Supply-Chain Strategies for MEMS-enabled products at ABB.

By

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Submitted to the Department of Civil and Environmental Engineering and the Sloan School of Management in partial fulfillment of the requirements for the degrees of

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Abstract

MEMS (Micro-Electronic Mechanical Systems) is an emerging and promising technology. It offers the promise of unique competitive advantages to companies able master the difficulties associated with it. One of those difficulties is manufacturing. Each new product poses a very unique fabrication challenge. The development of the fabrication process has to go hand in hand with the development of the product itself, and sometimes even drives it.

ABB has identified MEMS technologies as a platform to improve its product line. It is currently developing a series of new products that will be enabled by MEMS. It has decided to outsource most if not all of the fabrication of its components. This presents it with a series of challenges related to the design and management of the associated supply-chain.

This thesis focuses on the challenges faced by ABB in this journey. More specifically, the thesis will:

- Give a brief description of the efforts at ABB to incorporate MEMS technologies into their product portfolio
- Report on the work done to survey the existing vendor pool for process competencies and to develop methods to find matches with ABB product needs
- Describe the development of a database to anchor ABB's MEMS knowledge base
- Analyze and describe the tactical options open for ABB in the design of its Supply-Chain for MEMS Manufacturing
- Identify the factors for success and the potential pitfalls going forward for ABB.

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Contents

Table of Contents

Abstract 3
Acknowledgements 4
Contents 5
Table of Contents 5
List of Figures 7
1 Introduction 8
1.1 Justification and Objectives for the thesis 8
1.2 Thesis overview 8
1.3 ABB: Company background 9
1.4 ABB current corporate strategy and structure 11
1.5 ABB and Research and Development 12
2 MEMS: development & manufacturing 14
2.1 MEMS: Brief description 14
2.2 MEMS Manufacturing 15
2.2.1 Background on MEMS manufacturing 15
2.2.2 MEMS Manufacturing in the marketplace 17
2.2.3 Commercial MEMS manufacturing considerations 19
2.3 MEMS design and development 20
3 Supply-Chain Design 23
3.1 Value-Chain Design: The ultimate core competency 23
3.2 Value-Chains and Technology Cycles 24
3.3 Value-Chain Framework analysis methods 26
4 ABB MEMS initiative 30
4.1 The goal for MEMS at ABB 30
4.2 In the beginning, there was BODNAP 31
4.3 Then, there was ADAMM 32
4.4 ABB MEMS Manufacturing Principles: 33
4.5 Current MEMS Research and Development at ABB 33
5 ABB manufacturing vendor database development 35
5.1 Identification of existing MEMS processes 35

5.2 ABB Current Project Survey 37
5.3 Supplier Survey 40
5.4 MEMS Database 41
6 Strategic issues for ABB MEMS initiative 45
6.1 The technology cycle and MEMS 45
6.2 Value-Chain Frameworks for ABB and MEMS 47
6.2.1 Customer importance. 47
6.2.2 Technology evolution rate ("Clockspeed") 47
6.2.3 What is the company's competitive position? 48
6.2.4 What is the status-quo of the supply base? 48
6.2.5 How integral is the element to the overall product or system? 49
6.3 MEMS at ABB and the make-buy matrices 49
6.4 Implications on the decision to outsource 50
6.4.1 External options. 51
6.4.2 Relationship Management 52
6.4.3 The MEMS Competence Center 54
7 Factors for success and potential pitfalls going forward for ABB 57
7.1 Why it should go really well 57
7.2 Why it could go wrong 59
8 Concluding remarks 61
References 64

List of Figures

Figure 1: Thesis structure 9

Figure 2: New ABB structure 11

Figure 3: High-level design issues and their relationship to modeling and analysis. 21

Figure 4: What drives competitive advantage? 24

Figure 5: Strategic Value Assessment: Evaluating Five Key Criteria 26

Figure 6: Organizational Dependency vs. Product Decomposability. 27

Figure 7: Organizational Dependency vs. Product Decomposability. 29

Figure 8: Example of Product Process Flow Map (disguised). 38

Figure 9: Pareto chart of process step usage across projects. 39

Figure 10: Supplier matrix. 40

Figure 11: Comparing suppliers and products.. 41

Figure 12: Simplified database structure. 42

Figure 13: Example of a possible database query and results 43

Figure 14: Make-buy matrix analysis for MEMS at ABB 50

Figure 15: Relationship set-up at the prototyping phase. 53

Figure 16: The role of the MEMS Competence Center. 55

1 Introduction

This chapter gives an overview of this study and the motivations for it. It also provides a model to illustrate the overall structure of the thesis. It describes the company that is the subject of this study, ABB (Asea Brown Boveri, Ltd.), as well as the traditional role and position within the company of the Corporate Research Centers, where the main effort for MEMS development takes place today.

1.1 Justification and Objectives for the thesis

The emerging field of MEMS (Micro-Electronic Mechanical Systems) offers potential growth opportunities to companies that can find a way to master the complexities associated with managing the technology in its current development stage. There are several key aspects to this, on the operations side.

ABB has identified MEMS as one of the technology platforms that will help them create innovative and profitable products in the area of process analysis, instrumentation, sensing and building automation. A decision has been made to outsource the MEMS production. This thesis will focus on the development and management of the associated supply chain. More specifically, the thesis will:

- Provide an introduction to the singularities of MEMS manufacturing
- Illustrate some of the current thinking about Supply-Chain design
- Describe the efforts done at ABB to incorporate MEMS into their product portfolio
- Report on the work done to survey the existing vendor pool for process competencies and to develop methods to find matches with ABB product needs
- Describe the development of a database to anchor ABB's MEMS knowledge base
- Analyze and describe the tactical options open for ABB in the design of its Supply-Chain for MEMS Manufacturing
- Identify the factors for success and the potential pitfalls going forward for ABB.

1.2 Thesis overview

Figure 1 serves as a model to illustrate how the components of this study are related to one another. It begins with a brief description of the MEMS field and the peculiar difficulties faced by any company trying to develop and manufacture MEMS-enabled products. It also provides a fast recap in Chapter 3 of strategic supply chain design concepts. The goal is to illustrate in Chapter 6 how these two circumstances meet in the case of ABB and its decision to outsource MEMS production. It also reviews the history and current strategy for MEMS development at ABB (Chapter 4), as well as the work done to survey the existing fabrication services market and develop a MEMS knowledge base at the Corporate Research Center in Ladenburg, Germany (Chapter 5). Finally, it addresses some of the issues going forward for the company, both factors for success and potential pitfalls in their current approach to MEMS development.

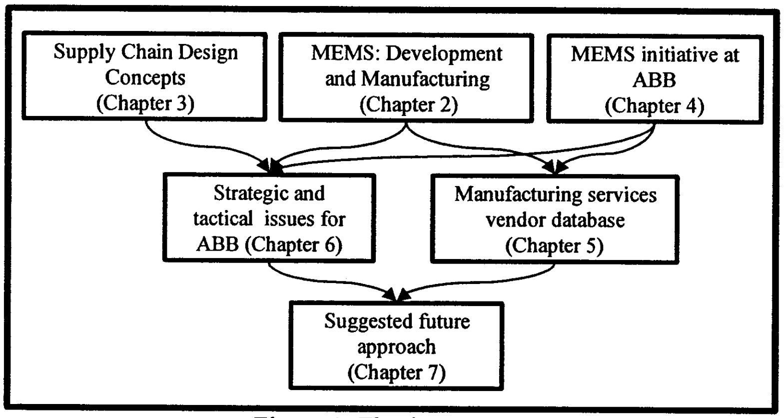

Figure 1: Thesis structure

1.3 ABB: Company background

An important element in considering the role and strategy around MEMS at ABB is its history. ABB was created by the merger in 1987-88 of two companies whose roots lie in the nineteenth century: Asea, founded in Sweden in 1890, and Brown Boveri, established in Switzerland in 1891. The two companies were among the surge of industrial enterprises established towards the end of the nineteenth century to provide equipment for the rapidly expanding electrical power industry. Both were very successful at it and by the time of their merger, they became the largest European industrial conglomerate in the electrical engineering arena. They also very rapidly acquired and/or allied themselves with a number of key players in their industry, such as the steam turbine division of AEG and Westinghouse's power distribution and transmission business.

The emphasis on global presence was in large part as a response to the nature of its customer base, which at the time was comprised mainly of government-owned or regulated utilities. This created a strong pressure for both a local presence and an array of products that was wide enough to cover the needs of vertically integrated power suppliers. This translated by 1998 into operating in over 140 countries with a wide variety of product lines, many of which were closely related in the eyes of the customer, and which were specifically tailored to the very different electrical standards across those markets.

In order to tackle the challenge of both local responsiveness and global scale, the company operated with a matrix structure of business and geography. The structure was designed to facilitate "integrated systems thinking" and encourage teamwork, but it had its drawbacks. Local product managers found themselves reporting to two bosses, and they sometimes were unable to provide a customer with the whole set of possible ABB products because they lacked the knowledge of their existence. Customers may have been pushed from pillar to post around the organization until they had located the product managers.

The final organizational structure was built around so-called Business Units (BU's). They were comprised of two or more profit centers and were focused on a single business and market. The average size of the local operating companies was about 200 employees, with about $50 million in annual revenues. The basic principle was to create highly focused local companies reporting both to a worldwide business manager, who would be responsible for achieving efficiency in that product line and growing the business on a global scale, and to a country manager responsible for coordinating the various businesses within a particular country. The different BU's were aggregated into Business Areas (BA's), which were run by a BA manager, who in turn was responsible for technology development, deciding on transfer prices among local operating companies in the BA, transferring business and technological knowledge within the BA. [i] Each BA also had a Technology Manager.

BA's were then in turn aggregated into Business Segments, at the highest level. A segment was lead by one member of the Executive Committee each, and the committee was comprised of seven members (one for each of six segments and one for Corporate Research). As competition became more globalized and as electrical power industries became increasingly deregulated, the ABB Executive committee decided to decrease the regional leader's role. In 1998 a reorganization was announced under which the layer of top regional management was stripped out, and clear lines of leadership for ABB's core businesses were reestablished. They culminated in the divestment of ABB's traditional large-scale power generation business in 2000.

1.4 ABB current corporate strategy and structure

Today, ABB has about 165,000 employees and roughly 400 factories in more than 100 countries. It had sales of $23bn in 2000. It is a large, decentralized, diverse company. It is still engaged in many and very diverse industries, only now it is nearer to a technical service company than a manufacturing one. It increasingly tries not just to sell single pieces of equipment but to work with clients on total systems solutions. It is also seeking to portray a new image under the slogan 'Brain Power'.

