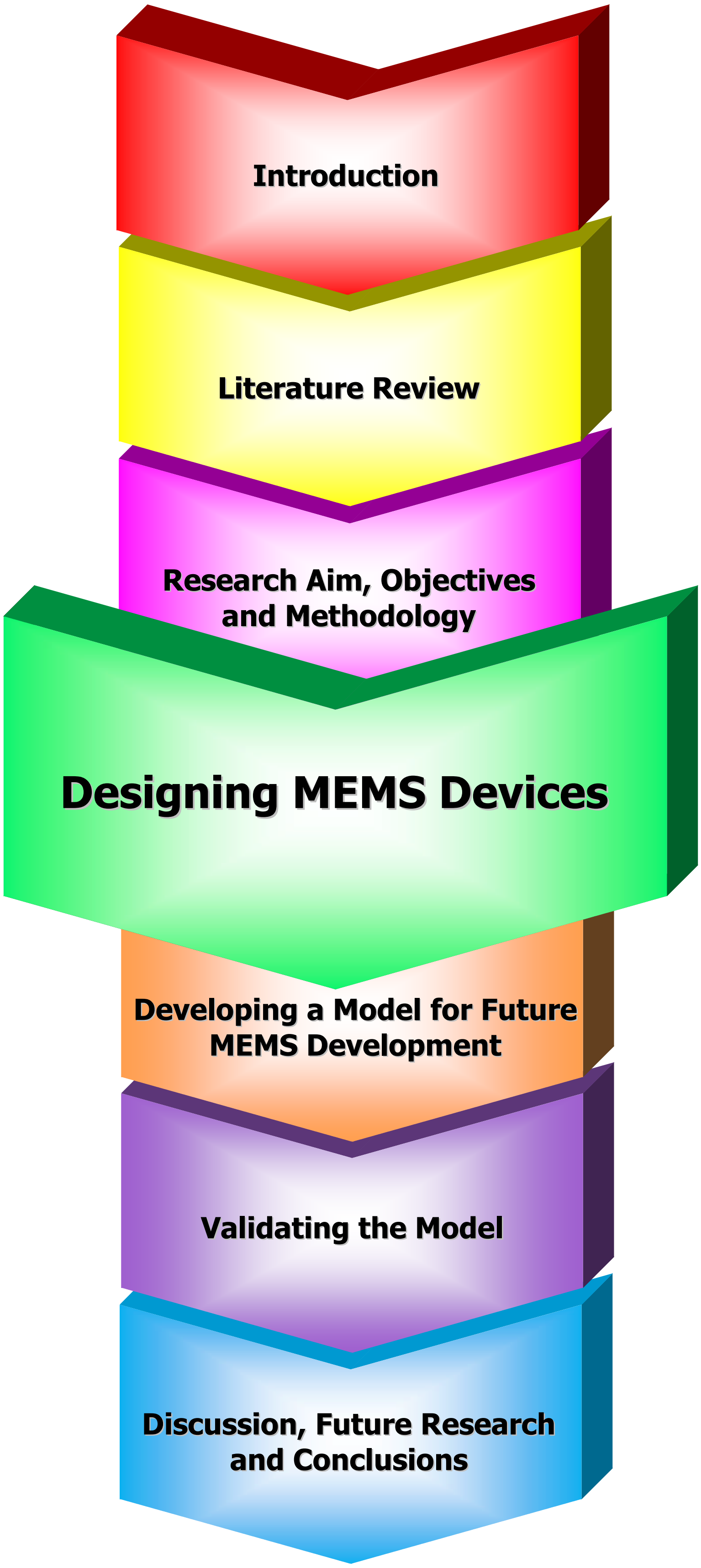
The proposed model will be validated by the design and MEMS experts for its validity of application when developing MEMS devices. The validation approach will directly address the proposed theoretical model for; its feasibility when developing future MEMS devices, areas of improvement in the current MEMS development process proposed by the To-Be model, accurate reflection of the generic MEMS development process using the chosen graphical process modelling technique, further enhancement and decomposition of the proposed model, and application when physically developing MEMS devices with consideration for manufacturing. The results from the research conducted, or proposed To-Be model, will be the end result of research combined with practical experience as obtained from the MEMS experts and practitioners in the micro/nano domain. This ensures the feasibility of the model which addresses the design and development aspects of MEMS devices.

3.10.Summary

Following the identification of the research gap in the previous chapter, this chapter has defined the objectives to be fulfilled by the research in order to fulfil the main research aim. The rational approaches defined in order to accomplish the objectives are presented, justified and a structured research methodology has been devised to flow in a sequential manner. This has been developed to capture the design methodologies used in the engineering and manufacturing domains, MEMS design practices as identified in literature, and to capture the current industrial MEMS development practices. The validation approach for the model and its validity has been described including the objective of the proposed To-Be model.

The following chapter presents the existing development process of MEMS devices and the method used to capture the current development techniques. The development of the As-Is model, using the IDEF0 process modelling tool, is presented and explained.

Chapter 4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4. Designing MEMS Devices

The previous chapter detailed the approach taken which has included the research aim, objectives, deliverables and research methodology. The research methodology has been described and illustrated in Figure 3-2. The research objectives are directly linked to the methodology. The techniques required to fulfil the objectives have been presented and are also linked to the development and validation of the model for future MEMS development.

This chapter presents the design practices currently employed when developing MEMS devices. The method used to obtain the information regarding the MEMS development processes is detailed. The As-Is model and the tool used for its development are explained including the criteria for selection, and the areas of improvement in the design of future MEMS devices are discussed including the validation of the As-Is model.

4.1. Capturing MEMS Design Practices

In order to capture the design practices and tools required for developing MEMS devices from the MEMS experts and practitioners, semi structured interviews were initially conducted. The semi structured approach consisted of interviewing the experts and practitioners, which totalled in four participants, with a semi structured questionnaire to acquire a generic overview of the MEMS development process. The generic overview of the different MEMS device types, allows for the development of the ‘As-Is’ and ‘To-Be’ models which are aimed at capturing current design practices and proposing a model which provides a generic structured framework for MEMS design that is not device specific but widespread for MEMS.

The following section describes the semi structured questionnaire including the questions posed to the interviewees, and the background (academic, research or industrial) of the participating experts and practitioners. The information obtained from the interviews has been used to create the As-Is model using the IDEF0 technique.

4.1.1. Semi Structured Questionnaire

The semi structured questionnaire was developed to capture the different design practices associated with the different MEMS devices and to present the obtained information in the form of a model which shows, a top level or high level view of the MEMS development stages from a generic perspective. The aim of the questionnaire is to capture the relevant information such as constraints, inputs and outputs of the development stages to create the model which utilises these to illustrate the flow of development for MEMS devices.

The questionnaire (Appendix A: Questionnaire for MEMS Experts and Practitioners) has a total of fifteen questions and is subdivided into the following five main sections which are also linked to the objectives as defined in section 3.2:

A. MEMS Devices:

A1. *What types of MEMS devices do you research?*

A2. *What are their intended applications?*

A3. *What type of MEMS components are required to perform the necessary functions?*

B. MEMS Design and Fabrication:

B1. *Do you have a generic product development cycle for MEMS devices which includes the different development stages?*

B2. *What methods do you use to design and fabricate MEMS devices?*

B3. *Do the current methods support design iterations that may be required when developing MEMS devices?*

C. Tools and Techniques:

C1. *What tools and techniques do you utilise to design and develop MEMS?*

C2. *Do the tools and techniques you use present any constrains or limitations to the development process?*

C3. *Have you considered the DFX design methodologies, such as Design for Manufacture (DFM) used in the engineering and manufacturing domains, when developing MEMS?*

D. <u>Constraints and Limitations:</u>

D1. *What are the main limitations encountered when designing and developing MEMS devices?*

D2. *Are there any stages within the design process that constrain the further development of MEMS?*

D3. *How do you overcome obstacles in the development of MEMS devices?*

E. <u>Future Improvements:</u>

E1. *Are there additional tools or techniques required which could prove beneficial to yourself and the MEMS community?*

E2. *In your opinion, how could the development limitations and constraints be overcome or eliminated completely?*

E3. *Can you suggest any improvements to the current MEMS development process which would benefit future MEMS devices?*

4.1.2. MEMS Experts and Practitioners Background

Interviews using the semi structured approach were conducted with three experts and one doctoral researcher, who are all currently researching different MEMS devices for varied future applications which include; microfluidic devices for blood monitoring and analysis for the medical profession, microsensors and microactuators for the automotive industry, resonators and comb drive microactuators for an artificial nose, and researching into the use of the Casimir effect[2] (also known as the Casimir force) for non contact transmission, application and actuation by use of repulsive force. Two of the contributing experts are applied scientists, in the Microsystems and Nanotechnology Centre within the Materials Department at Cranfield University U.K

[2] Named after the Dutch theoretical physicist Hendrik Casimir who first predicted in 1948, the existence of an attractive force between two reflecting plates - http://www.physicsworld.com/

(www.cranfield.ac.uk/sas/nanotech). Both hold senior lecturer and senior research fellow positions respectively and are chartered scientists. Areas of expertise include; micro-device design and fabrication, micro-injection moulding, magnetic properties of materials, energy harvesting devices, piezoelectric sensors and actuators in automotive, aerospace and medical applications.

The third expert, a research fellow, and doctoral researcher interviewed, are from the Micro-Engineering and Nano-Technology Research Group within the Department of Mechanical and Manufacturing Engineering at the University of Birmingham U.K (www.micro-nano.bham.ac.uk). Expertise and experience include genetic algorithm optimisation, MEMS, lithography and deep dry etching.

4.2. Selecting a Tool for the As-Is Model

This section presents the available modelling tools and techniques to construct the As-Is model for MEMS development. The different tools and techniques for process modelling are described, followed by the defined criteria for selecting the most appropriate methodology to represent a generic overview of how MEMS devices are currently developed including the existing design tools. Many process modelling tools and techniques are available but selecting the correct tool to model a particular type of process flow accurately is essential. Process flows can vary significantly depending on the type of information that is being represented and its intended purpose. Representing the activities or functions of an organisation developing products, can provide a visual framework of how certain activities are currently performed (As-Is), and more importantly, how they could be improved (To-Be).

The available modelling tools have been chosen for selection because each method has a clear definition (containing the concepts, motivation and theory), distinct discipline (syntax of the method in a computer interpretable format providing graphical visualisation), and multiple uses (Mayer *et al*, 1992).

4.2.1. Available Modelling Tools

Mayer *et al* (1992), explains that many system analysis and engineering methods use a graphical syntax to provide visualisation of the collected data in a way that displays the key information in an unambiguous way. In order to graphically represent the data collected from the semi structured interviews, the descriptive and modelling methods chosen for evaluation are the IDEF (integrated definition methods) and data flow diagram methods, which are described below:

- **IDEF0:**
  - A function modelling method that is designed to model decisions, actions and activities of an organisation or system. IDEF0 models enable establishing of the scope of analysis for particular functions or activities and for future analyses.
  - It enhances domain experts' involvement and consensus decision making through graphical devices, and indentifies the activities performed, what is required to perform those activities, what the current system does correctly and what could be improved.
  - The IDEF0 method promotes the hierarchical decomposition of activities using a top down approach which assists in keeping in scope with the model and within the boundaries of the represented decompositions.
- **IDEF1:**
  - Method for analysis and communication in establishing requirements for what information is or what should be managed by an organisation. IDEF1 is commonly used to identify; what information is currently managed in the organisation, which of the problems identified during the needs analysis are caused by lack of managing appropriate information, and to specify what information will be managed in the To-Be implementation.
  - IDEF1 is an analysis method rather than a design method that is used to provide managers with insight and knowledge to establish a good information management policy.

- **IDEF1X:**
  - Design method for accomplishing the *design system activity* and not suited to serve as an As-Is analysis method. It is more suited for the designing of databases once the information requirements are known and the use of a relational database is confirmed. This methodology focuses on actual data elements in a relational database.
- **IDEF3:**
  - Assists domain experts in capturing and recording their knowledge about process flow and object state transitions in their environment. IDEF3 utilises scenarios to model the process flow for descriptive activities and is based upon the concept of capturing decisions and causality relations regarding situations and events in a form understandable to the domain experts.
  - The IDEF3 process flow diagrams consist of structures; known as the unit of behaviours, junctions, links, referents and elaborations, which generate and manipulate the descriptive activities. The basic graphical description used to represent the activities, within the context of a scenario, are unit of behaviours which can be further decomposed.
- **Data Flow Diagram:**
  - Used to provide a clear graphical representation of the functions within an organisation. It uses a detailed hierarchical approach to analyse the individual functional areas in a top down manner. Data flow diagrams begin by defining the context activity which represents the whole system to be analysed. This is then decomposed into a level 1 diagram which depicts the organisations key functional areas. The levels at which the model is decomposed is dependant on the number of processes and representation of hierarchy.
  - Data flow diagrams utilise five graphical symbols to represent the data type and flow which are known as; *external entity* (unique identifier for originating data), *process* (transforming data within system), *data flow* (information flow), *data store* (storing information) and *resource flow* (physical materials).

4.2.2. Criteria for Selection

Representing the data collected from the interviews conducted with the MEMS domain experts, into an As-Is model and future To-Be model for MEMS development, requires the selection of a modelling tool and technique that is suitable for analysing the current processes and recognising future improvements. In order to select the most appropriate modelling tool and technique, from the available modelling tools presented in the previous section, the following criteria for selection has been defined based on the; data collection technique (semi structured interviews), capturing knowledge of MEMS development processes from the domain experts and to illustrate this in the form of an As-Is model for analysis:

1) Graphical Syntax (*GS*)
2) Function Modelling (*FM*)
3) Hierarchical Decomposition (*HD*)
4) Supports As-Is Modelling (*As-Is*)
5) Supports Future To-Be Modelling (*To-Be*)
6) Domain Expert Involvement (*DE*)
7) Identification of Process Constraints (*PC*)
8) Identification of Physical Resources (*PR*)

Modelling tool selection based on the criteria has been performed using the matrix for selection which is illustrated in Table 4-1 . The matrix (Table 4-1) confirms the selection of the IDEF0 process modelling tool which is explained in the following section including the IDEF0 methodology and concepts. The construction of the As-Is model for MEMS development using this technique is described in section 4.4.

Criteria / Tool	***GS***	***FM***	***HD***	***As-Is***	***To-Be***	***DE***	***PC***	***PR***
IDEF0	✓	✓	✓	✓	✓	✓	✓	✓
IDEF1	✓			✓	✓			
IDEF1X	✓							
IDEF3	✓	✓	✓			✓	✓	
DFD	✓	✓	✓	✓				✓

Table 4-1: Matrix for modelling tool selection

4.3. IDEF0 Process Modelling Tool

The IDEF0 (integrated definition methods) activity modelling tool is a technique which provides visual representation for analysing a whole system or process as a set of interrelated functions or activities in a sequential manner. It is a useful communication tool which utilises cell modelling graphical representation for establishing the scope for functional analysis. The IDEF0 model characterises the required functions or activities and what is required to perform the activities (Mayer *et al*, 1992).

4.3.1. IDEF0 Methodology and Concepts

The IDEF0 model interprets the whole process for example; developing a model for MEMS design and development, as a collection of activities and represents the model as a set of hierarchical activities beginning with the top level activity called the *context activity* which is also known as the top level. The levels underneath the top level are known as *child decompositions* which represent the sub processes of the *parent* activity (Figure 4-2). The following constituents in the IDEF0 model are illustrated in Figure 4-1 and consist of:

- ***Activity or Function Name:***
    - The initial step for creating the model known as the top level or context activity, whereby this clarifies the objective of the activity or function and generally consists of a single verb including a common noun.
- ***Input:***
    - The inputs represent information, for example customer requirements, that are to be converted by the particular activity to produce outputs. The input arrows enter from the left side of the activity box.
- ***Control:***
    - The control constituent applies rules that regulate the imposing constraints of an activity. Controls can be in the form of procedures, regulations, standards, and can be used to describe items that initiate an

activity to begin or end. Control arrows enter the top of the activity box and affect the functionality of the activity.

- ***Output:***
    - o Output of an activity is a direct result of the information produced by the activity. Each activity should have a minimum of one output as an activity that does not produce an output should not be included in the model. Output arrows exit from the right side of the activity box.
- ***Mechanism:***
    - o Mechanisms are the physical resources required to perform the activity which can include; people, machinery, equipment and software tools. The mechanism arrows enter the bottom of the activity box and unlike the control and output arrows, mechanisms are optional and not a prerequisite.

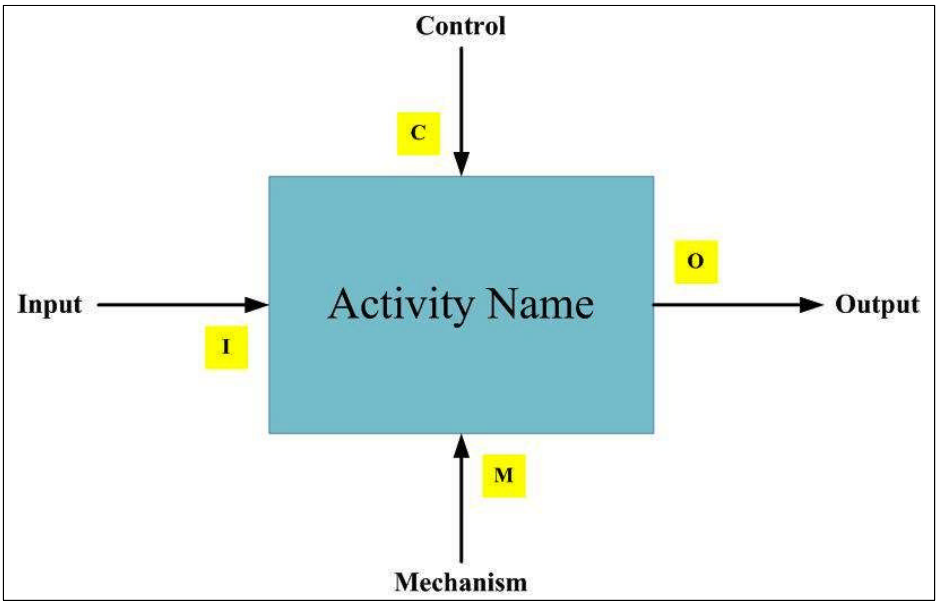


Figure 4-1: IDEF0 constituents

The decomposition of the IDEF0 model, from the parent activity into the child decompositions, is performed to divide an activity into its constituent activities. Sequentially, each of the individual activities can be decomposed into their own constituent activities which then create a new decomposition diagram as illustrated in Figure 4-2. The number of decompositions is not restricted and is dependant upon the level of complexity of the process and available information to create the IDEF0 model.