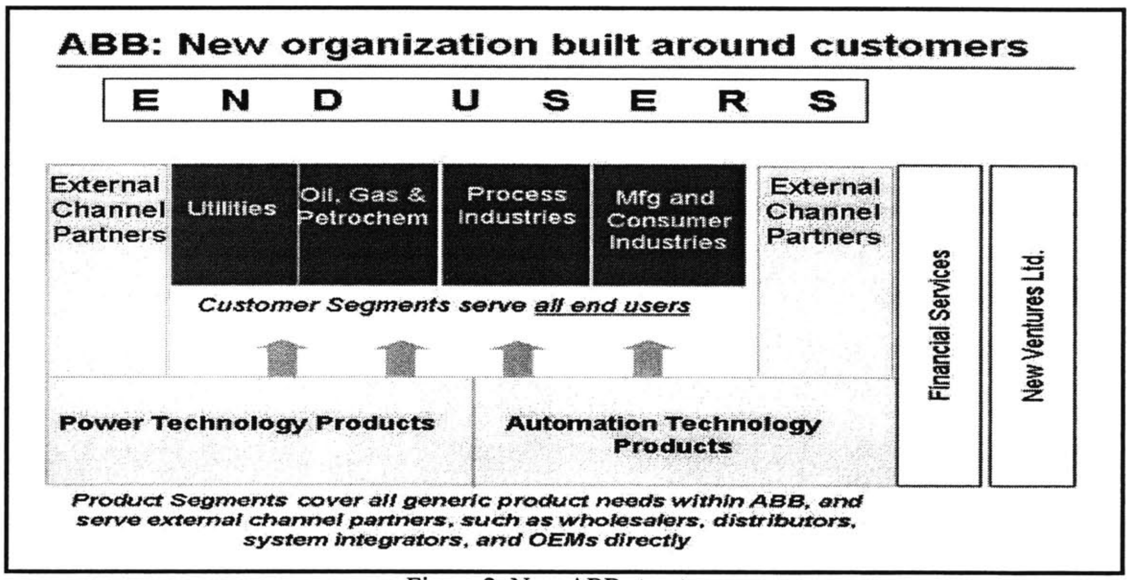

Figure 2: New ABB structure

The new organizational structure was announced at the beginning of 2001. It is shown in Figure 2. Instead of multiple ABB product units serving the same customer, often working with different terms and conditions, dedicated units representing ABB's total offering of products, services and solutions will serve customers. This way, ABB can maximize the number of products and services it sells to each customer. It is also expected to increase the interaction of employees and customers, as well as to lower barriers to cooperation within the company.

It is expected that the reorganization (which included a reduction of 8% in the worldwide labor base) will create value for all stakeholders by combining superior domain know-how with collaborative commerce and world-class products and services. This should enable ABB's customers to gain competitive advantage from technology advances and new market developments so that they can better meet the needs of their own customers. For employees, it is supposed to provide common processes that free people up to focus on value-creating activities. It also gives them a way to share in the value that they create.

Under the new structure, ABB was divided into seven company divisions. It was based on the creation of four divisions serving utilities, process industries, manufacturing and consumer industries, the oil, gas and petrochemicals sectors, and two divisions going to market through ABB's four industry divisions as well as external channel partners with power technology and automation technology products. The realignment was supported by common group processes and infrastructure throughout ABB in key areas such as front-end, supply chain management, e-Business and information systems. One of the main elements of the customer-centric organization is the build-up of a key account management structure for ABB's strategic and major accounts.[ii]

1.5 ABB and Research and Development

The role of the Corporate Research Centers also changed significantly in the last two years. Up until 2001, the CRC's had been treated within the company structure as independently as a Business Segment. Their funding was provided by a combination of corporate funds and research work contracted internally by different BA's and sometimes even BU's on a project-by-project basis. There was approximately one CRC for each major country where ABB had operations (resulting in about 15 CRC's throughout Europe, for example).

The BA's had each its own Technology Development teams. Within the CRC, there were Technology and/or Product Program Managers, who were responsible for broad research initiatives intended for a combination of BA's. The CRC's followed the matrix structure internally, where each group of researchers were headed by a manager who in turn reported to both the local CRC head as well as the BA manager. The role of the local CRC management was mostly to take care of local regulatory affairs as well as administrative tasks. Nowadays, it is the BA technology managers that provide the main push for new initiatives or projects at the CRC's. In the future, and under the new corporate structure described above, the CRC's will be merged into regional research areas, one in Europe, one for the Americas, and one for Asia. The role of the regional managers of the CRC's will be strongly diminished, and it is expected that the CRC's will also streamline their research groups according to the new structure.

The CRC's traditionally provided two kinds of services, new product/technology development, and existing product/technology improvement. In the first case, new projects sprung up mostly from a combination of technology push by the members of the CRC and also product pull by the BA's in response to changing consumer needs. The role of the CRC was to provide a working prototype and a fundamental understanding of a new product using the new technology or a new combination of existing technologies, and the BA was usually responsible for further development and product roll-out into the market.

Corporate Research plays an integral role in ABB's strategy. For example, 75% of ABB's business is based on new developments of products that were non-existent five years ago. The main goal is that each project has a clear market orientation, coordinated with ABB's technology strategy. In order to achieve this, ABB has developed a process called Business Technology Evaluation. It is used to understand competitors, customers, and technology.

2 MEMS: development & manufacturing

This chapter gives a brief introduction into the MEMS field, and outlines the peculiarities associated with the technology. It describes the current thinking about fabrication processes. It ends by underlining the difficulties associated with MEMS manufacturing and development.

2.1 *MEMS: Brief description*

These products have various names, including "micro-electronic-mechanical-systems" (MEMS), "micro-mechanical systems", "micro-machines", and finally, the "micro-systems technology" or MST, widely used in Europe. In general, MEMS are understood to be devices that involve functions other than or besides electronics, and which have one or several (if not all) key geometrical features in the micron range. In order to fabricate these products, current technology borrows most of its manufacturing processes from the IC (Integrated Circuit) industry, such as UV-photolithography, wet and dry chemical etching, etc., and builds on them. Newer, MEMS-specific fabrication technologies such as surface micro-machining and Deep Reaction Ion Etching (DRIE) have been developed over the last ten years as extensions to standard IC processes.

MEMS are chip-level devices that can be produced on a large scale, much like ICs. Because of this, MEMS can be made in high volumes at a low cost, provided the application warrants it. In addition, their extremely small size can be a distinctive advantage. For example, mechanical devices can become faster due to sharply reduced dimensions (i.e. the distance that the proof mass of a capacitive accelerometer has to move to produce a signal is as small as a few hundredths of a micron). Their lower inertia due to the low mass can be translated into higher reliability, using adequate design. Further, their small size enables the creation of devices that work better precisely because of these small dimensions, as is the case for Coriolis gyroscopes and capacitive accelerometers. Finally, there can be some advantages in a more robust interconnect with signal processing subsystems, such as is the case in integrated systems (i.e. those where the MEMS device is built on the same substrate as the CMOS circuits that transmit or analyze its signals).

It is advantages like these which have made MEMS so attractive to a variety of markets and applications. This "new" technology has been around for at least 25 years, and commercialization has only occurred since the early 1980s, and somewhat earlier for pressure sensors. As such, its level of implementation and market success has increased exponentially in the last five years. There are three key market drivers for MEMS: to improve product functionality, to improve product performance, and to reduce cost.

MEMS are usually divided into two classes: Actuators and sensors. Sensors are typically used to sense different physical parameters such as pressure or temperature, measure forces such as acceleration and flow, or detect specific chemical compounds. Actuators involve an interaction with the environment, such as micro-mirror arrays, micro-pumps, micro-valves, etc.[iii]

Some of the advantages of MEMS (such as cost-effective manufacturing) can only be realized in high sales volume products, however. The capital investment needed to fully own the production process is very high (in the tens to hundreds of millions of dollars). Thus, only applications that result in either high sales volume or will result in the economies of scale typical of the IC industry.

2.2 MEMS Manufacturing

Commercial manufacturing remains by far the biggest obstacle to full MEMS rollout into the marketplace. A quick search in current scientific journals and conferences will yield hundreds of working prototypes of sensors, actuators and other amazing Microsystems. However, only a very small fraction of these can actually be bought in the "real" world outside of academia. [iv] For example, there are about 150 to 200 references to different accelerometer solutions, but only 5 to 6 are currently in production. This is in large part due to the almost always insurmountable barrier presented by the challenge of finding convenient, economically viable solutions for large number production.

2.2.1 Background on MEMS manufacturing

The last ten to fifteen years have seen great growth in commercially available MEMS manufacturing technologies. Most MEMS devices use some form or combination of fabrication techniques typically seen in the IC industry. They build on three basic "building block" processes: (1) Those related to photolithography, (2) those related to material deposition, and finally (3) some type of etching (material removal), either chemical and/or mechanical. However, the primary difference between IC and MEMS fabrication is that the latter typically uses thicker films and deeper etches.

While silicon still remains the primary substrate material, micro-machining techniques have allowed the exploration and use of other materials such as plastics, metal, and glass. Whatever the material, the end result is a structure of a mechanical nature, with features in 3 dimensions. Silicon is the most common material mostly due to MEMS' extensive use of IC technologies, which have been developed using silicon as their basic building block. However, microfabrication that goes beyond conventional microelectronics gives way to a greater range of materials and the corresponding fabrication techniques, such as electroplating of metals, and molding and embossing of plastics.[v]

There are several ways in which MEMS production methods are classified today both in academic circles and in the industry, but in general, the most accepted are those that classify existing methods according how the device is formed through etching, given that both lithography and material deposition are common to all forming methods. For example, a typical classification is:

1. Traditional bulk micro-machining
2. Sacrificial Surface micro-machining
3. HARM or High Aspect Ratio MEMS

Traditional bulk micro-machining usually refers to processes that etch very deeply into the substrate, mostly in an isotropic manner, or following the directions of the substrate crystalline structure. The resulting shapes depend on the masking layer patterns and the physical and chemical characteristics of both the etchant and the material to be removed. This the dominant production technology for pressure sensors, for example, and it is also the oldest.

Sacrificial Surface micro-machining (SSM) refers to processes that make use of the selectivity of the etchant to remove a layer of deposited material in order to "release" the resulting free-standing structure made from another deposited material.[vi] The most significant SSM-based commercial product is the air-bag accelerometer for the automotive industry.

HARM production methods such as LIGA, Deep-UV and DRIE are only slowly becoming more commercially viable. Thanks to these production methods it is now possible to cut features all the way through the wafer thickness with a precision of a few microns.[vii] The sidewalls produced by these methods have astoundingly high aspect ratios of up to 200:1 (hence the name), with good to very good surface qualities.

2.2.2 MEMS Manufacturing in the marketplace

One of the most important difficulties in MEMS manufacturing relates to physical plant needs. The capital investment required to fully own the production process is very high (in the tens of millions of dollars), which means that a high sales volume is needed to justify the full vertical integration of a product or product line. This has divided the MEMS manufacturing field into two main categories, high-volume and low- to medium-volume. Only companies with a high-volume product will integrate vertically and fabricate the products themselves. If a company has a product with low sales volume, they are forced to find vendors or strategic partners that will manufacture the product for them.

Over the last few years, these division lines have developed very clearly in the US. In the first one, large companies have totally integrated the fabrication into their operations (such as Motorola, Honeywell and Analog Devices). They own the process and their product families are built on core technologies developed around their existing capabilities. They usually do not offer manufacturing services to the outside world, and consider their fabrication process flows and technologies proprietary and part of their competitive advantage.

Within the smaller companies, two subgroups developed, but only one survives today. The first one was comprised of small companies (such as Chronos, Intellisense, Novasensor) that decided to own the fabrication facilities, but did not generate enough income to justify it. The larger companies bought them all out. Once they had been purchased, access for outsiders to their fabrication capacity was severely reduced, although some have opened up their capacity due to the sharp downturn in the telecom industry.