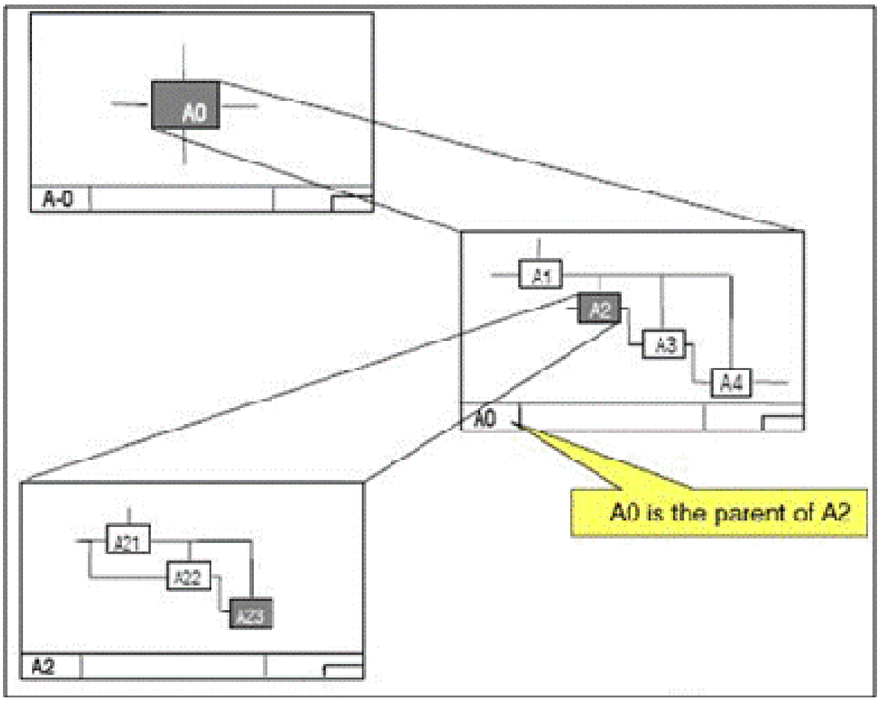


Figure 4-2: IDEF0 parent and child decomposition

4.3.2. Advantages of Using IDEF0

One of the main advantages of the IDEF0 tool is that it allocates a hierarchical decomposition of the overall process or system by structuring it at different levels of detail (Flores, 2007). Communication between the different departments of an organisation can be enhanced by developing process models using this technique due to its effectiveness in detailing the functional activities[3]. The application of the hierarchical structure provides the facility to develop As-Is models which utilise the top down approach in representing process flows.

Creating the As-Is model usually begins with data obtained from interviews with experts in a particular domain. The top level or context is defined followed by identification of the proceeding functions or activities which are then grouped depending on their relationship or similarity. This process constructs the hierarchy of the model to be analysed before developing the To-Be model.

[3] http://www.idef.com – IDEF0 Functional Modelling Method

4.4. As-Is Model of the MEMS Development Process

Development of the As-Is model, for the current development of MEMS devices, commenced with obtaining the relevant information from the semi structured interviews conducted. Experts in the area of MEMS with expertise on different MEMS device types were interviewed prior to the practitioners in order to develop the context activity, as illustrated in Figure 4-3. The hierarchical structure of the As-Is model is illustrated in Figure 4-4. A complete version of the As-Is model can be found in Appendix B: As-Is Model.

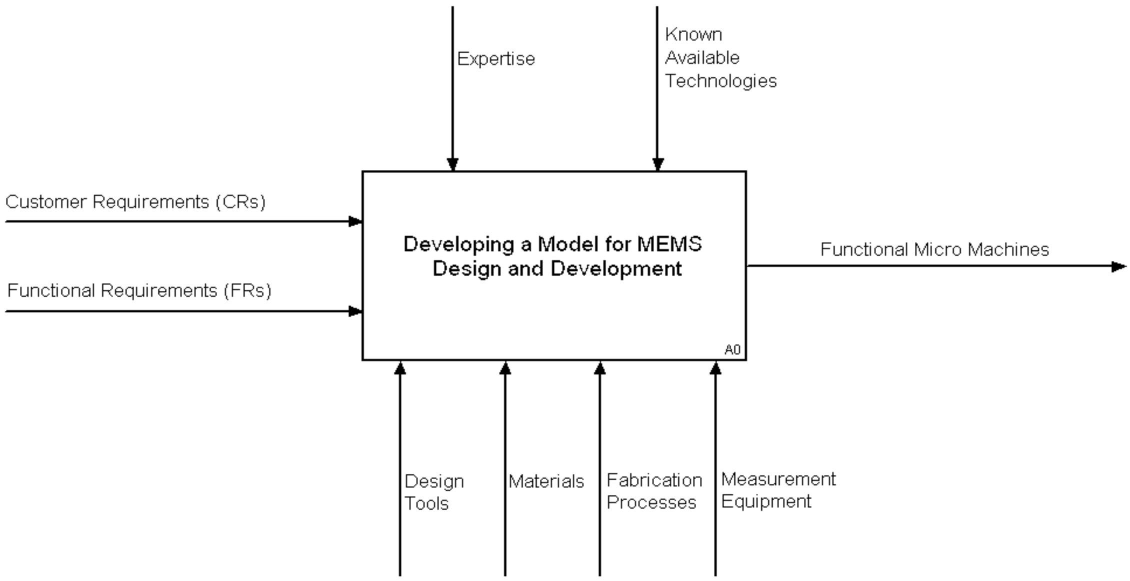


Figure 4-3: Context activity

The hierarchical structure of the As-Is model (Figure 4-4) begins with the context activity shown as the top level of the model then it is decomposed into the sub activities.

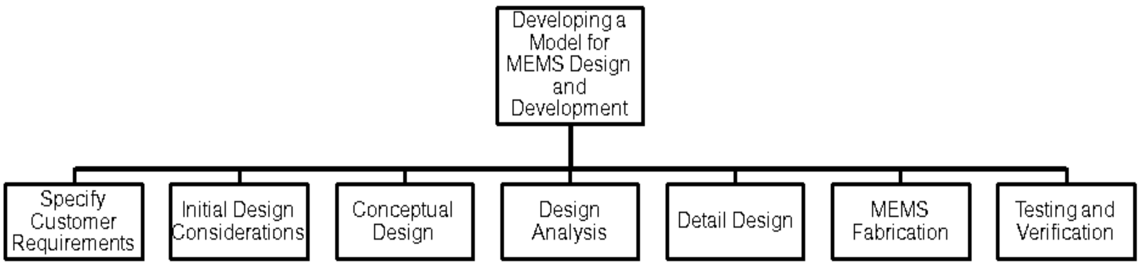


Figure 4-4: Hierarchical structure of As-Is model

4.4.1. Aim of the As-Is Model

The aim of the As-Is model is to map the current activities performed in the MEMS design process and how they are interlinked in order to develop functional devices at the micro/nano scale. The As-Is model illustrates in a structured manner, the development flow including the factors which control the activities and the elements required to ensure the successful output from each activity.

The visualisation provided by the As-Is model of the MEMS development process presents the information in a form which can be easily understood and interpreted by MEMS designers, engineers, researchers and experts. This provides a better understanding of the generic MEMS development process and the opportunity to analyse the model to identify areas of improvement. On recognition of the limitations within the current MEMS design process reflected by the As-Is model, necessary changes to the process including sub processes can be investigated and then implemented in the form of a To-Be model, as described in the following chapter.

4.4.2. Explanation of the As-Is Model – Context Activity

The initial phase of developing the As-Is model, as described in section 4.3.1, is to define the context activity which is illustrated in Figure 4-3 and Appendix B: As-Is Model. This is the representation of the main activity for this research which is to develop a model for MEMS development. The direct inputs into the context activity are the *customer requirements* (CRs) and *functional requirements* (FRs) which are converted into the output – functional micro machines. The physical resources required to produce the functional micro machines, which are stated as the mechanisms, are the; *design tools* (CAD, multi-physics solvers and functional properties analysis tools), *materials*, *fabrication processes*, and *measurement equipment*.

Constraining (control) the activity are the *expertise* and *known available technologies.* The controlling elements or constraints that have an effect on the development of functional micro machines are illustrated in detail on the decomposed model (child diagram) of the context activity (parent diagram) represented in Figure 4-5. The following sections detail the activities, inputs, controls, outputs and mechanisms associated with the decomposed activities of the As-Is model (Figure 4-5).

4.4.2.1. Activities

The following defined activities have been decomposed from the parent diagram (Figure 4-3) and are a direct representation of the activities illustrated in Figure 4-5:

A1. ***Specify Customer Requirements:***
- Specification of the MEMS device requirements i.e. device type, functionality and application.

A2. ***Initial Design Considerations:***
- Consideration of the design, technology, process and material constraints including the packaging of the product.

A3. ***Conceptual Design:***
- Conceptual development of MEMS devices which includes behavioural or functional simulations and conceptualising the structural device layout.

A4. ***Design Analysis:***
- Analysing the feasibility of the design and performing physical analysis using numerical computational simulations - quantitative analyses.

A5. ***Detail Design:***
- Construction of engineering drawings detailing dimensions and electronic schematics for the chosen MEMS device.

A6. ***MEMS Fabrication:***
- Producing the required MEMS device type using the applicable fabrication processes.

A7. ***Testing & Verification:***
- Testing the components; performance, reproducibility, reliability and quality, of the MEMS device.

4.4.2.2. Inputs

I1. ***Customer Requirements (CRs):***

- Requirements specified by the customer providing detailed needs of the MEMS device. These are captured and elicited in order to define the product specification (*product definition*).

I2. ***Functional Requirements (FRs):***

- The functions required to perform the necessary operations by the MEMS device and specification of the particular characteristics of the various independent MEMS components.

4.4.2.3. Controls

C1. ***Expertise:***

- Skill, knowledge and ability, in a chosen area of research, of the MEMS experts, designers, engineers and researchers required to ensure the successful development of the MEMS devices.

C2. ***Known Available Technologies:***

- Technologies that are recognised by the MEMS experts and practitioners, and those which are currently available for the design and development of MEMS.

4.4.2.4. Outputs

O1. ***Functional Micro Machines:***

- Practical microdevices that fulfil the intended application, satisfy the functional requirements, and encompass a variety of functions at the micro scale using multidisciplinary science and engineering principles.

O2. *Activity Outputs:*

- Product Definition
- MEMS Requirements
- Initial Configurations
- Design Feasibility
- MEMS Specifications
- Manufactured MEMS Device(s)
- Feedback
- Reconfigure
- Conceptual Redesign
- Reanalyse
- Detail Redesign
- Rework

4.4.2.5. Mechanisms (Tools and Techniques)

M1. *Design Tools:*

- Tools required during the development stages to design and analyse the MEMS devices. This includes software; for designing the physical layout of the devices and corresponding components (CAD), multi-physics solvers (COMSOL) and equation based modelling (Matlab), analysis of the different functional and structural properties such as computational fluid dynamics (CFD), stress analysis (FEA) and magnetic field strength.

M2. *Materials:*

- Varying materials including; silicon, quartz and plastics that are used to fabricate and produce the numerous microsystems.

M3. *Fabrication Processes:*

- Microfabrication processes or micromachining techniques utilised in manufacturing the MEMS components and devices.

M4. *Measurement Equipment:*

- Tools and techniques for the design and functional verification of the microfabrication processes, MEMS functionality and reliability.

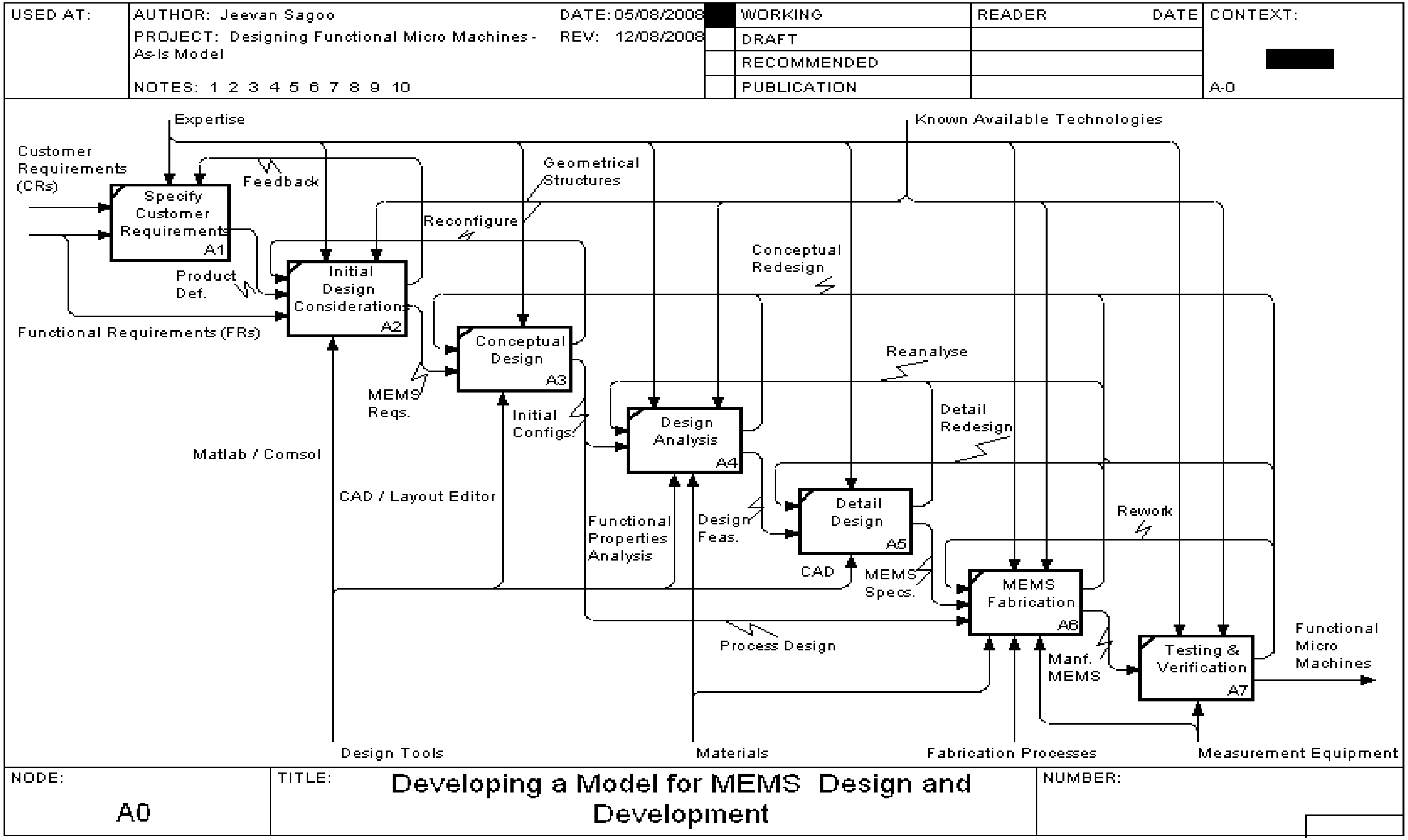


Figure 4-5: Decomposition of the context activity – Node A0

4.4.3. Explanation of the Decomposition Model – Node A0

As illustrated in the decomposition model of the context activity (Figure 4-5), the beginning phase of the MEMS development process commences with the specification of the customers requirements activity (A1). This activity translates the customer and functional requirements into a defined MEMS product, based on the customers and functional requirements, which is controlled by the domain expert (*expertise*). The entire MEMS development process as illustrated is controlled by the expertise of the MEMS experts. It must be noted that this activity (A1) is only applicable and integrated in the process when customers request the development of specific MEMS devices. MEMS experts and researchers will begin at the initial design considerations activity (A2) where the functional requirements are a direct input rather than customer requirements.

The initial design considerations (A2) activity is controlled by the MEMS expertise and the known available technologies. At this stage, the functionality of the MEMS device to be developed is considered which includes; the design constraints, material selection, fabrication process selection based on the known available technologies, electro-mechanical systems and packaging requirements. Design tools used by the experts in this activity are equation based modelling and multi-physics solvers, such as Matlab[4] and COMSOL[5], which analyse the functional requirements of the MEMS device. The output from this activity (A2) is the initial specification of the MEMS requirements. There is also a feedback output which acts as a control on activity A1 if the requirements specified by the customer cannot be achieved. This is communicated back to the customer by the experts who will verify the feasibility of the intended device.

The conceptual design phase (A3) utilises the MEMS requirements to initiate conceptual designs of the intended MEMS devices using design tools such as; CAD and a layout editing tool for schematic capture and simulation including photo-mask development capabilities. Initial configurations for the MEMS device are the direct

[4] Matlab and Simulink are product families produced by Mathworks Inc, – www.mathworks.com
[5] COMSOL multi-physics and simulation environment – www.comsol.com

output from this activity which consists of the geometry, dimensions, materials and processes. A reconfigure loop is also an output from this activity which is an input back into the initial design considerations if the created concepts are not feasible for further development. The complex geometrical structures of the MEMS devices control this activity and expertise is required to define the initial configurations. Another resulting output (*process design*) from this activity (A3) provides an input into the MEMS fabrication activity (A6) because the initial configurations of the selected materials and processes are linked to the fabrication of the devices, therefore the most applicable fabrication technique(s) can be selected.

Next stage in the development process is to perform a design analysis (A4) or analyses on the conceptualised designs, before developing prototypes, using functional properties analysis methods such as; FEA for material and geometry stress analysis, CFD for fluid flow analysis, and other multi physics solvers such as COMSOL to analyse the electromagnetic-structural, thermal-structural, fluid-structure and electromagnetic-fluid interactions. Three dimensional models of the MEMS devices are created to analyse the physical phenomena in actuators, sensors, microfluidic devices and piezoelectric devices. Information on the available materials including their properties are required to perform the mentioned analyses which are controlled by the experts, who have acquired knowledge of the chosen tools, and known available technologies for MEMS development. Outputs from this activity include; a conceptual redesign loop back to the previous activity (A3) to redesign the device depending on the results of the performed analyses, or confirmation of the designs feasibility which is an input into the following activity – detail design (A5).