The other group of small companies is comprised of the ones that have tried to outsource their production from the very beginning. Their main constraint has been that the number of independent vendors is very small. It is also usually the case that no single vendor has 100% of the manufacturing capabilities needed for a specific design. In the case of a specific start-up company trying to introduce a new type of optical switches to the marketplace, they found that it is nearly impossible to find vendors that exactly matched their process design.[viii] Each offered a different process flow for the same product, which resulted in different final designs for the same device.

In Europe, on the other hand, a very interesting development is occurring with so-called fabrication "clusters", such as Europractice. These clusters offer the whole gambit of MEMS manufacturing technologies and services as a group. They are set up as a supporting network of manufacturing facilities, design houses and competence centers. Their stated intention is to lower barriers to entry through concepts such as Multi-Project-Wafer (MPW), in which several different devices are fabricated on the same wafer, in order to reduce prototyping and low-volume production costs. The wafers would then be sent along all the relevant different members of the cluster to provide the processing steps needed. This approach opens up volume manufacturing plants at companies such as Robert Bosch (the inventors of DRIE) to outside design. Some companies, such as SensoNor, offer MPW services in their own fabs. In the US, a cluster called MEMS exchange was launched a few years ago.

There is a great gap in available supply lines for medium range volume production. If a company wants to fabricate a sizable (e.g. over 20,000) number of devices that have been successfully prototyped in an experimental "fab" (short for fabrication facility), it usually turns out that the line where the prototype was initially fabricated is not equipped to produce such a high number of devices. The next natural step for companies is to search for commercial silicon foundries that have the capability. What is usually found is that the clean-room equipment is not the same and works to different specifications than the equipment for the prototype. Also, it is very commonly the case that the original process used at the experimental foundry is not suitable for large-scale production.[ix] This results, as outlined below (2.3), in the need for a completely new design.

2.2.3 Commercial MEMS manufacturing considerations

Usually, the prototypes mentioned in the MEMS scientific literature were fabricated within experimental installations in universities, research institutes, and industry. There is however, very little literature available on commercial MEMS manufacturing. A few general but important issues can and should be mentioned, however.

The division of producers into the two main segments described in (2.2.2), namely high volume and low-to-medium volume, has resulted in a clear differentiation in terms of fabrication abilities among the existing fabricators. Robust manufacturing capabilities exist mainly for products where there are opportunities for high volume production. Companies that have fully integrated fabrication and have enjoyed the advantages of high volume, such as Analog Devices with accelerometers or Motorola with pressure sensors, are now able to successfully manufacture their products with relatively high yields, as well as reliability and repeatability.

This development points to a very important difference between MEMS manufacturing and traditional "macro" fabrication: MEMS manufacturing capabilities and know-how are product-specific, and not process-specific. It could almost be said that MEMS manufacturing is still at the craftsmanship stage (except for cases like the ones noted above). Therefore, developing an adequate manufacturing competence is very costly and difficult, making it the most significant barrier to entry.

Quality control and quality assurance standards for MEMS are few or non-existent outside the operations of integrated manufacturers. Frequently, the quality of many MEMS devices fabricated at either academic or commercial facilities is low. Also, the repeatability of the processes is sometimes inconsistent. Part of the problem is that the technology is so new that the fabricators do not yet know how to define quality, much less measure it.

The accessibility of companies, both small and large, to MEMS fabrication facilities is somewhat reduced, too (see Chapter 5). Currently, most companies who wish to explore the potential of MEMS technology have very limited options for getting devices prototyped or manufactured. Still, it is believed that many of the largest beneficiaries of MEMS technology will be firms that have no capability or core competency in microfabrication technology, and access by these companies is critically important to their successful utilization.

2.3 MEMS design and development

Designing commercial MEMS remains very much an art form or craftsmanship that usually requires a team of highly skilled engineers and scientists whose knowledge base covers a wide array of disciplines, with the associated overhead in management costs. The design cycle-time is usually large, sometimes in the range of years, mainly because it requires several iterations of process, device and system design, usually with fabrication of prototypes as part of the loop.[x]

Given that MEMS is an emerging technology, component and process standardization is very low. Each new product poses a very unique fabrication challenge. The designer of a MEMS device requires a high level of fabrication knowledge in order to pursue a successful design. Further, the development of even the most mundane MEMS device frequently requires a dedicated research effort directed at formulating a suitable fabrication sequence. An extensive knowledge of fabrication constraints is a clear prerequisite for design activities.[xi]

This in turn translates into several key considerations in MEMS development. At a high level, it means that it is a highly iterative process that has to take into consideration the technological capabilities and current limits in the state-of-the-art, the manufacturing implications of each design, an evaluation of the competition, and the projections of market acceptance of the new technology. These considerations are then compared vs. the conceptual device or solution, which itself is modeled and analyzed using a number of numerical and analytical tools (see Figure 3).

The resulting estimated performance characteristics of the model are then compared against the considerations outlined above. It is important to note that the modeling and analysis step is the critical step in MEMS development. It is also in this stage that a deep knowledge base of fabrication is needed in order to make the iterative process more efficient. A developer with a keen sense of current fabrication constraints will be sure to include them from as early as possible into his modeling and analysis considerations.

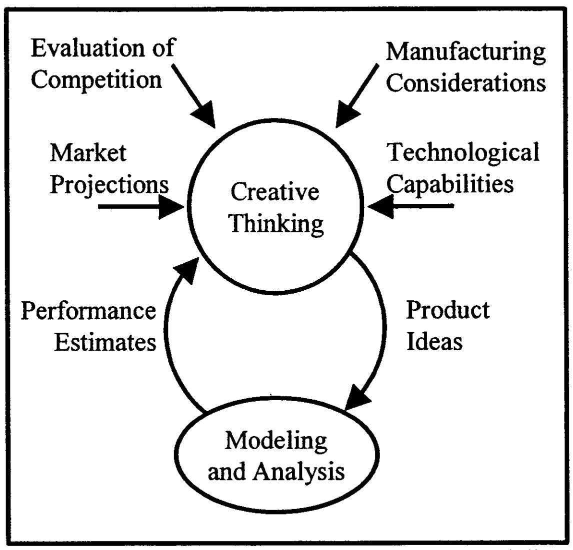

Figure 3: High-level design issues and their relationship to modeling and analysis.[xii]

In this thesis, I focus on the particular difficulties associated with the iteration between "modeling and analysis" and "manufacturing considerations" from Figure 3. In most cases, what drives process design is the interaction between the realities of device performance, manufacturability, and cost[xiii]. A complex, iterative process emerges where the designer has to go back an forth between desired shapes and plausible processes. Modeling becomes of the utmost importance, as the final manufacturing cost of a device produced in high volumes will be dominated by the achievable yield, which itself can be highly dependent by the minutiae of the specific chosen process steps.[xiv]

The give-and-take between design and fabrication translates into process availability sometimes being more important than the product idea itself. In the case of outsourced manufacturing, it is often the case that developing a device with two different vendors will result in two completely different designs. This is because the vendor's available process flows ultimately determine how a product is built.

Also, and as initially stated in (2.2.3.), there is a gap to be bridged between prototype fabrication in an experimental setting, and commercially viable manufacturing of final products.[xv] The usual initial production levels needed for marketplace introduction of the products are either too high to be fabricated within the constraints of a university-based facility, and too low to be attractive for a silicon foundry with a large enough production facility.

There is also marked difference between fabricating a prototype or a series of prototypes in a few runs with a few wafers under very controlled circumstances in an experimental lab and manufacturing several thousand devices with high-yield, high-repeatability, low-cost process sequences. The factors of success change from simply being able to get a functioning prototype done to fabricating a sellable device with high reliability and minimized fabrication costs.

3 Supply-Chain Design

"The old maxim that a chain is as strong as its weakest link is as true in business as it is in mechanical systems".
Charles Fine, Clockspeed

This chapter gives a short recap of current thoughts about Supply-Chain design, with a special focus on considerations around vertical integration vs. outsourcing. This is especially important for ABB given their decision to outsource MEMS production (see Chapter 4).

3.1 Value-Chain Design: The ultimate core competency

The design of a company's Value-Chain has been identified in the last few years as a critical component of a successful business strategy. Companies cannot count on a static, permanent set of relationships among the different players along the chain. The distribution of comparative power along the chain can be expected to fluctuate, and companies have to be keenly aware of this and adapt to it in order to survive. This in turn implies that competitive advantage is a perishable good in nature that needs to be captured time and time again.[xvi] It depends on "a particular set of conditions that exist at a particular point in time for particular reasons".[xvii]

It follows very easily then that the companies that are able to understand the underlying dynamics of the value chain in their markets, are able to identify the sources of comparative advantage (however short-lived they might be) and act accordingly, will be better suited to gain and retain competitive advantage. In fact, it is emerging as the only sustainable core capability.

Before continuing with this notion of dynamic Value Chains, it is important to recognize that designing the relationship with the group of companies that will provide a company with parts and services is no longer, in C. Fine's words, about "[simply] *collaborating organizations*" but about "chains of *capabilities*"[xviii]. A company needs to understand how many of the various steps of the Organizational, Technology, and Business Capability chains[xix] they want to control themselves, and implement their strategies accordingly (more on that in 3.3).

3.2 Value-Chains and Technology Cycles

Further, it is important that organizations recognize the development stage of the technologies they employ. This is of cardinal importance in terms of understanding what the implications are of integrating most if not all processes internally, vs. outsourcing them. Only a few years ago, the notion persisted that being able to do most business processes internally was a powerful competitive advantage.

Nowadays, however, it is believed that vertical integration will slow companies down unnecessarily. A lot of hype surrounds companies such as Cisco, which seem to have developed an uncanny ability to outsource most if not all of their manufacturing and product development to companies that they then either merge with or acquire outright.[xx] There is a caveat, however, and that is related to understanding what the circumstances are that allow Cisco to get away with it.

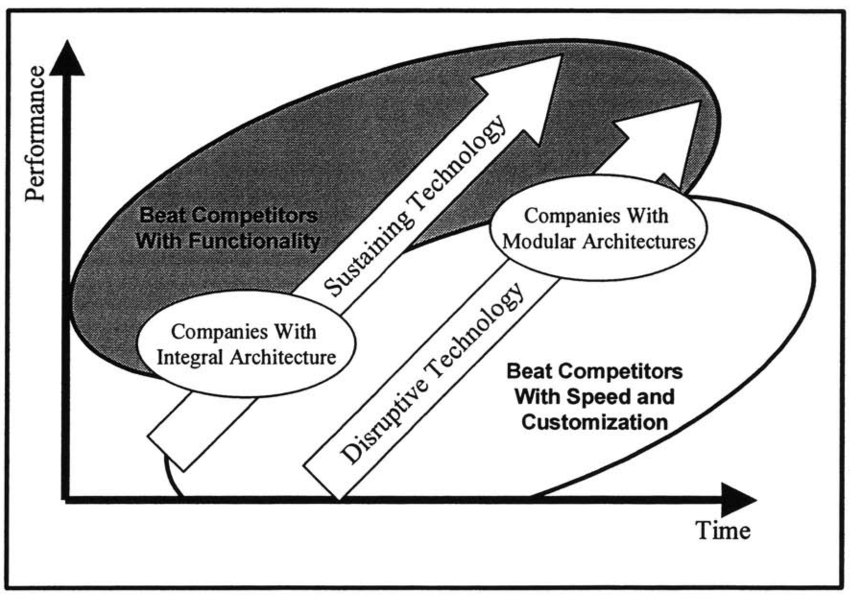

Figure 4: What drives competitive advantage?[xxi]

According to Christensen in [[xx]], in order for a company to succeed in outsourcing a piece of the Value Chain to a supplier, it must meet three conditions,

1. It must be able to specify what attributes it needs
2. The technology to measure those attributes must be reliably and conveniently accessible

3. It must have a clear understanding of what is needed when a supplier delivers a variation

In order for these three conditions to be met, the prerequisite is the availability of necessary and sufficient information and know-how, so that markets can emerge along the stages of the value chain. However, in the cases where this information either does not exist or is not available in a mature, standardized enough format, where there is insufficient information about how changes in product design will affect manufacturability, or how changes in manufacturing technology will affect product performance, integration becomes imperative.