Detail design activity (A5) generates the final detailed engineering drawings and schematic diagrams for the dedicated MEMS devices and these result in the final specification (output – *MEMS specifications*) detailing the materials, fabrication process, packaging and assembly requirements. The tools commonly used are CAD based (AutoCAD) which are also used to design the required masks (photolithography) and moulds (microinjection moulding) for the fabrication equipment and processes, and are controlled by the experts’ knowledge of their chosen design tool. A *reanalyse* output which loops back to the previous activity (A4) illustrates the necessity to reanalyse the design due to fabrication process constraints which are imposed by the known available technologies in the following activity (A6). The final specifications of the MEMS device generated y this activity (output) link into the following activity (A6) which is to fabricate the MEMS devices including prototypes.

Activity A6, (*MEMS fabrication*) represents the physical processes, materials and techniques required to manufacture the MEMS devices and components. Controlling this activity is the expertise of the MEMS developers which is also linked with the known available MEMS technologies. The physical resources required to perform this activity are the; materials (plastics or silicon), fabrication processes (microinjection moulding, photolithography, wet and dry etching and micromachining processes such as FIB – focussed ion beam milling), and process measurement equipment to monitor and measure the fabrication processes. The two outputs from this activity are; the manufactured MEMS devices which input into the following and final activity (A7) of the MEMS development process, and a reiteration to the previous development processes (design changes) depending on the outcome of the fabrication process. The reiteration output is linked into the following three loops as shown on the model (Figure 4-5): *detail redesign*, *reanalyse* and *conceptual redesign*. The reiteration of the device development using the loops to go back to the previous stages (A5, A4 and A3) depends on the type of non-conformity or fabrication process constraints.

The final activity (A7) of the MEMS development process, as illustrated by the As-Is model in Figure 4-5, is testing and verification of the manufactured MEMS devices from activity A6. Measurement equipment is used at this stage to test and verify the functionalities, performance, quality and reliability in application of the fabricated MEMS device. Devices produced that fail in functionality or do not conform to the specifications can be reworked which requires them to return back to the previous development stage (A6 – MEMS fabrication) for rework and re-fabrication or follow the existing reiteration loops depending on the results obtained from the testing and device verification. The results obtained from the actual fabrication may not correlate with those acquired by mathematical computational methods or simulation in activity A4 resulting in the requirement of new concepts utilising the knowledge gained of the tried and tested methods. This can sometimes be referred to as designing for process redesign. Once the MEMS devices have been fabricated to the specifications (revisions maybe necessary), and testing and verification is complete, the final output from this activity and model is ‘functional micro machines’. The description of the output is provided in section 4.4.2.4. Controlling this activity (A7) are the known available technologies and testing methods for the device parameters, and expertise of the MEMS developers regarding the testing and technology required to verify the functionalities of the MEMS devices.

4.4.4. Recognition of the Process Constraints and Limitations

This section examines the constraints and limitations imposed on the MEMS design and development process as illustrated by the As-Is model (Figure 4-5) and the information provided by the MEMS experts and researchers from the interviews conducted. As depicted in Figure 4-3, there are two control elements which regulate the imposing constraints of the main activity and decomposed activities. The constraints; *expertise* and *known available technologies*, are constituents which initiate the beginning or completion and affect the functionality of the defined activities. The main controlling constituent is the expertise of the MEMS designers which controls each of the individual development stages (activities A1 to A7) which are highlighted in Figure 4-6.

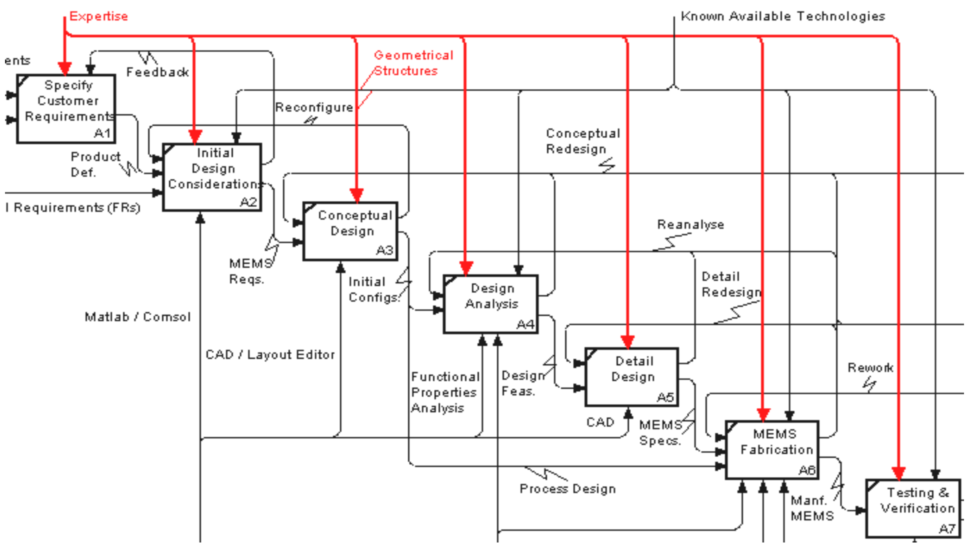


Figure 4-6: Expertise control

Restrictions in the MEMS development process include the controlling of each activity by the experts which in itself is a demanding task. The experts use specific design tools and techniques that they are comfortable with and have knowledge of. It can be time consuming in learning new and unfamiliar software. Another issue that arises with the MEMS development process is the lack of available software modelling tools to model the many diverse properties of MEMS at the micro scale.

The interaction of the MEMS experts at each of the development stages signifies that the MEMS development processes are devised by the experts with an *ad-hoc* approach due to the lack of physical predictive models therefore the development is based on the known process restrictions of the available technologies. Devices that are developed using a 'trial and error' approach, causes major restrictions in the development process due to the time taken in redesign and redevelopment activities as illustrated in Figure 4-8. The existing available MEMS technologies that are known by the experts is the second controlling constituent of the development process as highlighted in Figure 4-7.

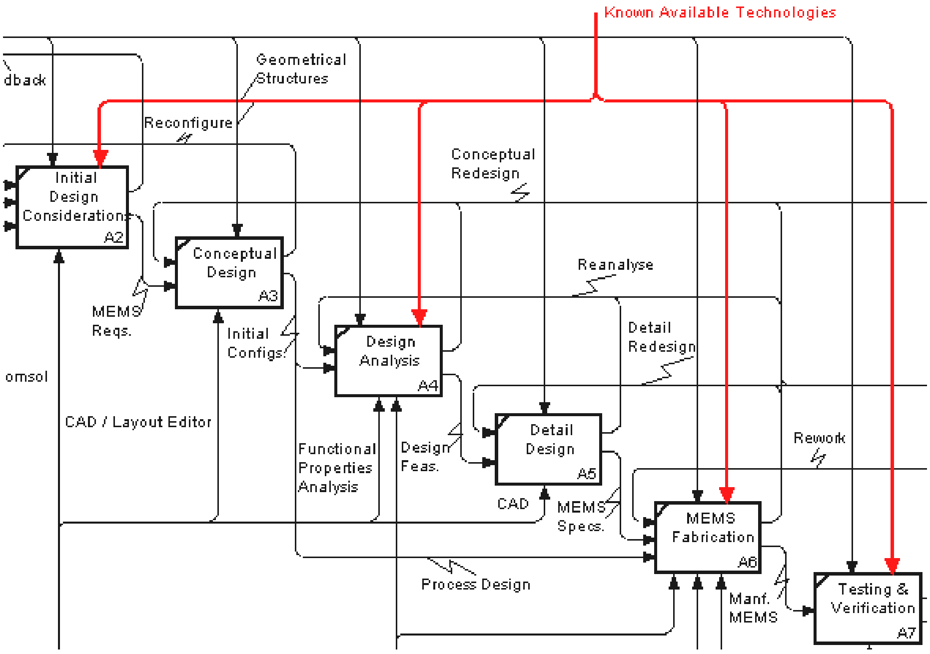


Figure 4-7: Known available technologies control

The known available technologies control activities A2, A4, A6 and A7 as illustrated (Figure 4-7). Progression in the development of MEMS devices is limited by the existing technologies used and known by the experts, and in addition due to the technological advances required to produce the complex three dimensional micro machines. New aspects or parameters in the MEMS design, such as the use of the Casimir force, requires a novel approach in the development process and new technology to use and measure the effects produced. However, understanding of the new technologies and having to research and develop them for future use, can be difficult and time consuming to understand therefore, it is efficient in terms of time and cost of the development to use the known technologies which are understood better by the experts and researchers. This also applies to adapting the existing known technologies to conform to the MEMS specification which also limits the progress of development.

As a result of the 'trial and error' approach used in the MEMS development process, several reiterative process loops; *feedback, reconfigure, conceptual redesign, reanalyse, detail redesign* and *rework*, as highlighted in Figure 4-8, are present in the process because of the; research based development, incorrect initial specifications, unavailability of the required materials, technology is based on older existing technologies and is not fully developed to produce complex structures and components at the micro scale, current measurement facilities limit the testing of MEMS parameters, researching into the problems regarding the product and process requires many iterations, and lack of design tools which integrate the different MEMS applications.

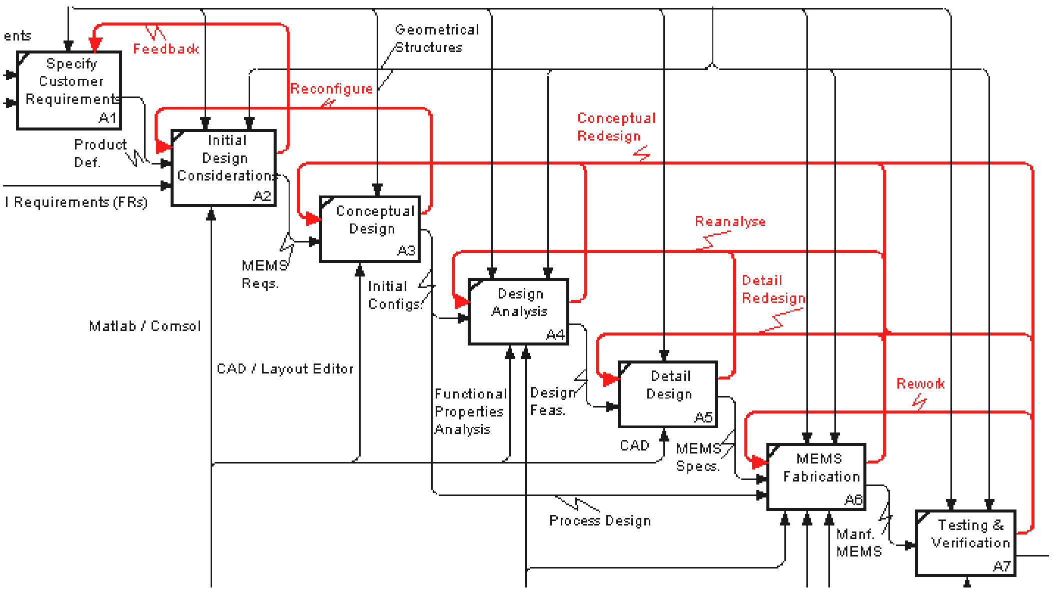


Figure 4-8: Reiterative process loops

4.4.5. Identifying the Areas of Improvement

Recognition of the constraints and limitations in the MEMS development process, identified by the As-Is model and analysis in the previous section, has enabled the identification of areas in the development process that can be improved. Taking into consideration the identified opportunities for improvement described in this section, a To-Be model for future MEMS development is proposed and explained in the following chapter which addresses the development limitations identified by the As-Is model. The following identified areas of improvement in the MEMS development process have been listed below, and explained in the following sections detailing how these can be implemented into the proposed To-Be model for future MEMS design:

1. Inclusion of requirements management tools to capture and elicit the following classes of requirements to provide a comprehensive specification of the MEMS device; operational, functional, non-functional, business and customer (use of requirements management tools and QFD to analyse the feasibility of the requirements)
2. Consideration of high volume, low cost manufacturing in the MEMS design process (application of DFX methodologies)
3. Reduce the number of reiteration processes (possible application of concurrent engineering principles, and formal ways of testing and measuring the different stages in product development – definition of product development success factors)
4. Structured design methodology for MEMS eliminating the *ad-hoc* approach, and an assessment of the technologies available for MEMS

4.4.5.1. Managing MEMS Requirements

Information obtained from the experts in the semi structured interviews and depicted in the As-Is model (Figure 4-5) and Figure 4-9: Assessing feasibility of customer requirements, illustrates that the requirements inputs (CRs and FRs) into activity A1 (*specify customer requirements*) are controlled by the experts but in an informal way. This is indicated by the absence of a 'mechanism' in activity A1 (Figure 4-9) which confirms that the physical resources required to perform this activity are absent. Fedder, (1999) verifies this in the literature review conducted (section 2.8.1) by explaining that the high level specifications of the MEMS devices are provided in a informal written format specifying the functional requirements before the design concepts are embodied into a high level abstract product definition.

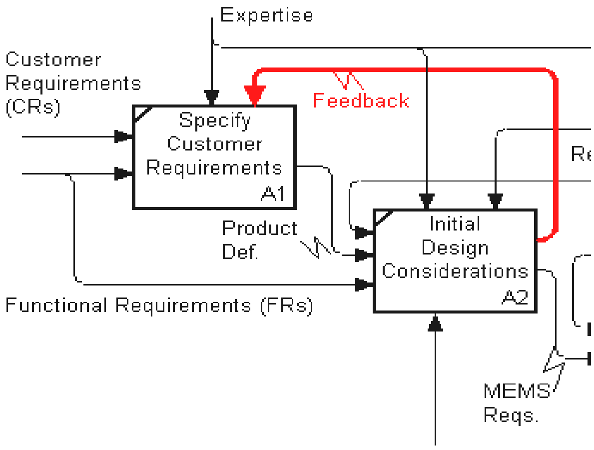


Figure 4-9: Assessing feasibility of customer requirements

As illustrated by the highlighted feedback arrow from activity A2 back to A1 in Figure 4-9, managing the requirements with available tools and techniques, including the QFD analysis, utilised by the engineering and manufacturing domains, can improve the current development process by providing proven tools and techniques to the MEMS experts which removes the existing feedback reiteration loop due to the informality of the requirements specified. A reiteration between activities A1 and A2 can be a continuous process before proceeding onto activity A3 which is a slow and time consuming process that hinders the overall MEMS development process.

Managing requirements appropriately is considered a fundamental aspect of product development in the engineering and manufacturing domains, therefore utilisation of the requirements management and analysis tools, such as QFD, can provide the MEMS experts and community with established techniques to verify the feasibility and practicability of the diverse MEMS requirements.

4.4.5.2. MEMS Manufacturing Considerations

Fabrication of the MEMS devices is represented as activity A6 in the As-Is model and the output from activity A3 (*conceptual design*) is highlighted in Figure 4-10 illustrating the current development stage in which the manufacturing of MEMS is considered. However, due to the intricacy of the MEMS, many devices are still in the research and development phase focussing on the functionalities and development of suitable technologies, therefore high volume and low cost manufacturing of the devices is not considered until activity A6. It is at activity A3 when the initial configurations of the MEMS device including the process design requirements are specified. This could be incorporated into earlier activities such as A1 and A2.

The introduction of an additional activity in the MEMS development process that would assess the limitations of the known available technologies and to examine them to see if they are adaptable to accommodate the new MEMS requirements (high volume and low cost) would be beneficial. This would provide an advantage, if implemented in advance to the conceptual design phase (A3), in understanding the fabrication restrictions and therefore the technical feasibility can be assessed to recognize the manufacturing capabilities.

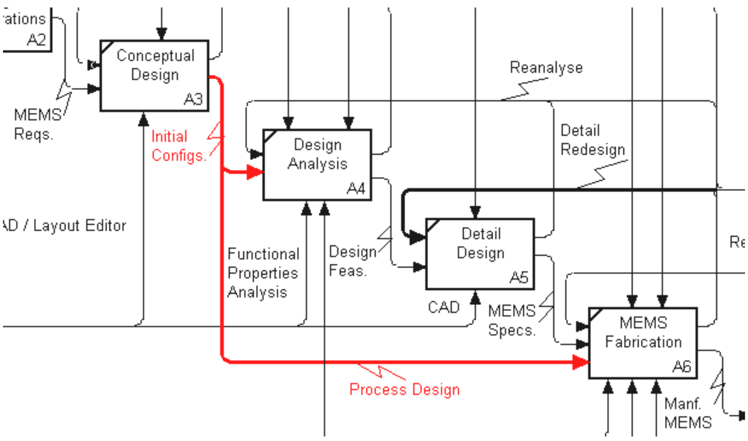


Figure 4-10: Process design for MEMS manufacturing

Application of design methodologies such as DFX (DFM and DFA) in the MEMS design and development process, as applied by Da Silva *et al*, (2002) and Schröpfer *et* *al*, (2004), would assist in addressing the following three components; *developing process requirements, identifying and evaluating existing processes, and packaging requirements*. Da Silva *et al*, (2002) described that using traditional manufacturing approaches when developing MEMS devices takes longer for MEMS products in achieving high volume manufacturing due to novelty of MEMS, lack of standard process flows and integrated design tools.

Schröpfer *et al*, (2004) stated that manufacturability should be embedded in a MEMS development framework, to consider the manufacturing constraints in the manufacturing phase, during the earlier phases of the MEMS development process. Consideration of the manufacturing constraints in the initial phases of MEMS development will result in a higher device yield, and the time taken to ramp up to volume production is significantly reduced.

4.4.5.3. Reduction of Development Iterations

The trial and error approach used in MEMS development due to the various constraints and limitations, as described in section 4.4.4, is a major contributing factor to the number of repetitive processes highlighted by the As-Is model in Figure 4-8. The reiterative process loops can be reduced with the introduction of additional activities (including metrics to measure the success of development at each individual activity) in the To-Be model that would alleviate the need to return to the former activity. Utilising methodologies and principles from the engineering and manufacturing domains, such as concurrent engineering, DFM, DOE and QFD, and integrating them into the MEMS development process will reduce the design reiterations that exist due to an unstructured approach. In summary, the integration of these methods would directly address the manufacturability of MEMS in the early stages of development.

Additional activities and mechanisms in the To-be model addressing the technical assessment and capabilities of the manufacturing processes would also facilitate the reduction of reiterations, as the technical feasibility of the equipment and processes would provide a greater understanding of what can be produced and to what limits.

Schröpfer *et al*, (2004) and Da Silva *et al*, (2002), stated that the success of a DFM approach for MEMS is measured by the ability to select the correct design option quickly and accurately during the conceptual design phase. Currently, MEMS experts begin with a single concept (A3) based on the requirements (A1) and initial design considerations (A2) then proceed with development and reiterate the design as required, but if the functionalities cannot be achieved due to the design, materials, fabrication processing capabilities or available equipment, the experts either adapt the technologies to suit their design or begin with the re-specification of requirements. This can be a very costly process which requires much iteration increasing the development time and effort.

Another important method of reducing the repetitive processing is to begin with many design concepts in the conceptual design phase (concurrent engineering) whereby these can then be developed and evaluated simultaneously (Da Silva *et al*, 2002). The conceptual design phase can then proceed onto the following activity (A4) for the design analysis, when a few concepts are available for evaluation. This also provides the experts with a way of retaining and using the knowledge gained for future concepts and analysis. Package design must also be considered during the conceptual design phase to avoid re-design (Schröpfer *et al*, 2004).

4.4.5.4. MEMS Design Methodology and Technology Assessment

Many authors in the literature reviewed (section 2.8.2) and experts interviewed have commented on the lack of standard process flows and design tools for MEMS which consider the high volume and low cost production of the dedicated devices. The proposed To-Be model for future MEMS design is aimed at providing the MEMS experts, researchers and practitioners with a structured framework for generic MEMS development which includes the utilisation of tools and techniques from the engineering and manufacturing domains. As described in sections 4.4.5.2 and 4.4.5.3, an additional activity or initial assessment of the known available technologies to produce the micro devices would eliminate this as a constraint in the development process, as illustrated by the As-Is model (Figure 4-3).

4.5. Validation of the As-Is Model

The As-Is model presented in this chapter has been validated by two MEMS experts from the Microsystems and Nanotechnology Centre at Cranfield University, both of who are registered charted scientists (*CSci*), members of the Institute of Physics, and hold senior research positions within the Materials Department at Cranfield University.

Validation of the As-Is model comprised of verifying the development activities, inputs, outputs, controls and mechanisms depicted by the IDEF0 modelling technique for the As-Is model. The graphical representation of the existing generic MEMS development process provided by the As-Is model, illustrated to the MEMS experts the development process, as captured from the semi structured interviews using the defined questions presented in section 4.1.1. The validation of the As-Is model was conducted with the MEMS experts to justify the development stages and tools and techniques currently utilised in the development of functional micro machines.

4.6. Summary

As defined in the research methodology, this chapter has captured the existing design practices utilised by the MEMS experts, researchers and practitioners when developing MEMS devices. The data collection approach using the semi structured interviews to capture the current design practices from the experts has been described including the selection of an appropriate modelling tool to graphically represent the existing development process in the form of an As-Is model. Criteria for selecting the most suitable modelling tool were presented which emphasised the attributes of the IDEF0 methodology to be the most appropriate.

Use of the IDEF0 process modelling tool to replicate the existing MEMS development practices (As-Is model), provided an illustrative representation of the generic MEMS development process as a collection of hierarchical activities. The decomposition of the context activity, as described by the IDEF0 methodology, was performed to divide the main activity into constituent activities that correspond to the sequential MEMS development phases. The As-Is model illustrated the current MEMS development flow including the factors which constrain the individual activities and the elements required to ensure the successful output from each activity. The individual activities have been explained including the; associated inputs and outputs, limitations and constraints that control the MEMS development have been recognised and discussed.

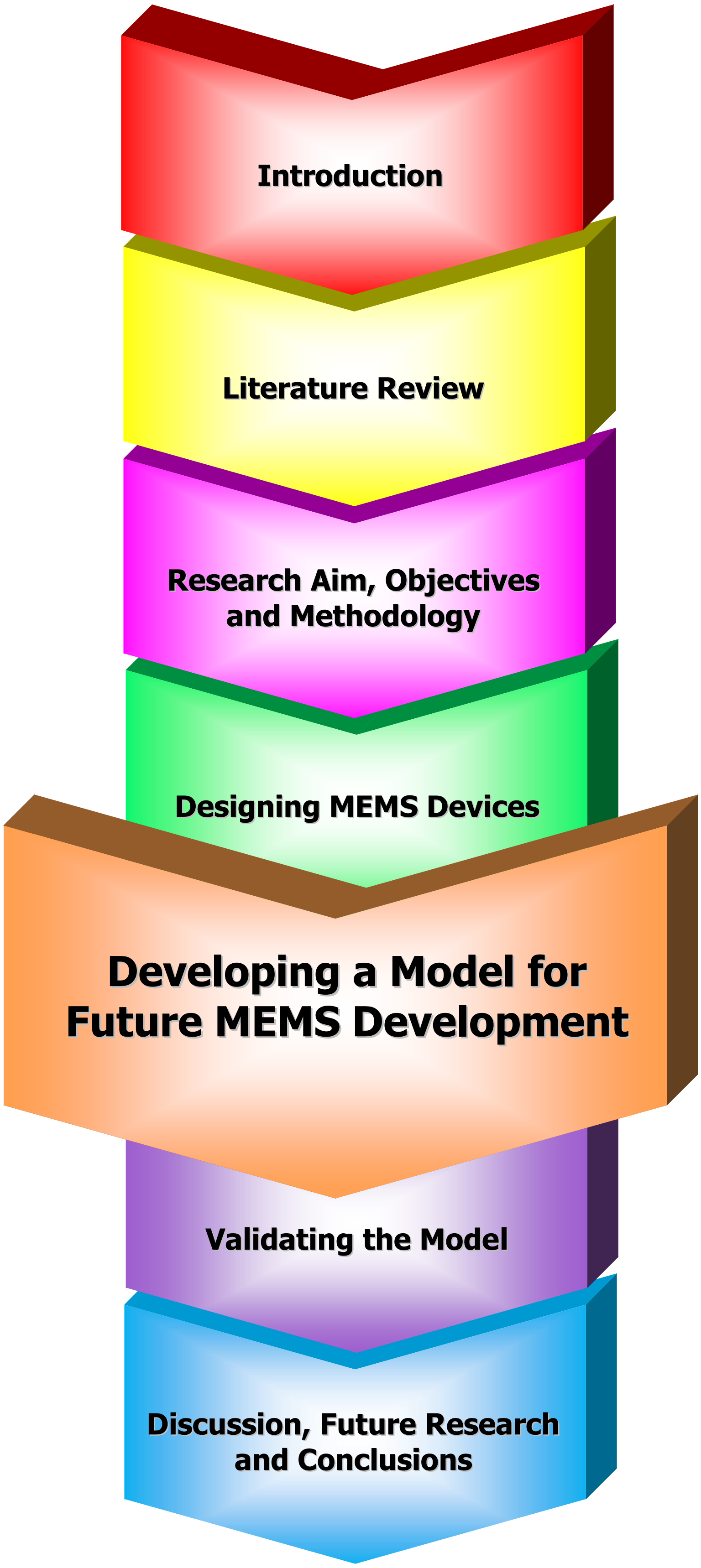
Analysis of the As-Is model has revealed the following areas of improvement in the existing MEMS development process that can be incorporated in the To-Be model for future MEMS design:

1. Managing MEMS requirements
2. MEMS manufacturing considerations
3. Reduction of development iterations
4. Design methodology and technology assessment for MEMS

Implementation of the identified areas for improving the existing MEMS design process have been described which include the integration of design methodologies from the engineering and manufacturing domains such as DOE, QFD, DFM and concurrent engineering principles. The literature reviewed in chapter 2 provided the author with an understanding of the available design methodologies used in the engineering and manufacturing domains, and how these have and could be applied to the MEMS domain and in particular, with an emphasis on high volume, low cost manufacturing of MEMS devices.

The following chapter presents the To-Be model for future MEMS development based on the analysis of the As-Is model and identification of areas of improvement in the existing development process. The To-Be model is a representation of how the existing development process could be improved compared to the As-Is model which identified how the MEMS development activities are currently performed.

Chapter 5


Introduction
Literature Review
Research Aim, Objectives and Methodology
Designing MEMS Devices
Developing a Model for Future MEMS Development
Validating the Model
Discussion, Future Research and Conclusions

5. Developing a Model for Future MEMS Development

The previous chapter presented the existing MEMS development practices in the form of an As-Is model using the IDEF0 modelling technique. Interviews were conducted with the MEMS domain experts and practitioners to capture the current development practices performed for the various MEMS devices. This information was used to create the As-Is model for analysis whereby, the constraints of the development process were recognised and the areas for improvement were identified and explained.

A model for future MEMS development is described and proposed in this chapter incorporating the suggestions for improvement described in the previous chapter. The proposed To-Be model, developed using the IEDF0 technique, represents improvements made to the current MEMS development process (As-Is) utilising proven design tools and techniques from the engineering and manufacturing areas such as DOE, QFD, DFM and concurrent engineering principles. The following sections detail the changes to the existing development process and the improvements provided by the To-Be model.

5.1. Proposed To-Be Model

The To-Be model proposed to the MEMS community for the development of future MEMS devices has been created using the IDEF0 modelling technique as described in the previous chapter. IDEF0 was selected as the chosen modelling tool based on one of the chosen criterion which was its ability to analyse existing processes with the objective of further improvement. The To-Be model is aimed at providing the MEMS experts, researchers and practitioners with a structured model for generic MEMS design and development which uses tools and methodologies from the engineering and manufacturing disciplines to consider the manufacturing of dedicated MEMS devices earlier on in the MEMS product development process.

As explained in section 4.3.1, the IDEF0 model interprets the entire development process as a collection of activities beginning with the top level activity called the context activity which is also known as the parent activity. The parent diagram for the To-Be model is illustrated in Figure 5-1 and the child decomposition activities are illustrated in Figure 5-2.

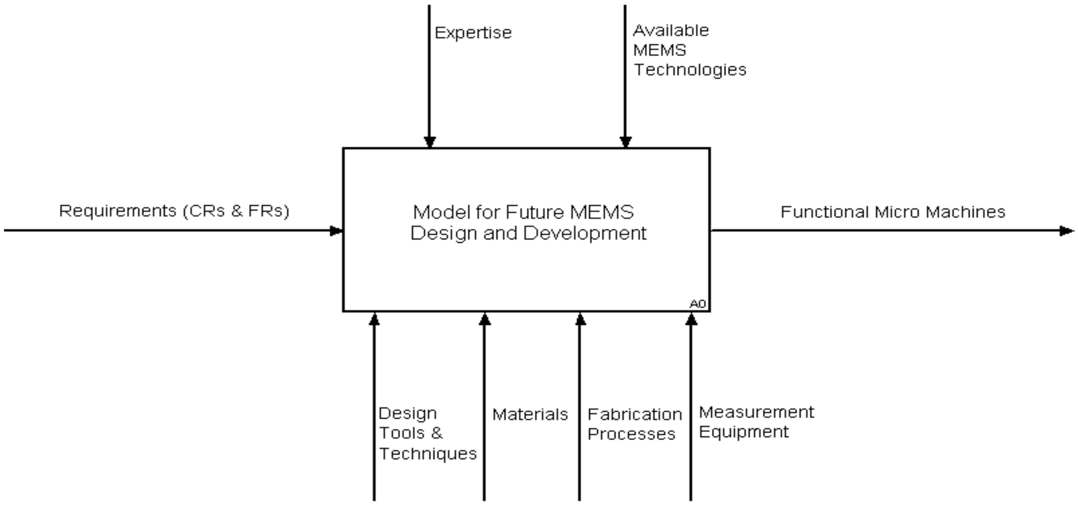


Figure 5-1: Context activity of the To-Be model

The context activity for the proposed model (Figure 5-1) has been renamed to '*Model for Future MEMS Design and Development'*. In comparison to the context activity of the As-Is, the following changes have been made to the To-Be model:

- Single input incorporating the various classes of requirements (customer, functional, non-functional, business and operational).
- 'Available MEMS Technologies' changed from 'Known Available Technologies'.
  - New MEMS technologies are currently in development and some are available for the MEMS community which are not always considered by the experts due to unfamiliarity. This also acts as a constraint to the development process thereby, it is suggested to the experts and practitioners to analyse the available technologies for MEMS.
- 'Design Tools and Techniques', as a mechanism, has been renamed from 'Design Tools' to contain the design methodologies from the engineering and manufacturing areas, in addition to the design and development tools used for MEMS.

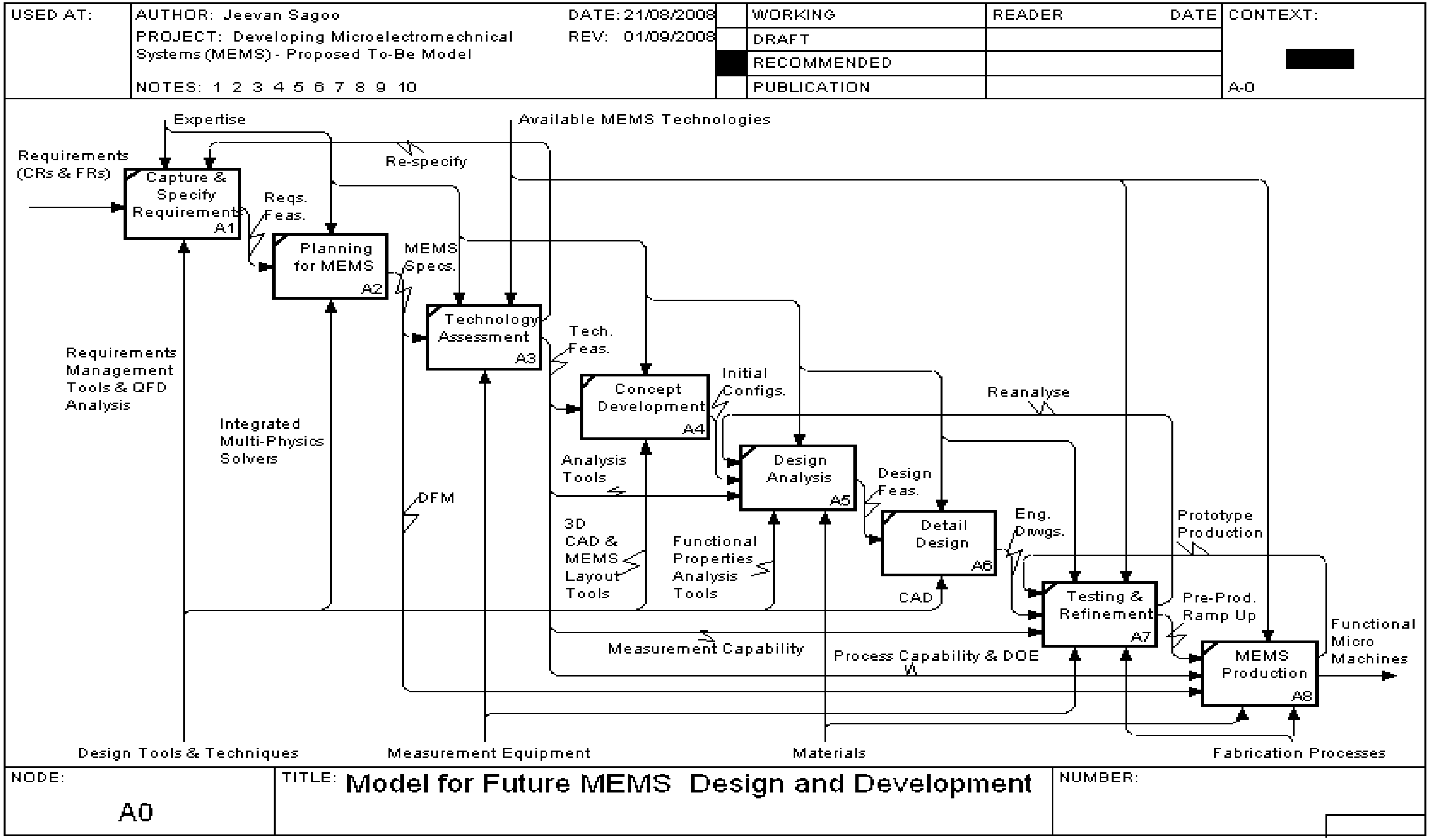


Figure 5-2: Proposed To-Be model for future MEMS development

5.2. Changes to the Existing MEMS Development Process

This section describes the changes made to the existing MEMS development process illustrated by the As-Is model. The decomposed activities (Figure 5-2) of the proposed To-Be model illustrate an additional activity to the development process for future MEMS development. This has also been highlighted in Figure 5-3 as the *Technology Assessment* activity (A3).

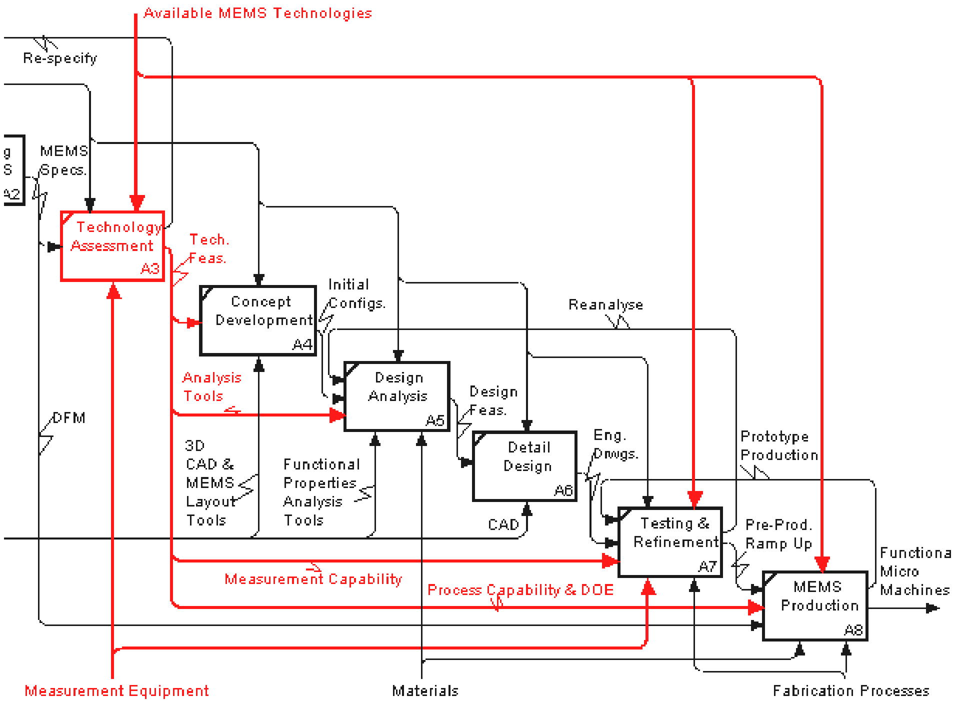


Figure 5-3: Technology assessment activity

A generic product development framework, as defined by Ulrich and Eppinger (2008), with two additional activities bespoke for MEMS (A1 and A3), has been adopted for the To-Be model. Activity A2, in Figure 5-2, illustrates that the activity has been changed from ‘Initial Design Considerations’ to ‘Planning for MEMS’, and the ‘Testing and Refinement’ activity has been placed before the ‘MEMS Production’ activity, which coincides with the generic product development framework (Ulrich and Eppinger, 2008). Activity A3 – Technology Assessment has been defined for the MEMS experts and practitioners to assess the available MEMS technologies required for the dedicated MEMS device type. MEMS specifications are an output from activity A2 into activity

A3 which are then validated again by performing an assessment of the available technologies to verify if the requirements can be fulfilled. If the technology assessment concludes that the requirements can not be fulfilled due to the technological limitations, they can be re-specified using the *re-specify* feedback loop back to activity A1 – ‘Capture and Specify Requirements’.