Christensen maintains that vertical integration becomes a competitive advantage when a company bases its competitive offering on providing complete solutions to customers whose needs have not been yet completely satisfied by existing, available products, and when the ability to extract the most performance possible through design of each of the major subsystems is the key to success (the equivalent to the 'Beat Competitors with Functionality' space in Figure 4).

On the other hand, when the technology has evolved to a point where the key customer driver is responsiveness and the need for customized solutions, companies that rely on modular, standardized interfaces for their subsystems enjoy the advantages of speed and low overhead costs by virtue of being able to rely on a set of suppliers to manufacture and develop their subsystems ('Beat Competitors with Speed and Customization' in Figure 4).

The design of the relationship plays also a primordial role. Roberts and Liu discuss this in depth in [[xxii]]. Depending on what stage in the technology life-cycle the product is in, companies have to choose between an "alliance, joint venture, licensing, equity investments or mergers and acquisitions, to accomplish their technological and market goals over a technology's life-cycle." If a technology is the initial, "Fluid" phase, entrants will usually prefer to either form technology alliances with established companies to jointly pursue the new technology and set the industry standards, or established companies will acquire start-ups or set up venture equity funds. If it is in the final, "Discontinuities" phase, incumbents will tend to try to identify new technologies and either realign their core competencies or acquire niche companies while divesting non-aligned assets.

In the case of ABB and MEMS this presents an interesting conundrum, for on the one hand, MEMS technology is still very much in the "Fluid Phase", where there is a great degree of market and product uncertainty and there is a high potential for exponential market growth. However, when seen through the lens of the existing markets that ABB intends to serve with MEMS-enabled products (e.g. gas chromatographs for natural gas transport lines), it becomes clear that they are in the "Discontinuities" phase, as most of the sensors that ABB is trying to substitute with MEMS-enabled products are already in the market, and have been for a number of years. This is an opportunity at the same time, as it provides ABB with several options, as described in Chapter 6.

3.3 Value-Chain Framework analysis methods

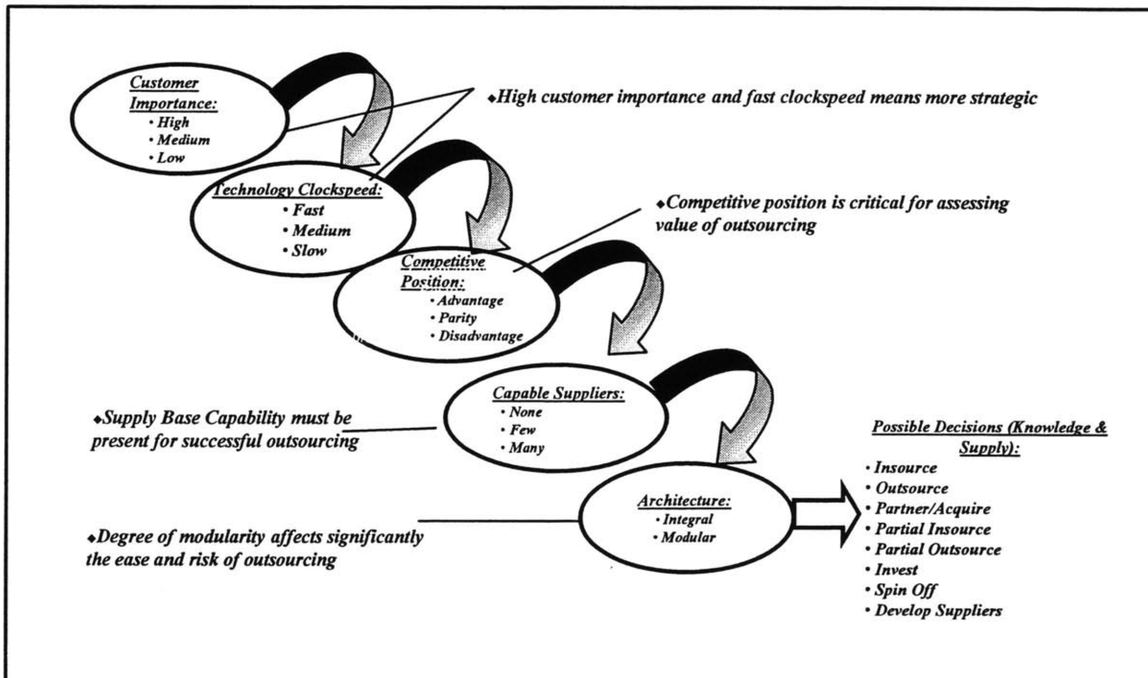

Figure 5: Strategic Value Assessment: Evaluating Five Key Criteria[xxiii]

A useful tool to understand the strategic importance of the different components or subsystems of a product family or a technology such as MEMS is the "Strategic Value Assessment" developed by Charles Fine in [[xviii]]. Using this process (see Figure 5), it is possible to obtain a qualitative understanding of the relative importance of supply and knowledge assets that combine into the product offering of a company. It is designed to help users to understand how each decision to outsource or to develop products and subsystems in-house interacts with:

1. Customer preferences
2. Technology evolution rate ("Clockspeed")
3. How well positioned the company is in terms of cost, quality, etc. vs. its competitors
4. The status-quo of the supply base
5. How modular or integral the element is to the overall product or system

When used in conjunction with an Economic Value Analysis, this framework allows a company to understand where the main areas of opportunity lie in terms of Value-Chain positioning for the different products in its portfolio.

This tool is also a very good complement to the framework discussed in [xxiv] and in more depth in [xxv]. Using these matrices, it is possible to also understand at a strategic level whether outsourcing is really the best option, or whether doing so will result in a disadvantageous position (see Figures 6 and 7).

	DEPENDENT FOR KNOWLEDGE AND CAPACITY	DEPENDENT FOR CAPACITY ONLY
ITEMS MODULAR (DECOMPOSABLE)	**A POTENTIAL OUTSOURCING TRAP** Your partners could supplant you. They have as much or more knowledge and can obtain the same elements you can.	**BEST OUTSOURCING OPPORTUNITY** You understand it, you can plug it into your process or product, and it probably can be obtained from several resources. It probably does not represent competitive advantage in and of itself. Buying it means you save attention to put into other areas where you have competitive advantage, such as integrating other things.
ITEMS INTEGRAL	**WORSE OUTSOURCING SITUATION** You do not understand what you are buying or how to integrate it. The result could be failure since you will spend so much time on rework and rethinking.	**CAN LIVE WITH OUTSOURCING** You know how to integrate the item so you may retain competitive advantage even if others have access to the same item.

Figure 6: Organizational Dependency vs. Product Decomposability.[xxvi]

In the first matrix (Figure 6), the vertical axis refers to the architecture of the element or subsystem to be outsourced. This architecture itself has three dimensions, in terms of Supply-Chain, Product and Process. The combination of the three (and each in its own right) can be either integral or modular.

To pass the "integrality" test, a product must have principal components that fulfill different functions and which most of the times have been purposely designed to work with each other. It is also the case when the functional requirements must be delivered by various subsystems and cannot be reduced to a single component or subsystem.[xxvii]

"Modularity", on the other hand, implies that components or subsystems have a high degree of interchangeability, such as a modern PC's, where all major components are "easily" interchangeable, and work with each other reasonably well. The standards for performance and for interfacing with each other are well established, and the information is available to users.

The horizontal axis refers to what kind of dependency is established regarding the outsourcing partners. Fine and Whitney classify dependency into two categories, dependency for capacity and dependency for knowledge. The first case refers to when companies are perfectly capable of producing the item themselves, but choose not to for diverse reasons such as available space or production resources. In the second case, companies lack the know-how or technical capacity to develop and produce the product, and turn to external suppliers to fill that role.

The second matrix (in Figure 7) tries to deepen this insight by incorporating two more dimensions of importance to the outsourcing decision. On the horizontal axis, a measure of the "Clockspeed" is included. "Clockspeed" is understood as a measure of the speed with which an industry or technology goes through its evolutionary cycles.[xxviii] A faster Clockspeed means that new technologies are constantly on the rise, whereas a slower Clockspeed means that the product life-cycle is measured in longer time intervals, such as is the case in automobiles, where new generations of models are introduced to the marketplace every four to five years.

The vertical axis is chosen to display the number of potential suppliers in the market, as a measure of the leverage that a company will have when it decides to outsource. Few suppliers usually means that buyer power is low, as the few suppliers get to set the rules in the marketplace. A great number of suppliers, however, points to higher market efficiency and the balance of forces is more tilted toward the buyers.

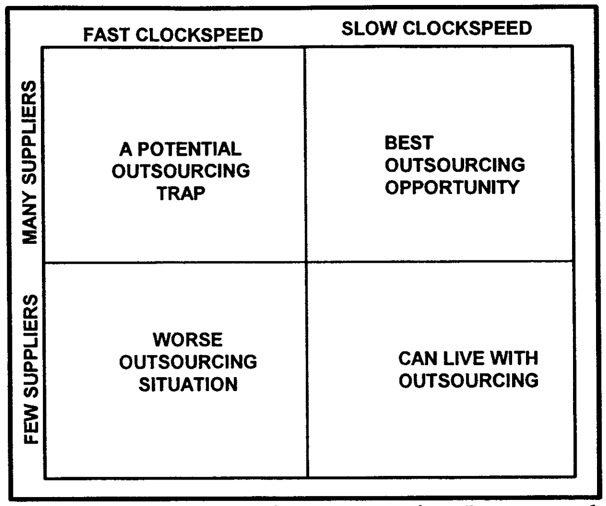

Figure 7: Organizational Dependency vs. Product Decomposability.[xxix]

Using these two analysis methods in parallel, a company can gain powerful insights into the strategic and tactical consequences of their outsourcing decision. These two were also chosen because of their relevance to the ABB case, where products are still under development and the final structure of the ensuing Supply-Chain has not been fully determined yet. They are used in Chapter 6 to analyze ABB's current MEMS manufacturing strategy.

4 ABB MEMS initiative

This chapter describes the history of the MEMS initiative at ABB, it's current scope and role that MEMS are expected to play in ABB's product portfolio. It also summarizes ABB's chosen manufacturing strategy for MEMS.