Controlling this activity (A3), as illustrated in Figure 5-2, is the MEMS experts’ assessment of the available technologies and the technologies currently available for MEMS. Outputs from the technology assessment activity (A3) are: *Technical Feasibility* (analysing the feasibility of technology and equipment available for MEMS development), *Analysis Tools* (investigation of the available functional properties analysis tools), *Measurement Capability* (recognition of the capability and limitations of the measurement equipment), and *Process Capability & DOE* (recognition of the capability and limitations of MEMS fabrication processes, and using statistical analysis techniques such as DOE to reduce the amount of prototype models thus minimising the amount of trial experimentation and to explore the different combination of design variables).

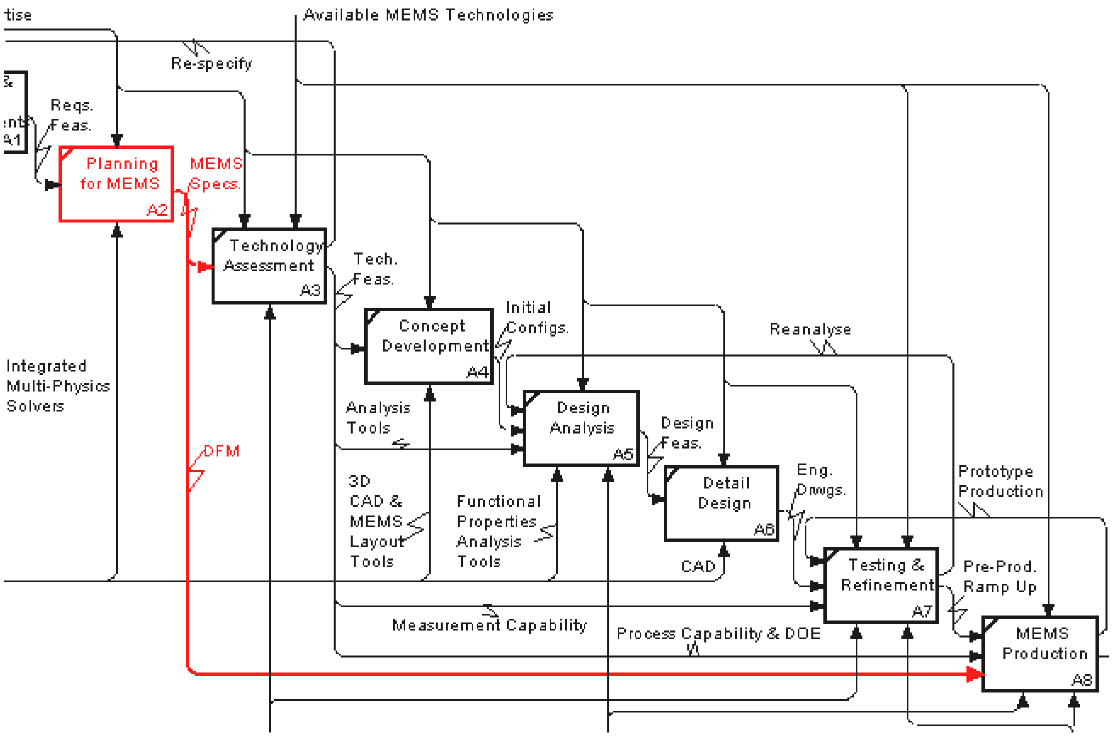


Figure 5-4: Manufacturing considerations in MEMS development

Activity A2 – 'Planning for MEMS' (Figure 5-4), involves, as previously described in section 4.4.3, equation based modelling and the use of multi-physics solvers to analyse the functional requirements of the MEMS device, also including the non-functional requirements such as the manufacturing, packaging and assembly to produce specifications for the MEMS device. Consideration of these and other non-functional requirements are now to be linked as an input into the 'MEMS Production' activity (A8) using the concurrent engineering principles such as DFM (design for manufacture).

Application of the DFM methodology (Figure 5-4), included as an output from the 'Planning for MEMS' activity (A2) to consider the manufacturing requirements which includes the; manufacturing, packaging and assembly, earlier on in the MEMS development process will assist in eliminating the ad-hoc approach and consequent redesigns of the MEMS devices. The trial and error approach to MEMS development is a major contributing factor to the amount of iterations which occur in the existing development process as highlighted by the As-Is model (Figure 4-8). Due to the intrinsic nature of MEMS, considering DFM in the MEMS development process, as illustrated by the To-Be model (Figure 5-2), is at an earlier stage than the generic product development process defined by Ulrich and Eppinger (2008) who have stated, DFM begins in the early stages of design such as the concept development phase.

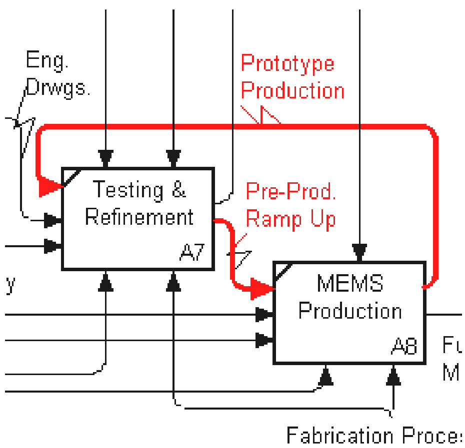


Figure 5-5: Prototype production loop

'Testing and Refinement' (A7) and 'MEMS Production' (A8) activities now include a *prototype production* loop to select the appropriate production factors and to test and refine the product and processes accordingly, as illustrated in Figure 5-5. Once the product and process parameters have been fully defined and tested for repeatability and reproducibility, production can be 'ramped up' or increased to full operational capacity to produce the functional micro machines. The number of physical prototypes can be optimised using the DOE technique to validate the technical feasibility of the different combinations of design variables. Activity A8 is not controlled by the experts at this phase of the development process although contribution would have been made during the prototype development stages. On completion and validation of the *pre-production ramp up* and *prototype production*, the MEMS devices can be manufactured without the involvement of the experts.

Requirements management tools and QFD analysis have been added as mechanisms to the 'Capture and Specify Requirements' activity (A1) highlighted in Figure 5-6. This has been implemented into the To-Be model from identifying the areas of improvement as described in section 4.4.5.1. The addition of the defined mechanism to this activity ensures the presence of a proven physical resource to perform this activity. Including tools to capture and elicit requirements accurately in a structured manner will eliminate the informal way in which MEMS requirements are currently managed by the MEMS experts (Fedder, 1999).

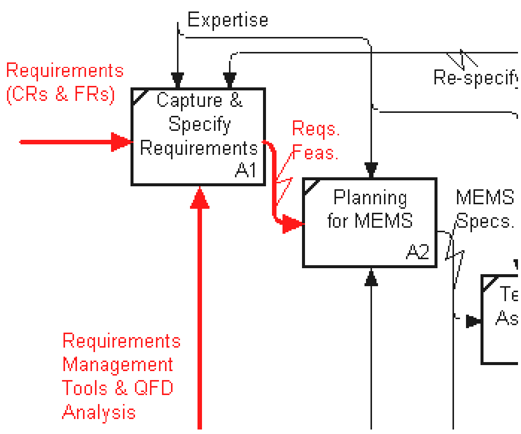


Figure 5-6: Analysing the requirements feasibility

Repetitive processes in the existing MEMS development process as highlighted by the As-Is model (Figure 4-8: Reiterative process loops) have been reduced to two in the To-Be model compared to the six in the current development process (As-Is).

The two remaining development iterations *re-specify* and *reanalyse* are highlighted in Figure 5-7. As described in the previous section, the technology assessment activity (A3) assesses the requirements feasibility and MEMS specification based on technological limitations to verify if the requirements can be fulfilled and if they cannot, they are re-specified according to available MEMS technologies and known parameters. Reanalyse loop from activity A7 returning back to the design analysis activity (A6) is required for devices such as the microfluidic MEMS devices due to the unavailability of physical predictive fluid models as the sizes of the microchannels are dependant on the viscosity of the fluid.

The development process for microfluidic devices is limited to the physical data obtained from literature by physical experimentation in fluid flow and blood flow in the channels. Attempts are being made to gain an understanding of the physical principles of the fluids from the actual data. This data is then used to design the microfluidic circuit. Analysing the rheology (studying the flow of blood) such as the viscosity of the fluid against the shear rate and using numerical analysis for quantification is performed at activity A6 and this can require iteration. This is also verified by Alting *et al*, (2003) whereby the chemistry, biology and flow mechanics all influence the design of the product (microfluidic device) and thereby the fabrication of the product.

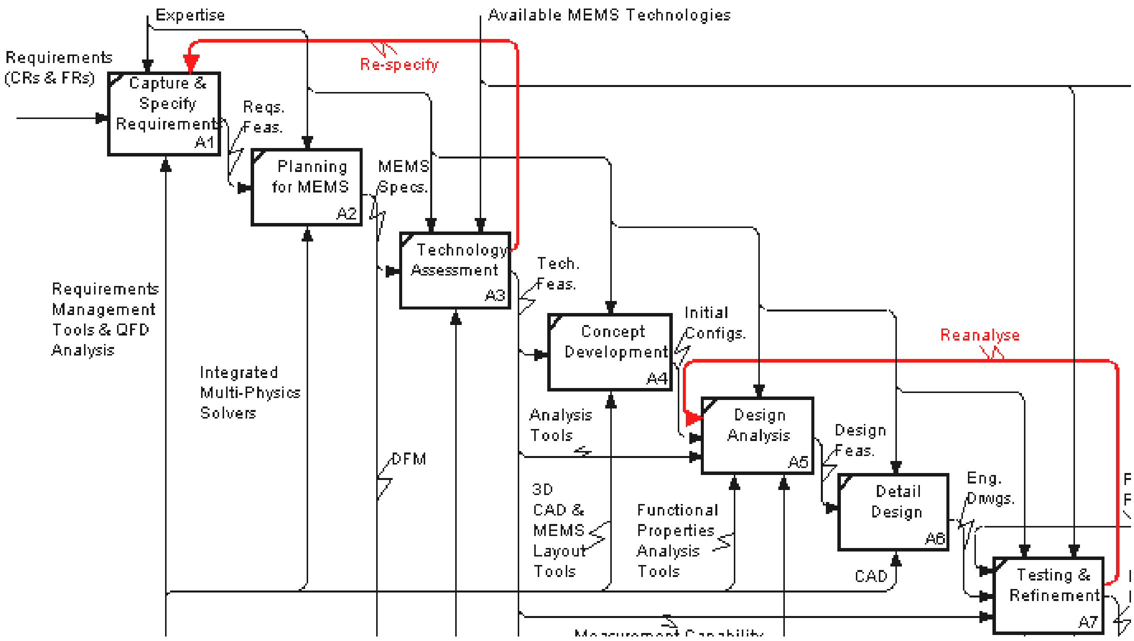


Figure 5-7: Proposed model development iterations

Integrating concurrent engineering principles into the area of MEMS would require for the MEMS experts to develop multiple concepts during the concept development stage (A4) and select the appropriate design option quickly and accurately based on the correct requirements and available MEMS technologies. Developing many concepts in the beginning stages of development allows for the MEMS experts to evaluate the different design options simultaneously before selecting the final concepts for further development and finally prototype production.

This provides the experts with knowledge of tested device parameters, although they may not be relevant to the chosen concept, but could be used for future devices. Consequently, the development of multiple concepts and concurrent approach to the MEMS development reduces the repetitive redesign loops and reduces the development time which resulted from the trial and error approach to develop and evaluate a single concept at a time. Analysis of the measurement and process capabilities in the beginning stages of development (A3) also reduces the design iterations as the process and measurement limits have been assessed prior to fabrication which provides the experts and practitioner’s information on what can be produced and the limitations of production and measurement equipment.

5.3. Improvements Provided by the To-Be Model

The improvements provided by the proposed To-Be model for future MEMS development compared to the existing development process (As-Is) have been summarised below:

- Addition of a ‘Technology Assessment’ activity (A3) in the MEMS development process to analyse the feasibility of tools, technology and equipment available for MEMS development
- Consideration for manufacturing, packaging and assembly using concurrent engineering principles such as DFM, early on in the development process reducing design iterations

- Reduction of the amount of design *reiterative process loops*, and introduction of prototype production runs using DOE to statistically analyse the design and production variables
- Use of requirements management tools to capture and elicit the specific requirements, and QFD to analyse the requirements feasibility
- Structured model illustrating the development process for generic MEMS devices with consideration for manufacturing, utilising tools and techniques commonly used in the engineering and manufacturing areas

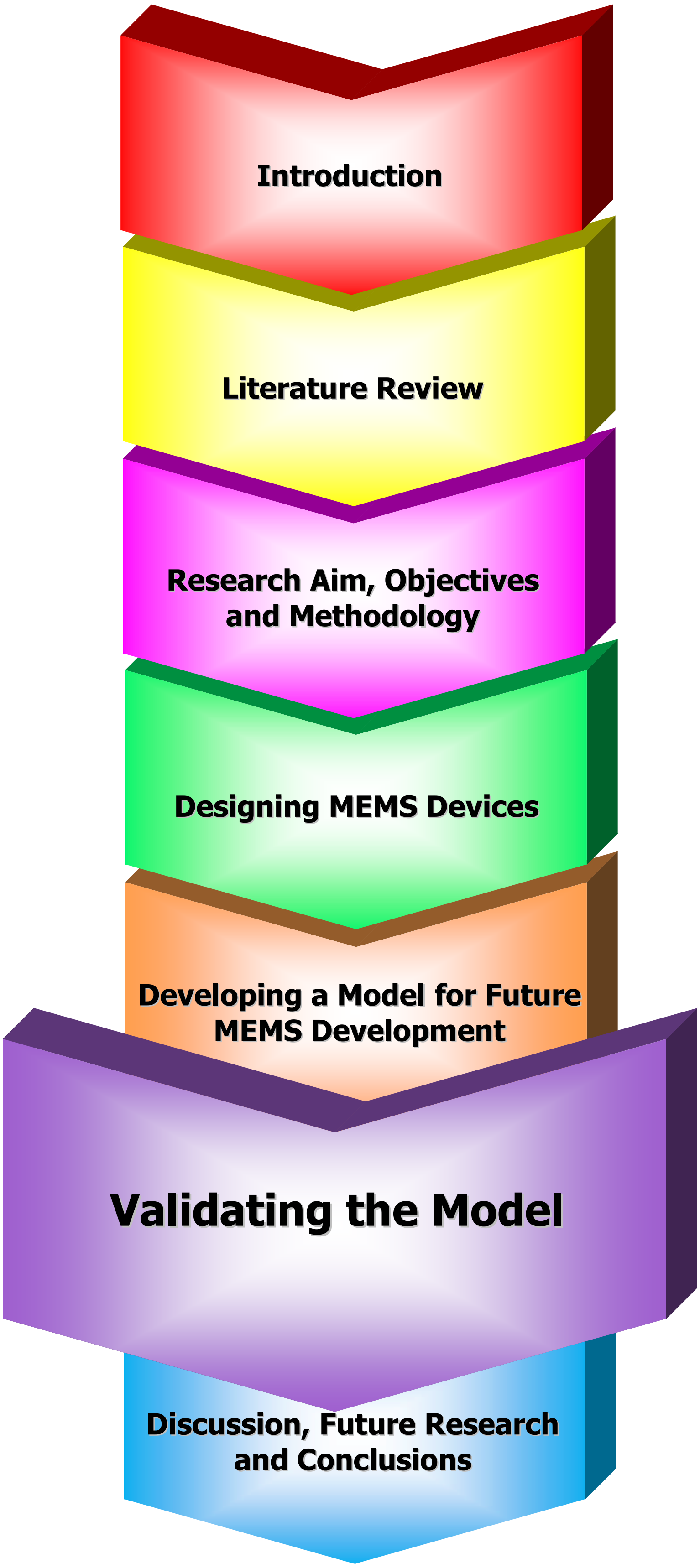
5.4. Summary

This chapter has detailed the implementation of the identified areas of improvement, described in the previous chapter, into the proposed To-Be model for future MEMS development. A generic product development process including design tools and techniques from the engineering and manufacturing have been adapted and applied to the generic model proposed for future MEMS development with additional activities. Concurrent engineering principles identified in the literature review chapter have been integrated into the MEMS development process utilising techniques such as DFM and DOE to consider manufacturing of MEMS and reduce the number of prototype models eliminating the current trial and error approach to MEMS development.

Changes to the existing MEMS development process have been explained in this chapter such as the inclusion of prototype modelling and pre-production ramp up before fabricating the MEMS devices, and incorporating QFD analysis and requirements management tools to capture, elicit and analyse the requirements feasibility. Improvements provided by the proposed To-Be model have been identified and summarised.

The following chapter defines the validation process for the proposed To-Be model to confirm its validity for MEMS development. Feasibility of the proposed model and the accuracy of the modelling technique are verified by the design and MEMS experts.

Chapter 6



Introduction
Literature Review
Research Aim, Objectives and Methodology
Designing MEMS Devices
Developing a Model for Future MEMS Development
Validating the Model
Discussion, Future Research and Conclusions

6. Validating the Model

The previous chapter proposed a theoretical model for the future development of generic MEMS devices. The To-Be model incorporated the identified areas of improvement into the MEMS development process by use of design tools and techniques from the engineering and manufacturing areas. Changes to the existing MEMS development process, illustrated by the As-Is model, were explained and the areas of improvement provided by the proposed To-Be model have been discussed.

Validation of the model, as presented in this chapter, consists of validating the theoretical model for its feasibility when developing MEMS devices, accuracy in reflecting the development process with the IDEF0 modelling technique, further enhancement of the To-Be model, and to verify if the model can be applied to the physical development of future MEMS devices. The following sections describe the validation process of the proposed model deployed by the research.

6.1. Validation Process

Validation of the To-Be model, proposed in the previous chapter, has been performed with an expert who is leading the research into design optimisation (product, process and multi-objective optimisation using evolutionary computing) within the Department of Manufacturing at Cranfield University, and a MEMS expert (senior research fellow) who is a chartered engineer (*CEng*) and a chartered scientist (*CSci*) from the Microsystems and Nanotechnology Centre at Cranfield University. A semi structured questionnaire (Appendix D: MEMS Model Validation Questionnaire) consisting of the following five questions was devised to address the model's feasibility for MEMS development:

V1. *Is the proposed model feasible for the development of generic MEMS devices?*

V2. *Are there any activities or elements in the model that are not feasible?*

V3. *Does the IDEF0 modelling technique accurately reflect the generic MEMS development process?*

V4. *Can the To-Be model be further enhanced or decomposed to accommodate the diverse MEMS device types?*

V5. *Can this model be applied to the physical development of MEMS devices with consideration for manufacturing?*

Responses to the specified questions (V1 – V5) provided by the domain experts were documented and have been summarised in the following sections.

6.1.1. Feasibility of the Model for MEMS Development

In response to the questions related to the feasibility of the To-Be model (V1 and V2), both experts agreed that the proposed model is feasible for the development of generic MEMS devices. Additional activities bespoke to MEMS combined with the generic product development process from the engineering and manufacturing domains, provides the MEMS community with a model that considers the manufacturing of MEMS devices without an ad-hoc approach. Manufacturing is now considered earlier in the MEMS development process.

Elements in the model that may not be feasible included additional resources may be required at the 'Technology Assessment' (A3) activity to perform the activity in order to conduct the assessment. Although requirements management tools have been stated as mechanisms for the 'Specify and Capture Requirements' activity (A1), new requirements management tools are currently in development for MEMS.

6.1.2. Accuracy of Modelling Technique

Responding to question V3 which addressed the accurate reflection of the modelling technique for MEMS development, both experts agreed that the IDEF0 process modelling technique accurately reflected the MEMS development process for the As-Is model and the proposed To-Be model. The advantages provided by the modelling technique are the graphical representation of the individual activities including the inputs and outputs from each, and the capability to recognise the process constraints and physical resources required to perform the activities. Another major advantage provided by the IDEF0 technique is its ability to decompose the model into sub activities which could prove useful for future analysis and further development.

6.1.3. Further Enhancement of the To-Be Model

Both of the experts confirmed that the To-Be model could be further enhanced by decompositions which would take into account the different MEMS device types. Introduction of activities and elements which are bespoke to the different MEMS device types as sub decompositions for example, a top level generic framework as illustrated by to the To-Be model then additional lower level processes which utilise the various MEMS technologies and tools for the diverse MEMS types.

Further decomposition of the model would provide ‘real value’ to the MEMS community using the IEDF0 modelling technique due to the accurate visualisation of the development process inputs, outputs, controls and mechanisms. Use of this technique can be used to create future bespoke models and for further analysis and consequent process improvements.

6.1.4. Applying the Model to Physical MEMS Development

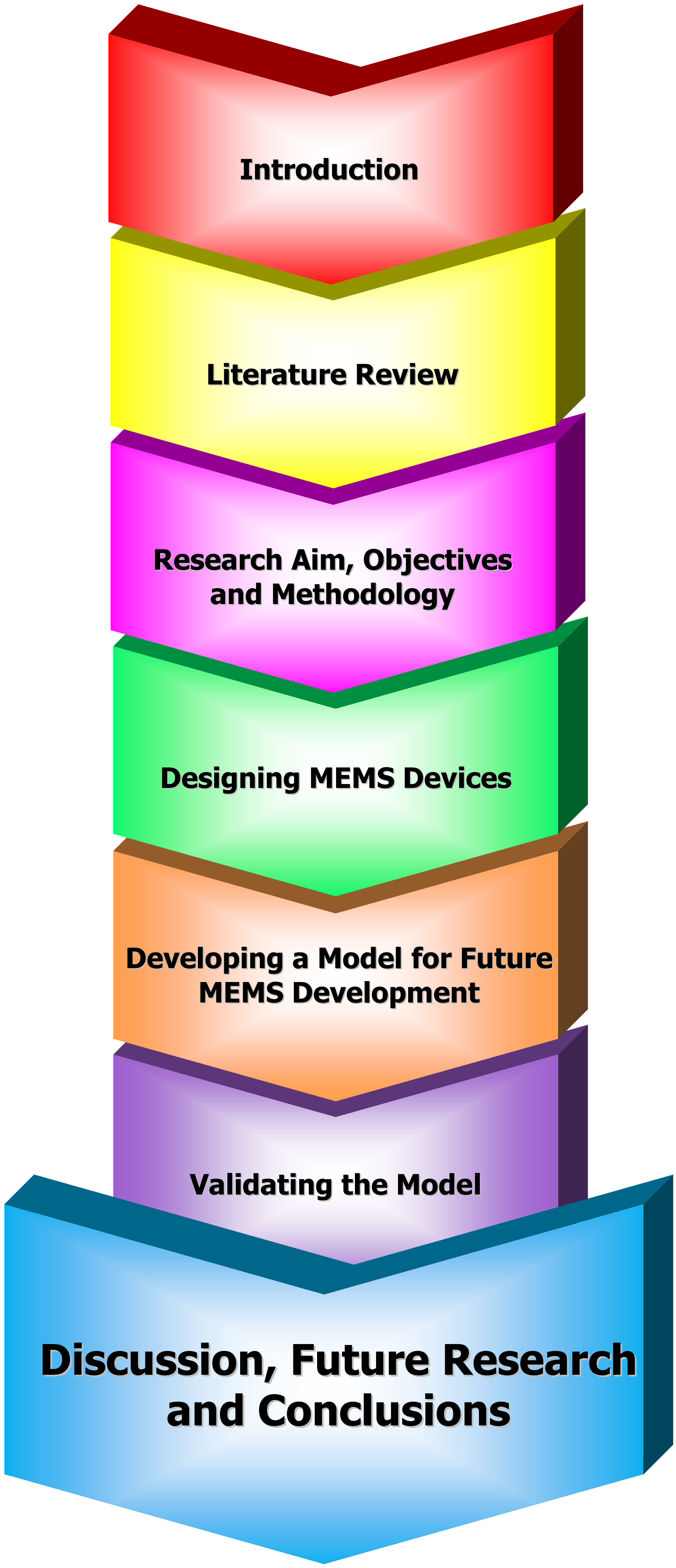
Question V5 queried if the proposed To-Be model could be applied to the physical development of MEMS devices. The experts stated that it would be possible to apply the model to develop generic MEMS devices. However, the model would require testing in a ‘real’ physical environment with actual MEMS devices with different applications (microfluidic devices, accelerometers, sensors). The integration of concurrent engineering principles such as DFM in the MEMS development process would also ease the manufacturability of MEMS and reduce the development time.

6.2. Summary

The validation of the model presented in this chapter has described the process deployed for validating the proposed model for future MEMS development. The theoretical model has been validated for its feasibility when developing MEMS devices, accuracy when reflecting the MEMS development process using the IDEF0 modelling technique, possible further enhancements of the To-Be model, and to verify if the model is valid when physically developing MEMS devices. Validation of the model has been performed by experts in the areas of design and MEMS using a semi structured questionnaire. The responses to the questions, which have addressed the proposed model's feasibility, provided by the domain experts have been summarised in this chapter confirming the validity of the proposed model for future MEMS development.

Validation of the proposed To-Be model has fulfilled the final objective of the research which was previously defined in chapter 3. The existing MEMS development practices have been captured, analysed and a new model using the IDEF0 methodology has been proposed for future MEMS development and has been validated by experts in the areas of design and MEMS. The following chapter concludes with the findings from the research discussing the review of literature, current MEMS design practices, identified areas of improvement to the existing MEMS development process, and a model for future MEMS design. Contributions made by the research are summarised including the limitations and areas of future research.

Chapter 7


Introduction
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7. Discussion, Future Research and Conclusions

The previous chapter detailed the validation process of the proposed To-Be model for future MEMS development. The process deployed for validating the theoretical model for its feasibility when developing MEMS devices and accurate reflection of the MEMS development process was presented. Responses from the domain experts using a semi structured questionnaire to validate the model were summarised and discussed.

Findings from the research including the review of literature, existing MEMS design practices, areas of improvement identified by the research resulting in the development of a model proposed for future MEMS development are discussed in this chapter. The three main areas of contribution made by the research are presented which also includes the research limitations. Finally, the conclusions are described which are related to the objectives defined in commencing chapters of this thesis.

7.1. Findings of the Research

This section targets the main findings from the results achieved by the research aligned with the objectives defined in chapter 3.

7.1.1. Review of Literature

The literature review highlighted the requirement of a structured design methodology for the MEMS community. The decreased pace in the MEMS development process was described as being caused by; the interaction and integration of the multi-physics involved, the novelty of approaches taken and more importantly, the lack of standard design methodologies for MEMS product development. However, none of the available literature reviewed had deployed the IDEF0 modelling technique to model the MEMS development process which provides graphical representation of the existing development activities including recognition of the constraints and identification of areas of improvement of the existing process which can be used to develop improved development models. The MEMS design process was identified by the literature to be generally performed with a trial and error approach which requires several iterations that is time consuming and costly. This was stated as a non ideal design methodology that is ineffective and inefficient for commercial MEMS product development.

The DFX approach has accentuated the consideration of the new and evolving design targets in the engineering and manufacturing domains. DFX approaches taken in the engineering and manufacturing sectors have showed great advantages for companies by assisting them to be able to meet the customer's requirements better, reduction in the time to market for products, and reduced total life cycle cost. Utilising the DFM approach in MEMS production can result in a higher device yield and the time taken to ramp up to volume production is significantly reduced.

7.1.2. Current MEMS Design Practices

From the literature reviewed and MEMS domain experts interviewed, several authors and MEMS experts confirmed that the current MEMS technology is based on older design tools borrowed from the microelectronics domain and fabricated on a trial and error approach, and that designing a process flow and corresponding device layout for MEMS devices relies on MEMS experts' experience and prior knowledge gained from similar devices and familiar design and fabrication tools. This was reflected by the As-Is model for MEMS development modelled using the IDEF0 technique to graphically represent the existing development process.

Use of the IDEF0 process modelling tool to duplicate the existing MEMS development practices (As-Is model) as performed by the experts and practitioners, provided a descriptive representation of the generic MEMS development process as a collection of hierarchical activities with individual constituents. The As-Is model illustrated the current MEMS development flow including the factors which constrain the individual activities and the elements required to ensure the successful output from each activity.

7.1.3. Recognise Constraints and Identify Areas of Improvement

Analysis of the As-Is model using the IDEF0 technique, revealed the development process constraints and limitations and eventual identification of the areas of improvement in the existing MEMS development process based on the literature reviewed in chapter 2. The following areas for improvement were then incorporated in the To-Be model for future MEMS design:

1. Managing MEMS requirements
2. MEMS manufacturing considerations
3. Reduction of development iterations
4. Design methodology and technology assessment for MEMS

7.1.4. Proposed Model for Future MEMS Development

Proposing a model for future MEMS design, which incorporates design tools and techniques from the engineering and manufacturing domains, was achieved based on the identified areas of improvement described in the previous section. A generic product development process including design tools and techniques from the engineering and manufacturing was adapted and applied to the generic model proposed for future MEMS development (To-Be) with additional bespoke activities.

Concurrent engineering principles identified in the literature review chapter were integrated into the MEMS development process utilising techniques such as DFM and DOE to consider the manufacturing of MEMS earlier on including the packaging and assembly, and to reduce the number of prototype models eliminating the current trial and error approach to the MEMS development. Changes to the existing MEMS development process include the inclusion of prototype production modelling, pre-production ramp up elements and QFD analysis to analyse the requirements feasibility, which reduce the design and development iterations, as highlighted by the As-Is model, due to the trial and error approach used by the MEMS experts to develop MEMS.

7.1.5. Validation of the To-Be Model

The findings from the validation of the To-Be model, performed by the design and MEMS domain experts, have verified the theoretical models feasibility for physically developing MEMS devices, accuracy of the To-Be model in reflecting the development process using the IDEF0 modelling technique, the To-Be model could be further enhanced, and that the proposed model could be applied to the physical development of future MEMS devices.

In order to apply the model generically, testing of the To-Be model would be required with physical MEMS devices using the model to develop different MEMS devices with different applications in a ‘real’ physical environment. Finally, a new model using the IDEF0 methodology has been proposed for future MEMS development validated by experts in the areas of design and MEMS.

7.2. Research Contribution

The research has contributed significantly by capturing the existing generic MEMS development process and representing this in an As-Is model using the IDEF0 modelling technique used widely in the engineering and manufacturing domains. Constraints and limitations in the existing development process were recognised by analysis of the As-Is model and areas of improvement were identified. The following points recapitulate the contribution made by the research:

I. Captured the existing MEMS design practices including the current tools and techniques in a graphical model (As-Is)
II. Recognised the constraints and limitations of the current MEMS design and development methods using the IDEF0 modelling technique
III. Proposed a theoretical model for the development of future MEMS devices which has been validated by design and MEMS experts

The literature review identified that there is a lack of structured models for generic MEMS development, but none of the sourced literature has used the IDEF0 technique to model the MEMS development process which showed a hierarchical view of the whole development process as a decomposition of structured activities. Utilisation of the IDEF0 methodology to illustrate the existing MEMS development process and proposed model for future development which integrates concurrent engineering principles such as DFM is a significant contribution.

7.3. Research Limitations

Two main limitations have arisen; from the proposed To-Be model for future MEMS development and the research itself.

Limitations encountered with capturing the current MEMS development practices have included a requirement for a higher number of experts and practitioners to develop the As-Is model and validate the proposed To-Be model. More experts from different MEMS backgrounds to decompose the To-Be model into further child decompositions would have proved advantageous for the research and proposed model for MEMS development. This would have allowed for the capturing of existing MEMS practices for many diverse MEMS device types. Although the lack of experts involved with the research has been highlighted, keeping in scope with the research timeframe, the experts and practitioners contribution to this research has proved successful.

Not testing the proposed theoretical model to actual MEMS device types, provided limitations to the validation process regarding the applicability of the model. Responses from both experts during the validation process explained how it would be possible to apply the model to develop generic MEMS devices, but the model would require testing in a 'real' physical environment with actual MEMS devices with different applications. The timeframe in which the research has been conducted has also limited; the development of the To-Be model which can now be further decomposed, collaboration with more MEMS experts, validation of the model performed by experts from different

MEMS backgrounds, and physical testing of the model with different MEMS device types and further enhancing the model to suit the various complex micro machines.

7.4. Areas of Future Research

Limitations faced by the research, as described in the previous section, can be reduced and eliminated through future research into the areas of design and MEMS development for different applications. Improvements and future developments are presented in this section.

The generic top level view of the MEMS development process for future devices can be enhanced by further decompositions which incorporate the diverse MEMS device types. This would provide the MEMS community with a comprehensive structured framework for developing MEMS devices for various applications, with a set of models that use engineering and manufacturing design methodologies to manufacture MEMS devices from the initial requirements capture stage through to MEMS production. The model, developed using the IDEF0 technique, can be tested and refined further by applying it to the physical development of MEMS devices. The literature review identified that some work has been performed in DFM applications which integrate concurrent engineering applications to the MEMS development process however, the design for MEMS or DFMEMS as a standalone methodology does not yet exist. Future research could contribute to the development of such a methodology.

Future research into the introduction of product development success factors, metrics to measure the different stages of MEMS product development, would provide a way of measuring the output from each activity (development stage) with defined measures. Work in this area has been published and is available which would prove useful for the MEMS community to measure the success of the MEMS product development at each individual stage before proceeding onto the next. The author has experience in the area of introducing measures for product development success to a prestigious automotive manufacturer in the U.K.

7.5. Conclusions

This section addresses the objectives and aim of the research which were presented in chapter 3. These are discussed sequentially to verify how this thesis has fulfilled each of the stated objectives and therefore accomplishing the main research aim.

The following research questions defined chapter 3 have been answered successfully:

- *What are the current design methodologies applied in generic product design and development with emphasis on engineering and manufacturing?*
  - Section 2.3 answered this question and presented the generic product development process defined by Ulrich and Eppinger (2008). Concurrent engineering principles and design methodologies such as DFX were identified as the proven methods used in the engineering and manufacturing areas when developing products.
- *Are the MEMS community aware of these methodologies used in the field of design?*
  - DFX approaches, such as DFM, have been applied to two MEMS devices and corresponding processes by Da Silva *et al*, (2002) and Schröpfer *et al*, (2004); on CMOS compatible metal nitride surface micromachining for a variable capacitor, and a DRIE (deep reactive ion etching) based SOI micromachining process for a comb drive resonator.
  - Interviews conducted with the MEMS experts showed that not all of the experts were aware of the QFD, DFX and DOE methodologies.
- *What are the current design tools and fabrication techniques used to develop MEMS devices?*
  - This question was answered by section 2.8.1 by the literature reviewed which described that the current MEMS technology is based on older design tools borrowed from the microelectronics domain and fabricated on a trial and error approach, and that designing a process flow and

corresponding device layout for MEMS devices relies on MEMS experts' experience and prior knowledge gained from similar devices.

  - Interviews conducted with the experts and development of the As-Is model has also illustrated the design tools currently used by the MEMS experts, and the existing development process using the IDEF0 modelling technique which was validated by two MEMS experts.

- *Are design methodologies such as DFX utilised when designing MEMS devices?*
  - Literature review identified, in section 2.8.3, the use of the more common design for 'x' (DFX) methodology DFM. Da Silva *et al*, (2002) and Schröpfer *et al*, (2004) introduced a generic framework and applied the DFM principles using case studies on two MEMS devices and fabrication processes. Their research concluded that using the DFM approach in MEMS can result in a higher yield and the time taken to ramp up to volume production is significantly reduced.
- *Can the DFX methodological approach be adapted and applied to the designing and manufacturing of MEMS devices?*
  - The literature review and the answer to the previous question assist in answering this question. Da Silva *et al*, (2002) and Schröpfer *et al*, (2004) applied the DFM approach to MEMS using two case studies and clearly stated that an important factor in enabling the effective design and maximising the probability of first pass success, while reducing the development time and cost of MEMS, is to have the materials properties and process information available early on in the design process.
  - Generic product development process has been adapted to integrate DFM for the MEMS development in the proposed To-Be model in section 5.1.