4.1 The goal for MEMS at ABB

MEMS offer a number of potential characteristics which result in tangible opportunities compared to conventional analyzing systems: [xxx]

- Low amount of reagents or consumables needed → low cost of ownership over the lifetime of the product
- Cost effective manufacturing → low investment cost
- Reduced power consumption → remote and wireless systems
- New functionality possible in micro-scale (e.g. Mass-Spectrometer: μm-dimensions mean no ultra-high vacuum necessary, easier and cheaper system setup) → increased performance
- Easily integrated diagnostic functions and web-cards → integrating instrument in advanced Process Automation Network

These and other similar considerations are the main thrust behind ABB's interest in MEMS. It is believed that with the right product mix, MEMS could account for somewhere between 300 and 400 million USD in extra annual sales for ABB. The BA's that would potentially benefit from MEMS are Automation Technology Products, Process Industries, Manufacturing & Consumer Industries, and Oil Gas and Petrochemicals. There is also a potential product for the Power Technology Products division.

ABB is widely renowned for its process instrumentation and automation products, and MEMS do genuinely seem to be the technology of the future in these industries, for the reasons outlined above and in (2.1). Currently, ABB is developing somewhere between 10 and 20 new devices for different BU's, most of them analyzing devices, and hopes to have the first products in the marketplace by the end of 2002. The projects are overseen by a Program Manager within Corporate Research, and MEMS technology was named as one of the three main cornerstones for ABB into the future by the Chief Technology Officer and Head of Group R&D and Technology

4.2 In the beginning, there was BODNAP

In early 1995, a project was launched by the Vice President of Technology in the BU of Instrumentation (part of the BA of Automation). After performing visits to 13 customers in 3 countries, and a careful analysis of existing technologies and customer needs, the BODNAP project was launched. It was intended as an integral solution to waste water quality measurement.

With a single chip, in a housing that was a little smaller than a watermelon, it was supposed to be used as a multi-parameter water analyzer for Biological Oxygen Demand, Nitrate, Ammonia and Phosphate (hence the name, of course). The use of MEMS was to give it two characteristics that would make it a step-change improvement over existing solutions in the marketplace, namely that it dramatically reduce the need of reagents, and was intended to operate unattended for 3 months, floating in the water treatment tanks.

The project had two main objectives, one was to introduce innovative technologies into the BU, and the other was to establish a relationship between the corresponding BA and Corporate Research.

A team was setup consisting of the VP of Technology for the Instrumentation BU, the Program Manager for MEMS from the German CRC (then in Heidelberg), and a project manager, also from the DECRC (DE as in Deutschland). After many iterations, the solution chosen was one in which all the elements of the analyzer were included on a 4" wafer, whose surface was completely used up by the device.

In order to develop the actual device, a research institute in Germany was contacted that had the adequate prototype manufacturing capabilities. A successful prototype was built by the CRC. The members of the team were awarded the ABB Technology Prize for the year 2000.

However, when the time came to deliver the project to the BU so that they would continue developing it into a sellable product, a series of previously uncovered obstacles sprang up, unexpectedly. First of all, the fact that the device was designed to be fabricated integrally in a single wafer meant that, for the product to be economically feasible, the manufacturing process had to have a 100% yield for all the components. A failure in any small subsystem meant that the whole wafer had to be discarded.

Also, they were unable to find a foundry that was willing or adequate for the volume manufacturing of the product. Finally, the designers in the BU had little to no know-how about MEMS. A decision was made to instead manufacture the device in plastic, using high precision micro-machining. It is currently still under final development.

4.3 Then, there was ADAMM

Although the BODNAP project could not be classified as an unqualified success, it was still very fruitful in that it helped to reframe the question of how ABB was to approach MEMS technologies. ABB was (and still is, and should be) convinced that it was a technology that showed a great deal of promise if they managed to integrate into their product portfolio. If done cleverly, MEMS will create innovative and profitable products in the area of process analytics, instrumentation, sensing and building automation, all of which are areas in which ABB has both a strong presence and a well-established track record.

A decision was made to focus ABB's application of MEMS technology in complex systems, such as water analyzers, gas chromatography, mass spectrometry, etc. The notion was that the miniaturization should result in improved performance and new low cost product concepts. The goal thus is to achieve high extra value, more than just copying macro systems and making them smaller.

As noted above, one major obstacle for commercial success of MEMS products in the areas ABB is interested in is a great lack of standardization of MEMS components and subsystems. A need for a so-called ABB 'toolbox' of standardized MEMS components and tools was identified, given that the company was seen as not able to afford to develop every component several times with each new application requirement. Initially, this standardization was to occur mainly internally.

Also, and given the constraints in new investments due to the conjuncture at the time, a decision was made that ABB was not to manufacture MEMS internally, but that a network of MEMS foundry services suppliers would be established and maintained (see 4.4).

In order to achieve these two goals, a project called ADAMM (ABB Design and Manufacturing for MEMS) was launched in late 2000. The stated goals of the project were to develop a set of tools and frameworks that would facilitate the dispersion of know-how and technology from its current base in the different CRC's that are currently involved in MEMS development to the BU's where the projects are to be implemented. It was also intended as an initial effort by ABB to create and maintain its knowledge base around MEMS technologies.

4.4 ABB MEMS Manufacturing Principles:

Although they are implicitly agreed on by all the participants, it is worthwhile to explicitly state the principles under which the MEMS initiative was launched at ABB[xxxi]:

- ABB will not manufacture MEMS components and subsystems. ABB will outsource MEMS manufacturing to strategic suppliers.
- ABB will buy in the packaged MEMS components / modules and fit them into ABB's production flow, which will consist mostly of the assembly of modules.
- ABB will define the quality criteria and develop test procedures to ensure quality.

Also, and not mentioned above, ABB intends to maintain its competitive advantage by patenting as many of their inventions as possible, and making sure that the Intellectual Property for the devices remains with the company that way. During 2001, for example, over 30 patent applications were submitted by the CRC in Germany concerning MEMS.

4.5 Current MEMS Research and Development at ABB

The strategy outlined above has had several implications on the way projects are managed. Currently, the approach is to contract with Research Institutes and Universities to do most of the Research and Development for each proposed device, as ABB has no fabrication facilities of its own. These institutions work concurrently on several projects, some of them for other companies, and some of them internal to their respective organization. In some cases, the Research and Development for ABB products is done by the companies that are expected to manufacture the product once it is fully developed.

Project Managers from the CRC are in charge of identifying potential candidates for MEMS enabling. They provide the leadership and thrust necessary for gathering the desired performance characteristics from the BU, contacting the adequate research organizations outside ABB, setting up a timeline and then seeing to it that milestones of the project are met. This position is also responsible for coordination among different Institutes for the same project, if needed, and for final integration of the proposed modules into a working prototype. The Project Manager also works as the main interface between the BU receiving the project and the Research Institute. Once the products are ready for roll out, the current thinking is that the BU will take over completely.

All of the Project Managers have advanced degrees in Physics or related disciplines, and most have previous experience with MEMS development from their academic years.

5 ABB manufacturing vendor database development

Given the particular constraints created by the strategy outlined in (4.4.), the primary focus of the ADAMM initiative at its inception was to implement a system, database or similar solution to gather the existing knowledge base at the CRC and to standardize the different manufacturing design aspects of ABB MEMS products in order to reduce time-to-market and costs. This chapter describes the work done to develop a database that started the company in this direction.

5.1 Identification of existing MEMS processes

In order to achieve the stated goals of ADAMM, the first step was to identify and to list basic, common processes for current and future MEMS products. This approach had two goals in mind. The first one was to begin with the standardization of the knowledge base by developing a common language among the members of the CRC and also in their interactions with the institutes and vendors. The second goal was to develop a "spinal column" of processes on which to base a supplier capability survey. Finally, this common listing of standard names was expected to allow a "bird's eye" comparison of both suppliers and the different existing ABB products in the pipeline, to identify potential fits and economies of scale.

As outlined in (2.2.1), there is no commonly accepted single standard for classification of MEMS Fabrication Processes. To complicate things even more, it is also the case that some processes can be considered as sub-processes of others, and some processes (such as UV Lithography) which are usually treated as a single step are in fact a combination of processes that are so common they are hardly ever used separately. Ultimately, a decision was reached to divide known processes among 11 different "Process Families"

This classification was intended to be the most logical one, as it tried to divide the processes according to their main functionality. The different "Process Names" were collated from interviews with Project Managers, MIT Faculty, and a thorough review of MEMS literature. A total of 78 processes were identified. The resulting list became:

Process Family Names	Process Names
Deposition / Coating	Anodization
	CVD - Atmospheric Pressure (APCVD)
	CVD - Low Pressure (LPCVD)
	CVD - Plasma Enhanced (PECVD)
	Electroplating
	Lamination
	Laser-assisted polymer deposition
	PVD - Evaporation
	PVD - Reactive Sputtering
	PVD - Sputtering
	Silicon Growth (e.g. epitaxy)
	Silk-Screening or Screen-Printing
	Sol-Gel Technique
	Spin Coating and spraying
Conversion	Doping of Si - Diffusion
	Doping of Si - Ion Implantation
	Oxidation of Silicon - Dry
	Oxidation of Silicon - Wet
Structuring	Cold Embossing
	EDM: Cavity sinking by Electrical Discharge Machining
	EDM: Wire - Electrical Discharge Machining
	Etching - Dry Anisotropic: Crio-RIE
	Etching - Dry Anisotropic: DRIE
	Etching - Dry Anisotropic: RIE
	Etching - Dry Isotropic
	Etching - Wet Anisotropic: KOH
	Etching - Wet Anisotropic: TMAH
	Etching - Wet Isotropic
	High precision Micro-machining
	Laser milling / abrasion
	Laser-assisted polymer deposition (for structuring)
	Lift-Off
	LIGA - UV
	LIGA - X-ray
	Molding: Hot Embossing
	Molding: Injection molding
	Rapid Prototyping / RDMP
	Sacrificial Layer - metals
	Sacrificial Layer - polymers
	Sand / Powder blasting
	UV-Lithography: SU-8
	UV-Lithography: Thick film
	UV-Lithography: Thin film
Wafer Bonding processes	Bonding - Adhesive
	Bonding - Anodic
	Bonding - Direct
	Bonding - Eutectic
	Bonding - Glass soldering
	Bonding - Sol-Gel
Entire Wafer Surface processing	CMP (chemical-mechanical polishing)
	ECP (electro--mechanical polishing)
	Grinding

Process Family Names	Process Names
	High precision Milling
	Lapping
	Mechanical polishing
	Planarization (deposition)
Die Separation	Laser dicing
	Sawing
	Scribing
Cutting-edge and immature processes	Charged Particle-Beam Lithography
	Double-sided lithography
	Extreme Ultraviolet Lithography
	High Resolution Powder blast micro-machining
	PEMS (Printed Electro-Mechanical Systems), Direct "drawing" with
	Scanning Probe
	Scanning probe machining
	Soft Lithography (e.g. non optical)
	X-Ray Lithography (nano-lithography)
Electrical Contacts	Flip Chip / BGA
	Wire Bonding (ball-ball, ball-wedge, wedge-wedge)
Sealing	Sealing by Glass Soldering
	Sealing by Glob-Top
	Sealing by Underfill
	Sealing by Wafer Bonding
Joining	Joining by Glass Soldering
	Joining by Laser Welding / Soldering
	Joining by Adhesive

Table 1. List of Processes.

This list was used as the starting point and main index for the database, also.