The first objective, to identify design methods for generic product development processes including DFX methodologies used in the engineering and manufacturing domains, was fulfilled by the literature reviewed in chapter 2 and is summarised below:

- Due to the increasing customer requirements, new scientific approaches to design are being taken.

- Generic product development process comprising of six defined phases was identified and the individual phases consisting of; planning, concept design, system-level design, detail design, testing and refinement, and production ramp up, were described.
- DFX methodologies including DFM and DFA have arisen due to the need from the mechanical engineering and manufacturing sectors to lower manufacturing costs without the quality of the product being affected.
- The development of DFX methodologies, such as DFD, DFR, DFE, and DFLC have been created to address the growing issues surrounding the environmental impacts caused by product designs including the generated waste and use of natural resources.
- DFX approaches applied in the engineering and manufacturing sectors have showed great advantages in being able to meet the customer's requirements better, reduced in the time to market for products, and reduced total life cycle cost.

The second objective, to capture the current MEMS design practices (As-Is model) including tools and techniques, has been achieved by identifying the current MEMS development practices from the available literature, as described in section 2.8, and semi structured interviews with the MEMS domain experts. The following statements conclude the fulfilment of this objective:

- The data collection approach consisted of semi structured interviews to capture the current design practices from the experts, including the selection of an appropriate modelling tool to graphically represent the existing development process in the form of an As-Is model, was presented in chapter 4 of this thesis.
- A matrix which defined the criteria for selecting the most suitable modelling tool was presented which emphasised the attributes of the IDEF0 methodology to be the most appropriate for developing the As-Is model. This methodology also allowed for the analysis of the existing MEMS development process (As-Is) whereby constraints to the current MEMS development process were identified.

- An illustrative representation of the current generic MEMS development process as a collection of hierarchical activities was illustrated by the As-Is model. The decomposition of the context activity, as described by the IDEF0 methodology, was performed to divide the main activity, ‘Developing a Model for MEMS Development’, into constituent activities that corresponded to the sequential MEMS development phases.

The third objective, to recognise the constraints and limitations of the current MEMS design methods, was successfully met from analysing the existing development process graphically represented by the As-Is model, information obtained from the conducted interviews and literature reviewed from where the following are concluded:

- Restrictions in the MEMS development process include the controlling each of the development phases by the experts which in itself is a demanding task. The experts use specific design tools and techniques that they are comfortable with and have knowledge of.
- The interaction of the MEMS experts at each of the development stages signifies that the MEMS development processes are devised by the experts with an *ad-hoc* approach due to the lack of physical predictive models therefore the development is based on the known process restrictions of the available technologies, as responded by the experts.
- Devices that are developed using a ‘trial and error’ approach, cause major restrictions in the development process due to the time taken in redesign and redevelopment activities as illustrated by the As-Is model in section 4.4.4.
- Literature identified that there is a lack of structured methodologies and available software modelling tools to model the many diverse properties of MEMS at the micro scale.
- Analysis of the As-Is model revealed areas of improvement to the existing MEMS development process illustrated by the As-Is model which were considered for the development of the proposed To-Be model.

The fourth objective, to propose a 'To-Be' model for future MEMS development, was achieved by the incorporating the identified areas of improvement in section 4.4.5 into the future model for MEMS development by use of the IDEF0 methodology which accommodates the creation of To-Be models based on its ability to graphically represent the process constituents. The following points contribute to accomplishing this objective:

- A generic product development process including design tools and techniques from the engineering and manufacturing, identified from the literature review, was adapted and applied to the generic model proposed for future MEMS development with additional activities bespoke to the MEMS domain.
- Concurrent engineering principles identified in the literature review chapter were integrated into the To-Be MEMS development process utilising techniques such as DFM and DOE to consider manufacturing of MEMS and reduce the number of prototype models eliminating the current trial and error approach to MEMS development.
- IDEF0 was selected as the chosen modelling tool based on one of the chosen criterion which was its ability to analyse existing processes (As-Is) with the objective of further improvement (To-Be).

The fifth objective, to validate the research conducted with experts in the area of MEMS, was achieved by using a semi structured questionnaire to validate the theoretical model for its feasibility when developing MEMS devices. The validation process consisted of addressing the following areas in order to fulfil this objective:

- Feasibility of the model for MEMS development
  - Expert's agreement of the proposed models feasibility for the development of generic MEMS devices. Additional activities bespoke to MEMS combined with the generic product development process from the engineering and manufacturing domains, provide the MEMS community with a structured model which considers the manufacturing of MEMS devices earlier on in the development process.

- Accuracy of the modelling technique
  - The IDEF0 process modelling technique used for the development of the As-Is and To-Be models accurately reflects the MEMS development process. The advantages provided by the modelling technique are the graphical representation of the individual activities including the inputs and outputs, and the capability to recognise the process constraints and physical resources required to perform those activities.
- Further enhancement of the To-Be model
  - To-Be model could be further enhanced by specific decompositions which would take into account the different MEMS device types and corresponding technologies and tools. Further decompositions for various MEMS devices, in the model would provide ‘real value’ to the MEMS community using the IEDF0 modelling technique due to the accurate visualisation of the development process.
- Applying the model to physical MEMS devices
  - It would be possible to apply the model to develop generic MEMS devices but the model would require testing in a ‘real’ physical environment with actual MEMS devices for different applications.

Finally, the main aim of this research, to capture the existing MEMS design practices and propose a model for future MEMS development, was accomplished by fulfilment of the objectives defined in chapter 3 and discussed in this chapter.

References

Alting, L., Kimura, F., Hansen, H. and Bissacco, G. (2003). *Micro Engineering*. CIRP Annals - Manufacturing Technology, vol 52, issue 2, (2003). p. 635-657.

Antonsson, E. (1996). *Structured Design Methods for MEMS, Final Report, A Workshop Sponsored by the National Science Foundation, Pasadena, CA.* (http://www.design.caltech.edu/NSF_MEMS_Workshop/)

Bao, M. (2005). *Analysis and Design Principles of MEMS Devices.* Elsevier, ISBN: 0-444-51616-6.

Booker, R. and Boysen, E. (2005). *Nanotechnology for Dummies.* Wiley Publishing Inc, ISBN: 0-7645-8368-9.

Boothroyd, G., Dewhurst, P. and Knight, W. (1994). *Product Design for Manufacture and Assembly.* Marcel Dekker, ISBN: 0-8247-9176-2.

Brück, R., Hahn, K., Popp, J., Schmidt, T., Wagener, A. and Wahl, M. (2006). *A MEMS-EDA-Methodology Based On Process Management.* Proceedings from the International Conference on Mixed Design (MIXDES), Gdynia, Poland. p. 198-201.

Calis, M. and Desmulliez, M. (2006). *Haptic Technologies for MEMS Design.* Journal of Physics: Conference Series, 34 (2006), p. 72-75.

Chen, H. and Mukherjee, S. (2006). *Modeling of the ground plane in electrostatic BEM analysis of MEMS and NEMS*. Engineering Analysis with Boundary Elements, vol. 30, p. 910–924.

Da Silva, M. G., Giasolli, R., Cunningham, S. and Deroo, D. (2002). *MEMS Design for Manufacturability (DFM).* Proceedings from the Sensors Expo & Conference, Boston, M.A.

Deb, K. (2001). *Multi-objective optimization using evolutionary algorithms*. John Wiley, New York, USA.

Fan, Z., Wang, J., Achiche, S. Goddman, E. and Rosenberg, R. (2008). *Structured synthesis of MEMS using evolutionary approaches.* Journal of Applied Soft Computing, 8 (2008), p. 579-589.

Fedder, G. (1999). *Structured Design of Integrated MEMS.* Micro Electro Mechanical Systems, 1999. MEMS '99. Twelfth IEEE International Conference, Orlando, FL, USA. p. 1-8.

Fedder, G. and Jing, Q. (1999). *A Hierarchical Circuit-Level Design Methodology for Microelectromechanical Systems.* IEEE Transactions on Circuits and Systems-II Analog and Digital Signal Processing, Vol. 46, No. 10, (1999). p. 1309-1315.

Fedder, G. (2000). *Top-Down Design of MEMS.* Proceedings of the 2000 International Conference on Modelling and Simulation of Microsystems Semiconductors, Sensors and Actuators (MSM' 00), San Diego, CA. p. 7-10.

Feynman, R. P. (1961). *There's Plenty of Room at the Bottom, in Miniaturization*. Reinhold Publishing, New York. p. 282-296. Cited in: Gad-el-Hak, M. (ed). (2006a). MEMS: Introduction and Fundamentals, The MEMS Handbook, Second Edition. CRC Press, p. 1-4.

Fiksel, J. and Wapman, K. (1994). *How to design for environment and minimise life cycle cost.* IEEE symposium on Electronics and the Environment, San Francisco, CA, U.S.A, May.

Flores, M. (2007). *Knowledge Management Course*. Linkingnets. Knowledge Acquisition and Creation Module. Cranfield University.

Gad-el-Hak, M. (2006a). *MEMS: Introduction and Fundamentals, The MEMS Handbook, Second Edition.* CRC Press, ISBN: 0-8493-9137-7.

Gad-el-Hak, M. (2006b). *MEMS: Design and Fabrication, The MEMS Handbook, Second Edition.* CRC Press, ISBN: 0-8493-9138-5.

Garcia, V. L., Akinwande, A. and Sanchez, M. M. (2007). *Precision Hand Assembly of MEMS Subsystems Using DRIE-Patterned Deflection Spring Structures: An Example of an Out-of-Plane Substrate Assembly*. Journal of Microelectromechanical Systems, Vol. 16, No. 3, (2007), p. 598-612.

Gurav, S.P., Goosen, J.F.L. and vanKeulen, F. (2005). *Bounded-but-unknown uncertainty optimization using design sensitivities and parallel computing: Application to MEMS*. Computers and Structures, vol. 83, p. 1134-1149.

Hall, J. S. (2006). *Nanofuture.* Manas Publications, ISBN: 81-7049-310-2.

Hubbard, T. and Antonsson, E. (1996). *Design of MEMS via efficient simulation of fabrication.* Proceedings of The 1996 ASME Design Engineering Technical Conference (96-DETC/DFM-1312) and Computers in Engineering, Irvine, California.

Hsu, T. R. (2008). *MEMS and Microsystems, Second Edition.* Wiley, ISBN: 978-0-470-08301-7.

Kota, S., Joo, J., Li, Z., Rodgers, S. and Sniegowski, J. (2001). *Design of Compliant Mechanisms: Applications to MEMS.* Journal of Analog Integrated Circuits and Signal Processing, 29, (2001). p.7-15.

Kuo, T., Huang, S. and Zhang, H. (2001). *Design for manufacture and design for 'X': concepts, applications and perspectives*. Journal of Computers and Industrial Engineering, 41 (2001), p. 241-260.

Lambert, A. and Gupta, S. (2005). *Disassembly Modeling for Assembly, Maintenance, Reuse, and Recycling*. CRC Press, ISBN: 1-57444-334-8.

Li, H. and Antonsson, E.K. (1998). *Evolutionary techniques in MEMS synthesis*. In: 25th Biennial Mechanisms Conference: ASME Design Engineering Technical Conferences (DETC), Atlanta, USA, 13-16 September.

Lindbeck, J. (1995). *Product Design and Manufacture.* Prentice-Hall, ISBN: 0-13-034257-2.

Mayer, R. J., Painter, M. K. and Dewitte, P. S. (1992). *IDEF Family of Methods for Concurrent Engineering and Business Re-engineering Applications.* Knowledge Based Systems Inc, 1992. (http://www.idef.com/pdf/IDEFFAMI.pdf)

Mukherjee, T. and Fedder, G. (1997). *Structured Design of Microelectromechanical Systems.* Proceedings of the 34th Design Automation Conference, 1997 (DAC97). p. 680-685.

Mukherjee, T. and Fedder, G. (1998). *Design Methodology for Mixed-Domain Systems-on-a-Chip.* VLSI '98. System Level Design. Proceedings. IEEE Computer Society Workshop. p. 96-101.

Mukherjee, T. (2003). *MEMS Design and Verification*. Proceedings from the International Test Conference, 2003, ITC 2003. Charlotte, NC, USA. p. 681-690.

Pahl, G. and Beitz, W. (1999). *Engineering Design, A Systematic Approach*, 2nd Ed. Springer, ISBN: 3-540-19917-9.

Ramsden, J. J. (2005). *What is nanotechnology?* Nanotechnology Perceptions, vol. 1, p. 3-17.

Reh, S., Lethbridge, P. and Ostergaard, D. (2000). *Quality Based Design for Reliability of Micro Electro Mechanical Systems (MEMS) Using Probabilistic Methods.* (http://www.ansys.com/industries/mems/mems-downloads/msm00_ansys_pds.pdf)

ReVelle, J. B. (2002). *Manufacturing Handbook of Best Practices.* St. Lucie Press, ISBN: 1-57444-300-3.

Roache, P.J. (1998). *Verification & validation in computational science and engineering*, Hermosa, New Mexico.

Schröpfer, G., McNie, M., Da Silva, M. and Davies, R. (2004). *Designing Manufacturing MEMS in CMOS Compatible Processes – Methodology and Case Studies.* Proceedings from the SPIE's Photonics Europe Conference – MEMS, MOEMS, and Micromachining, Strasbourg, France (2004).

Suh, N. P. (2001). *Axiomatic Design: Advances and Applications*. Oxford University Press, ISBN: 0-19-513466-4.

Suh, N. P. (1990). *The Principles of Design*. Oxford Series on Advanced Manufacturing. Oxford University Press, ISBN: 0-19-504345-6.

Thorpe, A. (2007). *The Designers Atlas of Sustainability*. Island Press, ISBN: 1-59726-100-9.

Tsai, C. Y., Kuo, W. T., Lin, C. B. and Chen, T. L. (2008). *Design and fabrication of MEMS logic gates.* Journal of Micromechanics and Microengineering, 18 (2008), p. 1-10.

Ulrich, K. and Eppinger, S. (2008). *Product Design and Development,* 4th Ed. McGraw-Hill, ISBN: 978-007-125947-7.

Vudathu, S. and Laur, R. (2007). *A Design Methodology for the Yield Enhancement of MEMS Designs with Respect to Process Induced Variations.* Proceedings of the 57th Electronic Components and Technology Conference, 2007. ECTC '07, Reno, NV, USA. p. 1947-1952.

Whatmore, R.W., Zhang, Q., Huang, Z. and Dorey, R.A. (2003). *Ferroelectric thin and thick films for Microsystems*. Materials Science in Semiconductor Processing, vol. 5, p. 65-76.

Xin, Z., Guangyi, S., Liang, R. and Guizhang, L. (2007). *On MEMS Design Automation.* Proceedings of the 26th Chinese Control Conference, 2007, Zhangjiajie, Hunan, China. p. 774-778.

Zha, X. and Du, H. (2003). *Manufacturing process and material selection in concurrent collaborative design of MEMS devices.* Journal of Micromechanics and Microengineering, 13 (2003), p. 509-522.

Zhou, N., Zhu, B., Agogino, A.M. and Pister, K.S.J. (2001). *Evolutionary synthesis of MEMS design*. In: Proceedings of the Artificial Neural Networks in Engineering, vol.11, ASME Press, USA, p. 197-202.

Zhu, M. and Kirby, P.B. (2006). *Design study of piezoelectric micro-machined mechanically coupled cantilever filters using a combined FE & microwave circuit analysis*. Sensors & Actuators A, vol. 126/2, p. 417-424.

Appendix A: Questionnaire for MEMS Experts and Practitioners

Aim

The main aim of this questionnaire is to capture the current design practices including the limitations utilised by MEMS experts and practitioners. The motivation for the research has arisen to distinguish if design methodologies such as *design for 'x'* (DFX) have been applied to the micro/nano domain and if not, could they be applied and what could be done to make them applicable and popular? In order to successfully identify and adapt the design methodologies which originate from the engineering and manufacturing domains, removal of constraints by identification of the MEMS design and fabrication processes are fundamental requirements. The motivation for the research has assisted in defining the main research aim which is to:

"Capture the existing MEMS design practices and propose a model for future MEMS development"

This questionnaire has been subdivided into five sections which are linked to the objectives as defined and highlighted in the following section.

Objectives

Collaboration with the practitioners and MEMS experts offers the necessary practical knowledge of MEMS design and fabrication techniques and the constraints and limitations faced when designing MEMS devices. The information captured from the experts and practitioners will also serve as a foundation when identifying the areas of improvement within the MEMS design process. To fulfil the main research aim; "Capture the existing MEMS design practices and propose a model for future MEMS development", it is necessary to divide the main aim into the following set of objectives:

- Identify design methods for generic product development processes including DFX methodologies used in the engineering and manufacturing domains
    - *Identify from literature review*
- Capture the current MEMS design practices (As-Is model) including tools and techniques
    - *Identification of practices from literature review*
    - *Semi structured interviews with MEMS experts and practitioners from industry*
- Recognise the constraints and limitations of the current MEMS design methods:
    - *Identify from literature review*
    - *Semi structured interviews with MEMS experts and practitioners from industry*
- Propose a 'To-Be' model for future MEMS development
- Validate the research conducted with experts in the area of MEMS

Exploitation of Findings

The main focal points of the research are; the identification of existing design tools and methodologies that have been utilised in the engineering and manufacturing domains and to examine if these can or have been applied in the design and fabrication of MEMS devices, and to perform an analysis which will identify the limitations encountered in MEMS design thus recognising the areas for improvement. Finally, it is intended to publish the results of the research in journal and conference papers where the topic will be introduced as the 'designing for functional microsystems' detailing the findings from the research and highlighting the areas of improvement for future MEMS design practices. The following findings from the research will be available on completion of the project:

1. Report on the design methodologies used in the engineering and manufacturing domains
2. Identification of the current MEMS design practices and design limitations
3. Recognition of the areas of improvement in the MEMS design process
4. A model for future MEMS design validated by experts in the MEMS area

A. MEMS Devices

A1. *What types of MEMS devices do you research?*

A2. *What are their intended applications?*

A3. *What type of MEMS components are required to perform the necessary functions?*

B. MEMS Design and Fabrication

B1. *Do you have a generic product development cycle for MEMS devices which includes the different development stages?*

B2. *What methods do you use to design and fabricate MEMS devices?*

B3. *Do the current methods support design iterations that may be required when developing MEMS devices?*

C. Tools and Techniques

C1. *What tools and techniques do you utilise to design and develop MEMS?*

C2. *Do the tools and techniques you use present any constrains or limitations to the development process?*

C3. *Have you considered the DFX design methodologies, such as Design for Manufacture (DFM) used in the engineering and manufacturing domains, when developing MEMS?*

D. Constraints and Limitations

D1. *What are the main limitations encountered when designing and developing MEMS devices?*

D2. *Are there any stages within the design process that constrain the further development of MEMS?*

D3. *How do you overcome obstacles in the development of MEMS devices?*

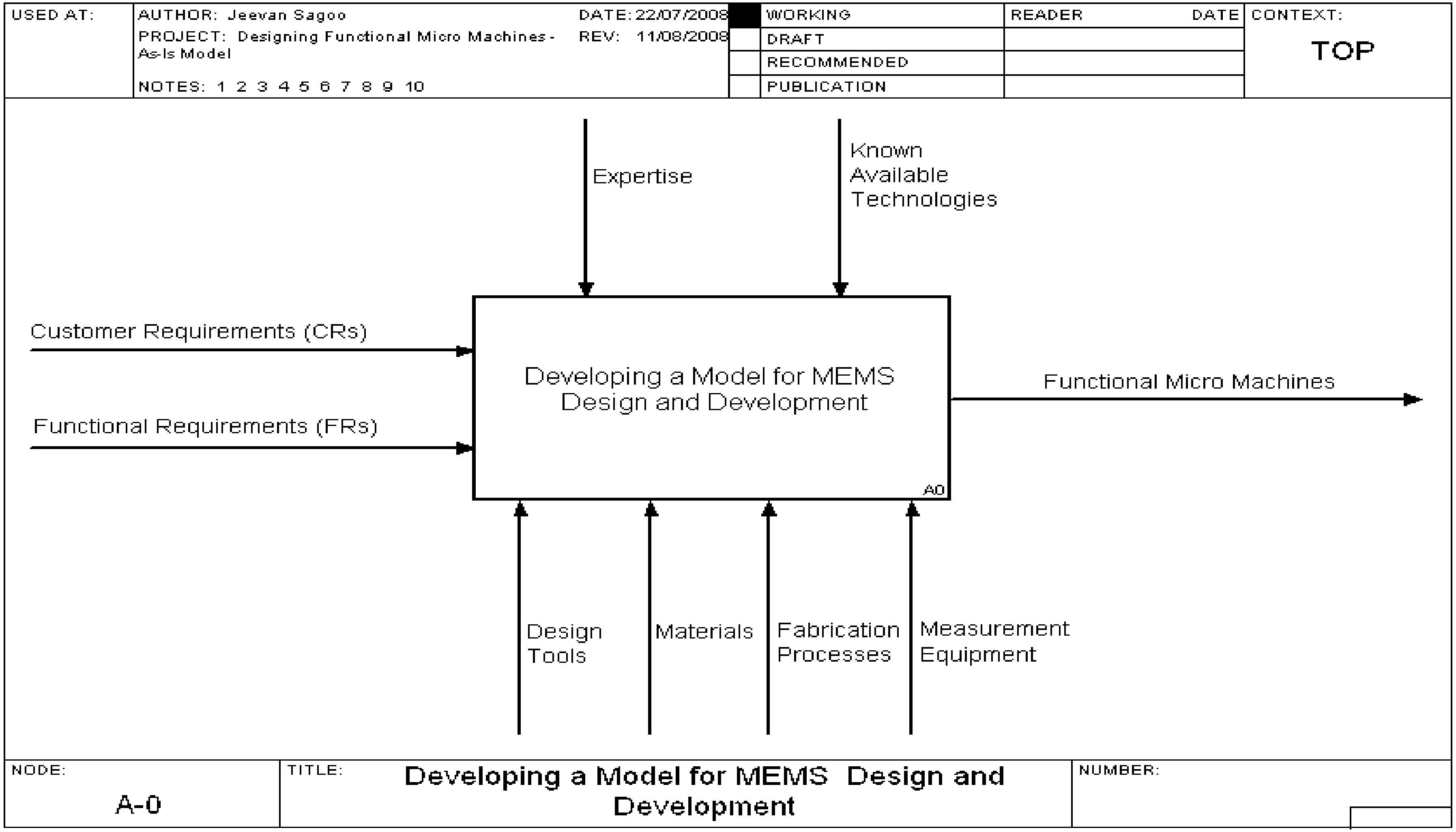
E. Future Improvements

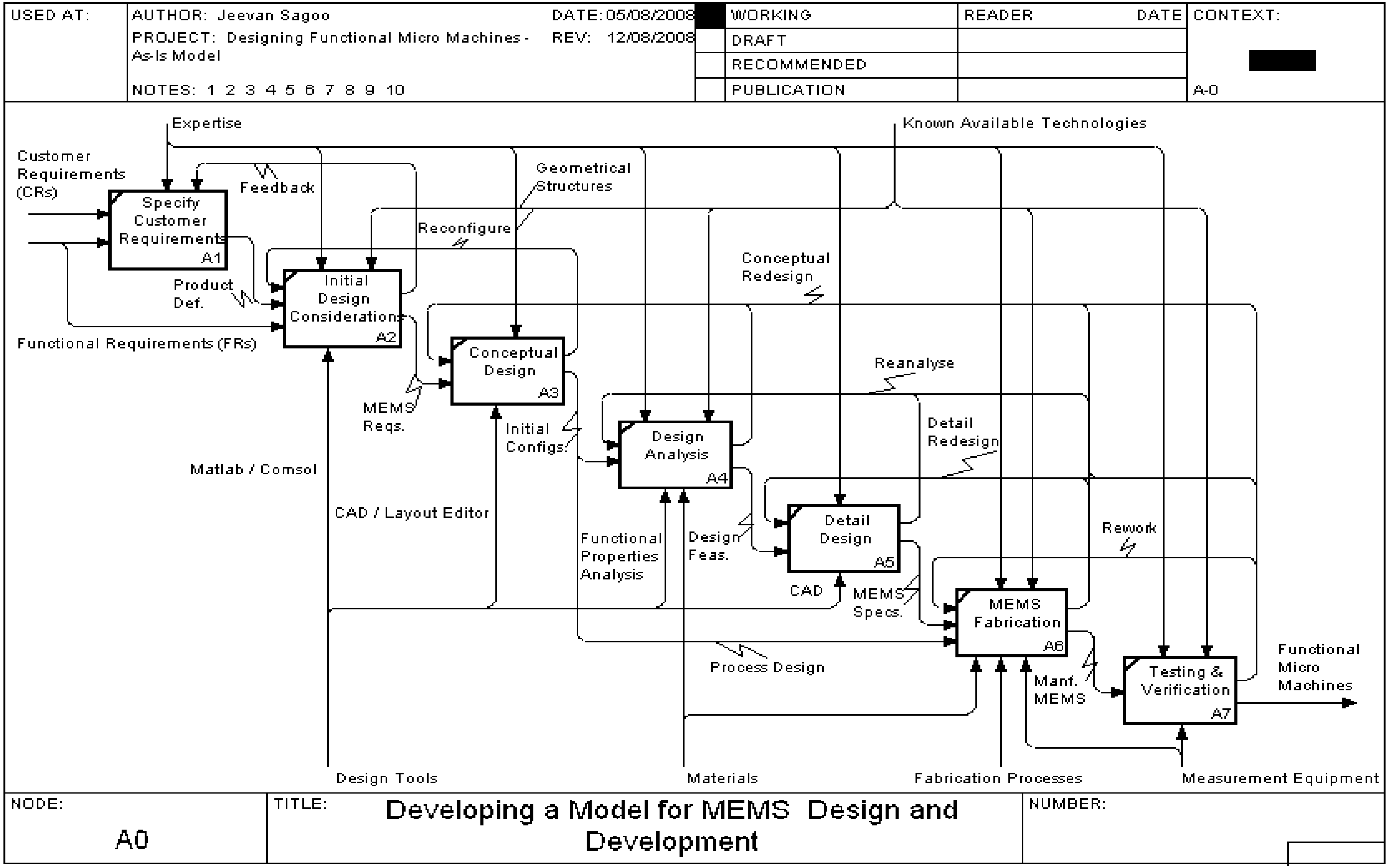
E1. *Are there additional tools or techniques required which could prove beneficial to yourself and the MEMS community?*

E2. *In your opinion, how could the development limitations and constraints be overcome or eliminated completely?*

E3. *Can you suggest any improvements to the current MEMS development process which would benefit future MEMS devices?*

Appendix B: As-Is Model

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AUTHOR: Jeevan Sagoo
DATE: 05/08/2008
REV: 12/08/2008
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DRAFT
RECOMMENDED
PUBLICATION
READER
DATE
CONTEXT:
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Expertise
Known Available Technologies
Customer Requirements (CRs)
Feedback
Geometrical Structures
Specify Customer Requirements
A1
Reconfigure
Conceptual Redesign
Product Def.
Initial Design Considerations
A2
Functional Requirements (FRs)
Conceptual Design
A3
Reanalyse
MEMS Reqs.
Initial Configs.
Detail Redesign
Design Analysis
A4
Matlab / Comsol
CAD / Layout Editor
Detail Design
A5
Rework
Functional Properties Analysis
Design Feas.
CAD
MEMS Specs.
MEMS Fabrication
A6
Functional Micro Machines
Process Design
Manf. MEMS
Testing & Verification
A7
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Fabrication Processes
Measurement Equipment
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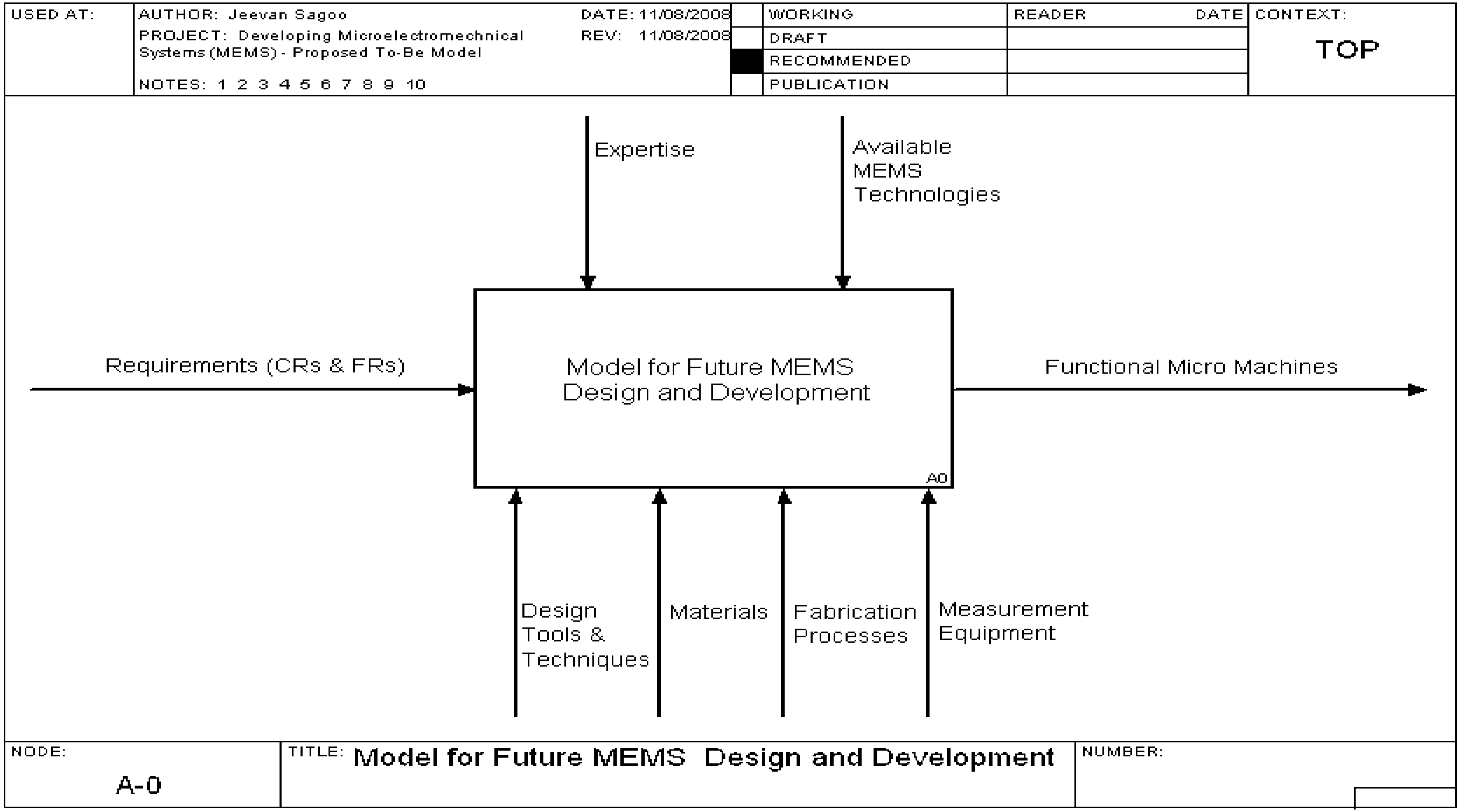
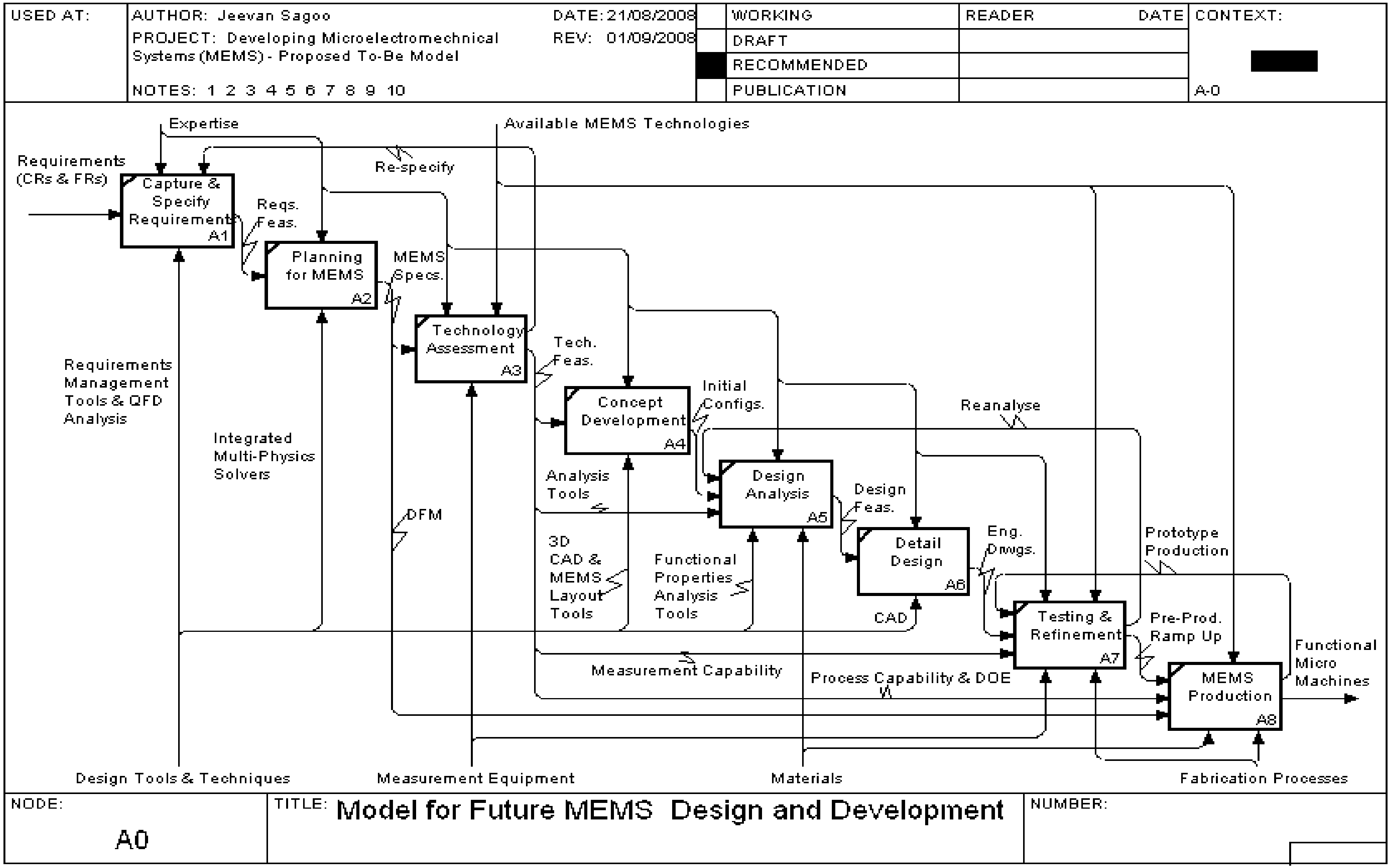
TITLE:
Developing a Model for MEMS Design and Development
NUMBER:

Appendix C: To-Be Model

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AUTHOR: Jeevan Sagoo
DATE: 21/08/2008
REV: 01/09/2008
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WORKING
DRAFT
RECOMMENDED
PUBLICATION
READER
DATE
CONTEXT:
A-0
Expertise
Available MEMS Technologies
Requirements (CRs & FRs)
Re-specify
Capture & Specify Requirements
A1
Reqs. Feas.
Planning for MEMS
A2
MEMS Specs.
Technology Assessment
A3
Tech. Feas.
Concept Development
A4
Initial Configs.
Design Analysis
A5
Design Feas.
Detail Design
A6
Eng. Drwgs.
Testing & Refinement
A7
Pre-Prod. Ramp Up
MEMS Production
A8
Reanalyse
Prototype Production
Functional Micro Machines
Requirements Management Tools & QFD Analysis
Integrated Multi-Physics Solvers
DFM
Analysis Tools
3D CAD & MEMS Layout Tools
Functional Properties Analysis Tools
CAD
Measurement Capability
Process Capability & DOE
Design Tools & Techniques
Measurement Equipment
Materials
Fabrication Processes
NODE:
A0
TITLE: Model for Future MEMS Design and Development
NUMBER:

Appendix D: MEMS Model Validation Questionnaire

V1. *Is the proposed model feasible for the development of generic MEMS devices?*

V2. *Are there any activities or elements in the model that are not feasible?*

V3. *Does the IDEF0 modelling technique accurately reflect the generic MEMS development process?*

V4. *Can the To-Be model be further enhanced or decomposed to accommodate the diverse MEMS device types?*

V5. *Can this model be applied to the physical development of MEMS devices with consideration for manufacturing?*