5.2 ABB Current Project Survey

A detailed survey of all current projects within ABB was made. This survey consisted in contacting the different project leaders and asking for a high-level description of the different process flows employed in their products. These process flows were then "normalized" against the defined process step list, and input into the database. A total of between 10 and 20 (the exact amount is proprietary information) projects were identified, each with somewhere between 8 to 20 process steps. These process steps were then input in the database for future reference.

The information gathered in this survey also helped to develop high-level process maps such as the one shown on Figure 8. These maps had two main functions. The first was to help identify which process types the projects were converging on, in order to understand whether there were any potential economies of scale or scope (the second function is outlined in 5.3). If, for example, it turned out that several products used a common process step such as Reactive Ion Etching, the notion was that this could be a first step towards determining whether the design of process flows for the different products could be somehow altered to make use of this fact.

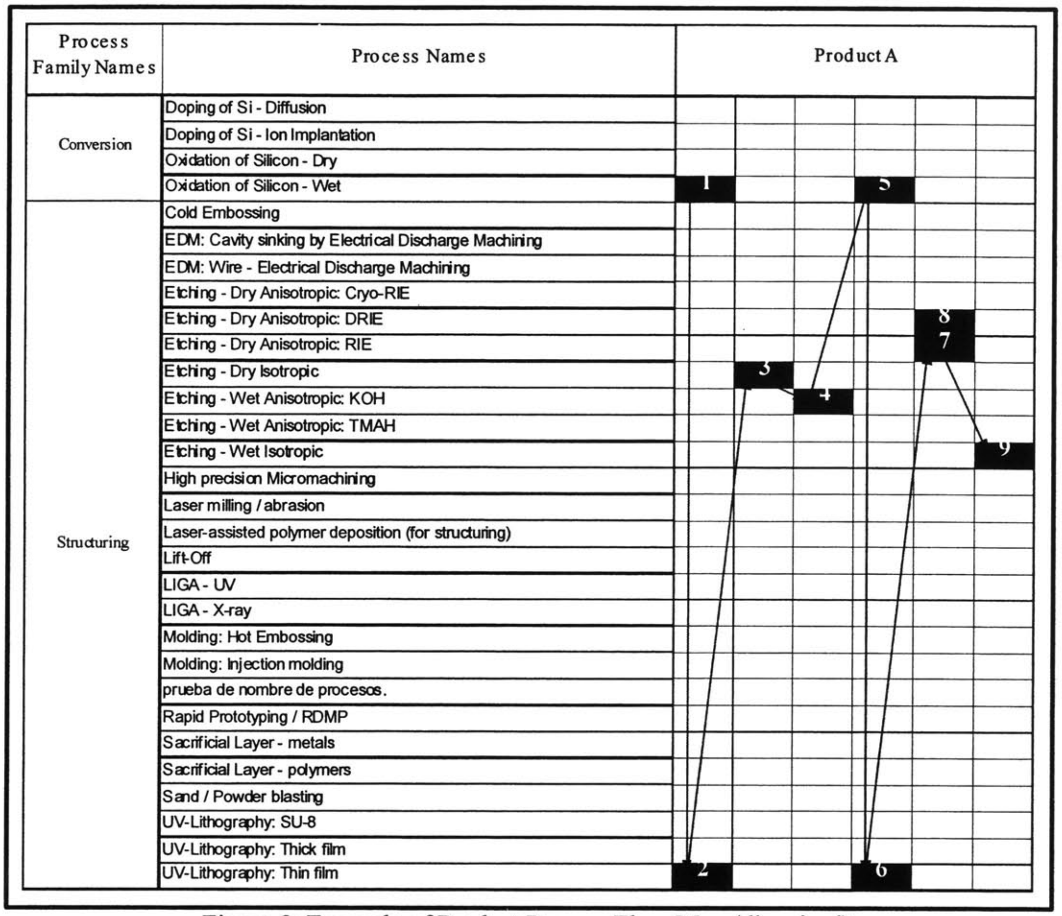

Figure 8: Example of Product Process Flow Map (disguised).

Once the number of process steps used by all projects was determined, a Pareto Chart was built (Figure 9). The analysis shows that 80% of the needed processes steps are represented by the following process steps, in order of importance:

1. UV-Lithography: Thin film
2. Etching - Wet Isotropic
3. Etching - Dry Anisotropic: RIE
4. CVD - Low Pressure (LPCVD)
5. Etching - Dry Anisotropic: DRIE
6. Etching - Wet Anisotropic: KOH
7. Oxidation of Silicon - Dry.

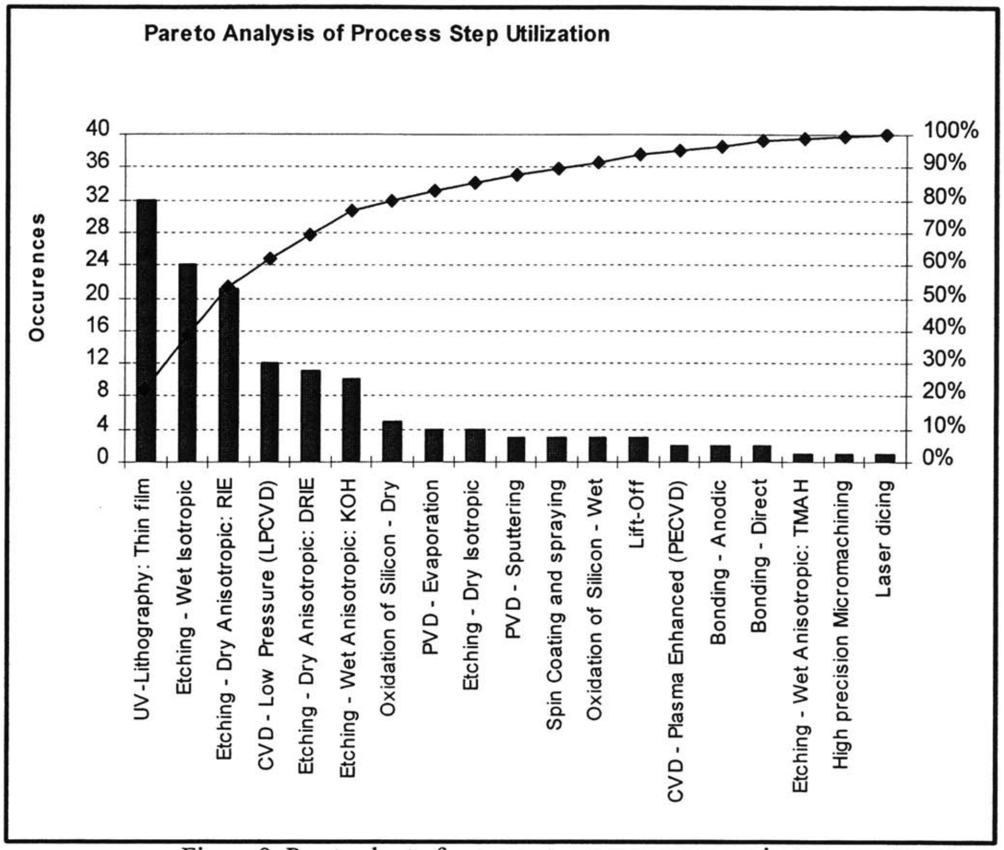

Figure 9: Pareto chart of process step usage across projects.

These represent a little less than 40% of the process steps used at least once throughout all the projects, and less than 15% of the total process steps identified in the original list.

This analysis does point to a potential area of opportunity for ABB to realize some scale benefits from the number of projects it is pursuing. However, at this high level of analysis it was not possible to determine whether the devices to be produced through these processes could somehow be amalgamated (e.g. so that several different devices can be built by a single vendor, doing multiple projects on a single wafer).

This analysis also provides another pleasant surprise, and it is the fact that none of the processes seen as potentially useful to ABB are in the cutting edge of MEMS manufacturing technology. Most of the processes considered here are fairly well understood and somewhat mature (at least within the MEMS world). This is also of importance for the discussion in Chapters 6 and 7.

5.3 Supplier Survey.

With the list at hand, a decision was made to sent out a detailed capability survey to the vendors initially contacted in the first half of 2001 by another LFM intern, Ms. Christine Wong. An electronic format was developed which was then sent out to 23 potential suppliers via email. The survey had several intentions. It was supposed to help ABB understand:

1. Which vendors were offering which processes
2. Which of the offered processes were done in-house and which ones were subcontracted by the vendors
3. Initial process parameters (e.g. Wafer Sizes, Precision, Minimum feature sizes) that the vendors were willing to specify
4. Materials that the vendors were able to work with

The results of the survey were then collated and input to the database. By the time this author left the CRC, a total of 19 companies had already answered the survey, 15 of which were based in Europe, and the rest in the Americas region. The survey itself contained an average of 5 questions per process step, which resulted in a total of slightly over 500 data points (negative answers were not counted). These were all input into a searchable database, as described in (5.4.)

	Company 1	Company 2	Company 3	Company 4	....
Anodization	n/a	Outsourced	n/a	n/a	
CVD - Atmospheric Pressure (APCVD)	n/a	Own	n/a	n/a	
CVD - Low Pressure (LPCVD)	Own	Own	Outsourced	n/a	
CVD - Plasma Enhanced (PECVD)	n/a	Outsourced	Own	Own	
Electroplating	n/a	Own	Own	Outsourced	
Lamination	n/a	Outsourced	n/a	n/a	
Laser-assisted polymer deposition	n/a	Outsourced	n/a	n/a	
PVD - Evaporation	n/a	Own	Own	n/a	
PVD - Reactive Sputtering	n/a	Outsourced	Own	Outsourced	
PVD - Sputtering	n/a	Own	Own	Outsourced	
Silicon Growth (e.g. epitaxy)	Outsourced	Outsourced	n/a	n/a	
Silk-Screening or Screen-Printing	n/a	Own	n/a	n/a	
Sol-Gel Technique	n/a	Outsourced	n/a	n/a	
Spin Coating and spraying	Own	Own	n/a	Outsourced	
⋮					

Figure 10: Supplier matrix.

Concurrently, a matrix was developed that charted the process steps on the vertical axis vs. the suppliers on the horizontal axis. Each intersection was marked with either "Own", "Outsourced" or "n/a", depending on the responses to the survey. They were also color-coded (see Figure 10, colors are not shown because of coloring constraints on the thesis). This matrix was then printed out at the same scale of the process maps described in (5.2.), which were printed out in transparencies, and then juxtaposed. This was a very crude but effective way to determine which vendors were eligible to be contacted as potential suppliers for a specific device (See simplified example in Figure 11).

Process Names	Company 1	Product A						Company 2
Cold Embossing	n/a							Outsourced
EDM: Cavity sinking by Electrical Discharge Machining	n/a							Outsourced
EDM: Wire - Electrical Discharge Machining	n/a							Outsourced
Etching - Dry Anisotropic: Cryo-RIE	n/a							Own
Etching - Dry Anisotropic: DRIE	n/a							Own
Etching - Dry Anisotropic: RIE	Own	■				■		Own
Etching - Dry Isotropic	n/a							Own
Etching - Wet Anisotropic: KOH	n/a		■					Own
Etching - Wet Anisotropic: TMAH	Own							Outsourced
Etching - Wet Isotropic	Own		■			■	■	Own
High precision Micromachining	n/a							Own
Laser milling / abrasion	n/a							Outsourced
Laser-assisted polymer deposition (for structuring)	n/a							n/a
Lift-Off	n/a				■			Own
LIGA - UV	n/a							Outsourced
LIGA - X-ray	n/a							Outsourced
Molding: Hot Embossing	n/a							Outsourced
Molding: Injection molding	n/a							Outsourced
prueba de nombre de procesos.	n/a							n/a
Rapid Prototyping / RDMP	n/a							Outsourced
Sacrificial Layer - metals	n/a							Own
Sacrificial Layer - polymers	n/a							Own
Sand / Powder blasting	n/a							Own
UV-Lithography: SU-8	n/a							Own
UV-Lithography: Thick film	n/a							Own
UV-Lithography: Thin film	Own	■	■	■	■			Own

Figure 11: Comparing suppliers and products. In this case, clearly Company 2 comes into question for Product A, whereas Company 1 does not offer two of the needed processes.

Finally, a review of the survey results reveals that for every one of the processes listed in (5.1) (except those listed as "Cutting Edge and Immature Processes") there was at least one positive response from a supplier willing to offer it. As was to be expected, no single supplier has every process available. It is important to note that the frequency distribution of offerings follows pretty much the same pattern as for the processes that ABB is looking into, which is very promising.

5.4 MEMS Database

Given the amount of data to be handled, and in order for it to be easily accessible in the future, a decision was made to incorporate all the received information into an electronic database. A relational database was designed and implemented, with the structure shown in Figure 12. It was designed to be highly searchable, and with the needs of both the members of the CRC and from the BU in mind. In the first case, it is expected that project managers will need information on a specific vendor or process, whereas the users in a BU will use it mostly as a reference for other projects.

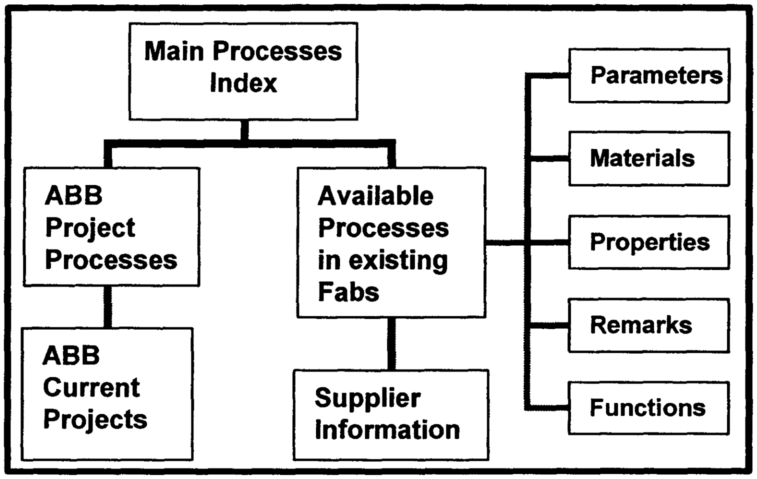

Figure 12: Simplified database structure.

The Main Processes Index serves as the foundation for the whole database. The database itself is divided into two main areas. The first one (depicted on the left in Figure 12) is the list of current projects, with a description of the projects, and the list of the process steps used in it with some high-level parameters or characteristics associated with each.

The second area is the one where the data gained from the survey is held, with some added, "general" information related to each process added to it. It is also linked to the database with the contact information for each supplier. (see Figure 13 for a figurative example that uses all the information that can be potentially stored for each process step). This is the main area of the database. The categories that were chosen to associate to each process step are:

1. Parameters: These are actual achievable process parameters (e.g. Thickness of a deposited film, minimum feature size for UV-Lithography, etc.) provided by the vendors, with corresponding tolerances. This table also lists whether the suppliers offer the process themselves or through subcontracting.
2. Materials: Vendors were asked to specify which materials they were able to work with for each process step.

3. Properties: Each process step has qualitative properties that are also included. These stem from both responses to the survey and from reviewing the literature and conversations with different experts in the field. Most of these properties are unique to each process and at a higher level, to each process family, and that is why they were given a separate index.
4. Remarks: Four types of remark categories were defined: "Advantages", "Disadvantages", "Design Rules", and "General". Remarks are intended to provide a common criteria against which to compare between different processes, across process families.
5. Functions: This last association was not implemented, due to time constraints. It is intended to serve as a way to start the association between processes and typical applications. A very simple association would be to associate the function "trench" with DRIE, for example. Also, a function can be shared over a sequence of processes.

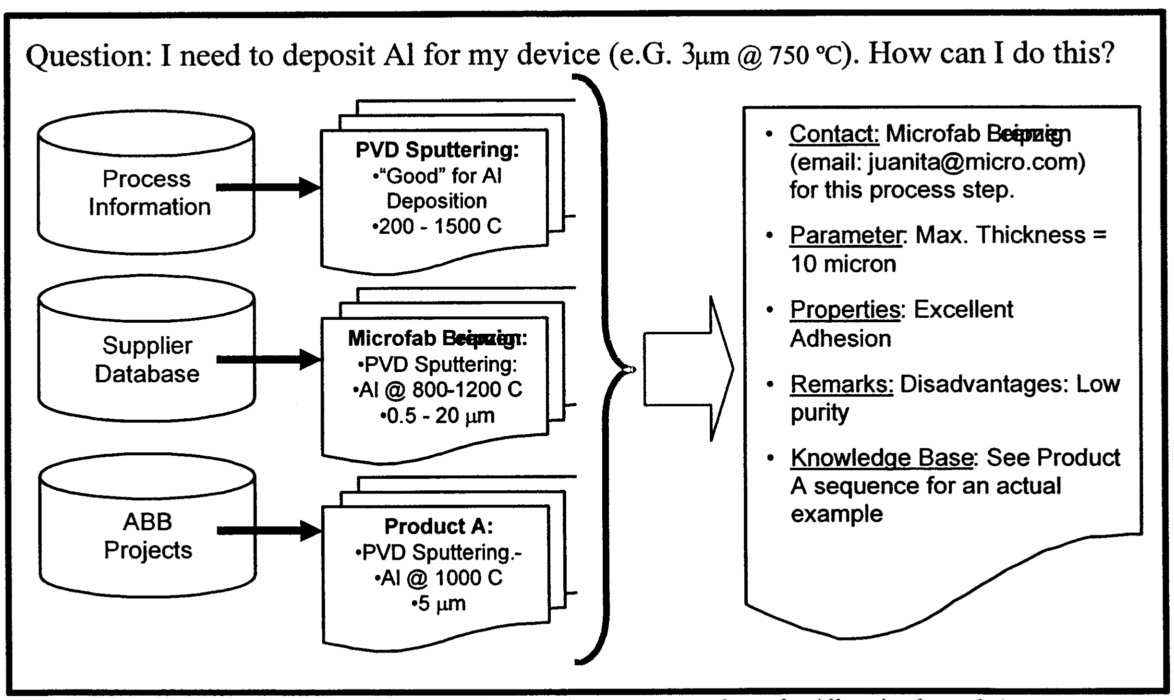

Figure 13: Example of a possible database query and results (disguised results).

The database was set up in such a way that the user can navigate through it relatively easily (provided he or she has very basic knowledge of MS Access). For example, if a user has identified a specific process offered by a company and its associated parameters, he can look up the contact information for the vendor, as well as look up examples of where this process step is used in other ABB projects. He can then consult the knowledge base to understand the qualitative characteristics of this process.

The biggest challenge with the database was not so much in setting it up, as it will be in keeping it up to date in the future. It was designed to be serviceable with little effort, and new information can be input into it easily.

However, as an initial step towards the anchoring of an ABB MEMS Knowledge Base, this database could prove to be of high value. The biggest difficulty that ABB will face in the world of MEMS is in managing the complexities of the technology (more on that on Chapter 6). Currently, most of the expertise and know-how resides in a few groups scattered around two or three Corporate Research Centers spread throughout Europe. The awareness of the potential of MEMS (and also of the difficulties in making them a reality) is not very well spread to the BU's that will in the end benefit the most from it. This database and the work done in surveying the existing process could potentially be used as part of a complete teaching tool to disseminate this know-how. If maintained properly, it will also be of great help as a reference and as an "organizational memory" depositary.

6 Strategic issues for ABB MEMS initiative

In the current MEMS marketplace, where the pace of technological innovation is accelerating to an ever faster pace, companies have to be sure-footed and act with both speed and cunning when entering it. This chapter uses the frameworks discussed in Chapter 3, as well as the singularities of MEMS manufacturing discussed in Chapter 2 to analyze the decisions described in Chapter 4.

6.1 The technology cycle and MEMS

As discussed in (3.2.), Christensen has set three benchmarks to understand whether a technology is in a development stage where vertical integration is no longer the predominant mode to gain competitive advantage. A company has to make sure it has robust answers to three questions, namely:

1. Is it able to specify what attributes it needs?
2. Is the technology to measure those attributes reliably and conveniently accessible?
3. Does it have a clear understanding of what it will do when there is variation in what is delivered by the supplier, or when changes in the attributes are needed?

The answers for MEMS at ABB are yes, maybe, and not really, respectively. The company has a long track rec6rd of working in the Instruments marketplace, which has given it a very tight understanding of the needs of its customers. ABB is also well renowned as a provider of first-rate measuring equipment for process industries. It has a very strong foundation in metrology, too. It is therefore very well positioned to use the advantages in MEMS technology for some of its sensors. It has a very clear understanding of what the specifications for each MEMS-enabled device are, and in fact follows their development very closely to make sure that the devices actually live up to their expectations. In terms of device attributes, then, it has a very good ability to specify what is needed.

However, MEMS technology has not developed to a point where there are universally accepted standards for quality, manufacturability, reliability and repeatability of processes, and such. The only means to find out whether a potential vendor has the attributes required for production of ABB's devices is to do several pilot runs, learning by experimenting. The main learning from having prepared and distributed the survey to vendors is the lack of a uniform language to even name processes the same way, for example.

At this point in time, ABB has not clearly defined what the organizational structure will be that will manage the relationships with its vendors once the products are past the prototyping phase. This makes answering the third question a rather complicated affair. As seen in Chapter 2, in the case of MEMS, design and manufacturability are very closely intertwined. As it is expectable that changes in the original product will be needed a few years after initial basic research and development, it is not very clear at this point what the process will be for handling those design and manufacturing process changes. Conversely, if a supplier of a subsystem decides to change some of its manufacturing equipment or processes, it will have an effect on the design and performance of the device. Again, the question arises of how ABB is planning to handle those contingencies.

If the ideas presented in section (3.2.) were followed to the letter, it would seem that vertical integration is the option that best would allow ABB to gain a competitive advantage in MEMS. It would allow ABB to base its offering on providing complete solutions to customers given its ability to extract the most performance possible through design of each of the major subsystems. MEMS technology is clearly at the early stages of the area denominated 'Beat Competitors with Functionality' in Figure 4. Still, the scale of the projects in terms of piece volume does not seem to justify the large investments that would be needed.

The risk of such an investment is accentuated by the high level of specialization of the installations needed to manufacture MEMS. The type of factory and equipment needed would be very difficult to utilize in other lines of products if the projects currently in R&D did not bear fruition in the marketplace for ABB. In colloquial terms, the risk is very high of getting stuck with a great, useless white elephant. ABB's current financial and strategic situation do not warrant such a situation.

The nature and management of the relationship with its vendors will become then the key success factor. Given the described situation, this analysis is of the utmost importance because the company needs to be keenly aware of the consequences of outsourcing production at such an early stage in the technology cycle and the subsequent tight relationship between development and manufacturing.

6.2 Value-Chain Frameworks for ABB and MEMS

Let us go one abstraction step below in the strategy analysis, and look at it through the analysis tools provided in (3.3.). The Strategic Value Added model asks that we go through the following 5 questions:

1. What is the relative customer importance?
2. What is the technology evolution rate ("Clockspeed")?
3. How well positioned is the company in terms of cost, quality, etc. vs. its competitors?
4. What is the status-quo of the supply base?
5. How modular or integral is the element to the overall product or system?

These questions are answered below.

6.2.1 Customer importance.

The customers at which this technology are directed are scattered around the world, and their needs vary from country to country. ABB is not pursuing any project where the MEMS-enabled device will be high-volume, but rather where they will be high-margin. In order to do this, its products have to be viewed as high quality and with high technological content. These products could become important in the future as part of ABB's new "integrated offering" strategy. Still, even the highest estimate of 400 million USD annual sales of MEMS-enabled devices throughout the company amounts to less than 3% of projected overall revenue in 2003[xxxii]. This would seem to point towards Medium to Low Customer importance.

6.2.2 Technology evolution rate ("Clockspeed")

MEMS are evolving at a very fast pace, although not necessarily as fast as semiconductors, even though both use the same production technology base. Given that very few products have been able to break the manufacturing barrier, it is really difficult to measure product evolution cycles.

There are few examples that can be utilized for measurements. The basic technology and solutions for accelerometers, for example, evolved dramatically only once since they were first introduced. This is illustrated in the case of the evolution of Analog Devices' ADXL family of accelerometers, where the evolution in manufacturing capabilities has allowed them to change their design from a closed-loop force-feedback system in the ADXL50 to an open-loop system in the ADXL150 that uses the advantages of increased linearity and accuracy in fabrication that are now achievable.[xxxiii] This evolution took about ten years to occur.

However, the pace at which working prototypes are announced, using ever-new production technologies and general insights about what is achievable with MEMS, does seem to point towards a relatively fast Clockspeed. It is widely believed in the industry that once a certain level of standardization in manufacturing is achieved, the market will grow exponentially and the number of available designs with it.[xxxiv]

6.2.3 What is the company's competitive position?

ABB does not necessarily enjoy a predominant position in all of its sensor markets. Sensors are usually sold as part of integrated solutions for automation, or as part of process industry projects. ABB does enjoy a well-deserved reputation for quality and high technology content, however. It also seems that ABB will enjoy first-mover advantage in MEMS. This could translate into a high barrier to entry for its competitors, given that the development time for MEMS is so long. In terms of substitutes, ABB serves markets with very specialized sensing needs, and it is therefore doubtful that customers will turn to substitutes, as there are very few. Its internal structure may have inhibited it from increasing its bargaining position over its suppliers, but with the new streamlined structure it would seem to be better positioned to do so. Overall, ABB's competitive position can be seen as strong to very strong.

6.2.4 What is the status-quo of the supply base?

As noted in Chapter 5, there are relatively few potential suppliers of MEMS-manufacturing services. Even if the complete supplier base around the world is considered, it is as yet unknown whether any supplier will be able to provide ABB with the complete range of fabrication processes it requires.

Also, the dynamic forces in the market should also come into consideration. Currently, there is a lot of unused demand in the foundry services market in large part due to the dire situation of the telecommunications industry. During the 1990's it was believed that MEMS showed a great promise as switches for optical networks, and a significant number of fabrication companies were set up in preparation for the perceived coming avalanche of products. With the telecomm industry in the doldrums and the corresponding lack of investment, a lot of extra capacity has been freed up in the last two to three years. This can not be expected to last, however. In the past, telecom equipment companies simply gobbled-up companies with MEMS manufacturing capacity, which in turn were no longer permitted to sell their capacity to the outside world. This could be the case again in the next five years.

On another dimension, ABB cannot consider that by outsourcing its MEMS production it will only be dependent on its suppliers for capacity. As has been discussed in Chapter 2 and further in (6.1.), design and manufacturing of MEMS are so closely related that they will inevitably become dependent to a certain degree on their supplier's manufacturing know-how. This could result in a very unwelcome dependency for basic device design, too, especially once the projects are no longer in the hands of MEMS experts at the Corporate Research Centers.

6.2.5 How integral is the element to the overall product or system?

MEMS are an integral part of all the products surveyed in Chapter 5, and at this point there is very low modularity and interchangeability among them. Although it is viewed as a possibility somewhere in an undefined future, currently the subsystems for each product are not being designed to potentially interact with other MEMS devices under development. The MEMS subsystems are all critical to the functioning of the envisioned equipment

6.3 MEMS at ABB and the make-buy matrices

The answers to the preceding questions enable us to map ABB's MEMS initiative in the two matrices reviewed in (3.3.), as shown in Figure 14. The items are fully integral to the whole design, although the dependency that will be established vis-à-vis its vendors will go beyond pure capacity considerations, as the suppliers will play an important role in developing the fabrication processes. On the matrix on the right, the suppliers are characterized as few, especially given the constraint in the lack of complete solutions offered by any single one. The Clockspeed of the technology is evaluated as slow to fast, because as discussed above, the pace of technology innovation in manufacturing technologies, although admittedly fast (it basically follows Moore's Law from the IC industry), is not as fast as it is for software development, for example.

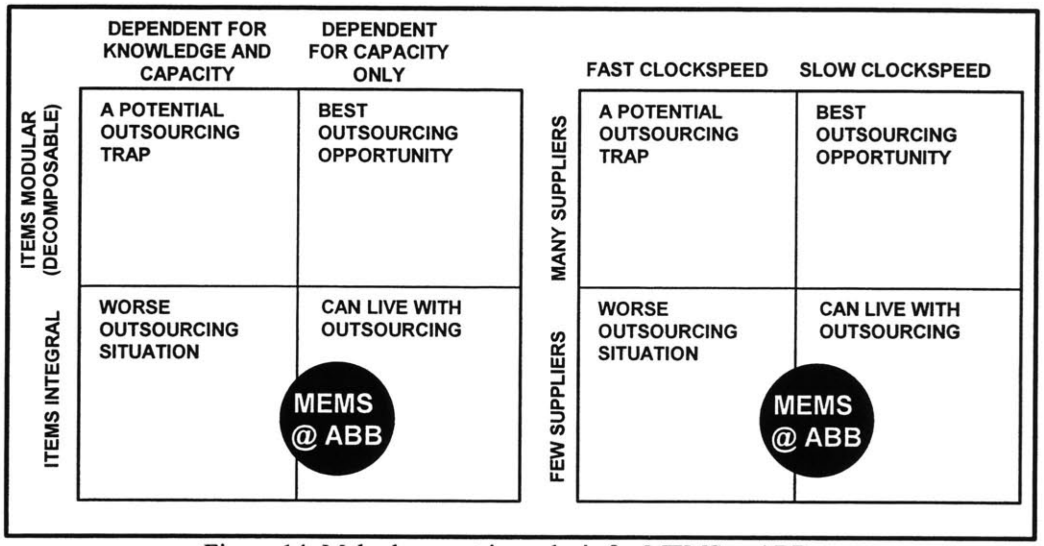

Figure 14: Make-buy matrix analysis for MEMS at ABB.

Outsourcing MEMS production is clearly not the most comfortable option. In the first matrix, the undetermined degree of dependency that can ensue from not developing a proprietary manufacturing capability combined with the integrality of the MEMS subsystems to the proposed products, could result in a very weak strategic position for ABB once the products are in full production. At the same time, the combination of accelerated Clockspeed and the limited number of suppliers could put the company in a very precarious situation.

6.4 Implications on the decision to outsource

The situation created by the low economic attractiveness of vertically integrating MEMS production, together with the singularities of the MEMS manufacturing market, combine into a powerful dilemma for ABB. Abandoning the technology altogether is not an option, as it has great promise to improve ABB's product offering, and its competitors can be expected to come up with MEMS-enabled products of their own sooner rather than later. At the same time, it needs to come up with a sustainable strategy to produce these products, and do so very promptly.

The company needs to develop a model that will help it to bridge the gap between being in a bad outsourcing situation and the need to outsource. Several options come to mind.

6.4.1 External options.

From an external strategy point of view, the company has several options at its disposal, as discussed in (3.2.). Its main priority is the development and preservation of a competitive advantage through MEMS technology. It is currently focusing on product development and a very aggressive patenting program. And this should remain its primary focus, too. At the same time, the company needs to develop a clear tactical plan in two different areas: Strategic Alliances and possible Acquisitions.

In terms of strategic alliances, the company must look for opportunities to form alliances that will then help set industry standards (e.g. for relatively commonly occurring, not entirely critical components such as micro-valves for gas flow control). Also, it should review its admittedly very powerful patent portfolio and look for opportunities to adopt a licensing strategy that will help it become the trendsetter for MEMS analyzers. Finally, it can look for alliances with other potential entrants in similar areas so that the core technologies are jointly developed but exploited in separate markets.

As for acquisitions, the company could look for opportunities to acquire (or at least become equity investors) in fabrication services start-ups or more established companies. Even if it does not get a controlling stake, it should at least insure its supply base by obtaining veto power against other companies taking over their production capability and edging them out of the market. This would shield them from the risk of investing in a white elephant and at the same time protect their supply base. Further, it would help ABB remain in control of its Intellectual Property, by making sure the vendors do not utilize ABB's IP for other projects or companies. It would also provide them with a quick exit-strategy in case they decide to change supplier or devices. There is a window of opportunity for this, given the situation described above for the Telecommunications industry, and ABB should act swiftly.

6.4.2 Relationship Management

In terms of the relationships with the vendors (whatever final form they should take), several key issues need to be addressed in order to assure a successful MEMS venture at ABB:

1. The relationships with the vendors need to be designed. As noted above, the company must decide which decision rights it will keep for itself, and how to manage them effectively. It must have a very clear guideline of the amount of Intellectual Property that it is willing to share with its partners and how much it intends to extract from them. It must also determine how it will manage deviations from the agreement, and how to enforce its covenants. It must have a clear understanding of what will be done internally to obtain the needed performance (in costs, quality, on-time delivery, yield, etc.) from its suppliers.
2. The infrastructure of relationships needs to be set up. Given the nature of MEMS development, the company would benefit from establishing working relationships with a large group of vendors very early on in its development process. It must also develop alternatives for itself among the pool of suppliers, so that if one vendor is unable to provide the needed amount and/or quality and performance of the devices, they are able to switch their production to another vendor with enough speed that it will not upset their customer base.
3. The evolution of the relationships needs to be well understood and managed. Given the tight knit between manufacturing and product development, the goals and incentives for the different players are different along the different stages of product development. At the development stage, for example, most of the emphasis and incentives will be on being able to come up with a working prototype or prototypes, and costs will not necessarily be the main measure of a supplier's performance. Once the device is in production, cost and yield become more important, and the incentive structure must be adjusted accordingly.

Also, and under the current system, at the development phase the main contacts between ABB and the vendors occur through the CRC (see Figure 15), and this relationship is then handed over to the BU once the project has been released for production. Thus, the interface with the vendor changes.

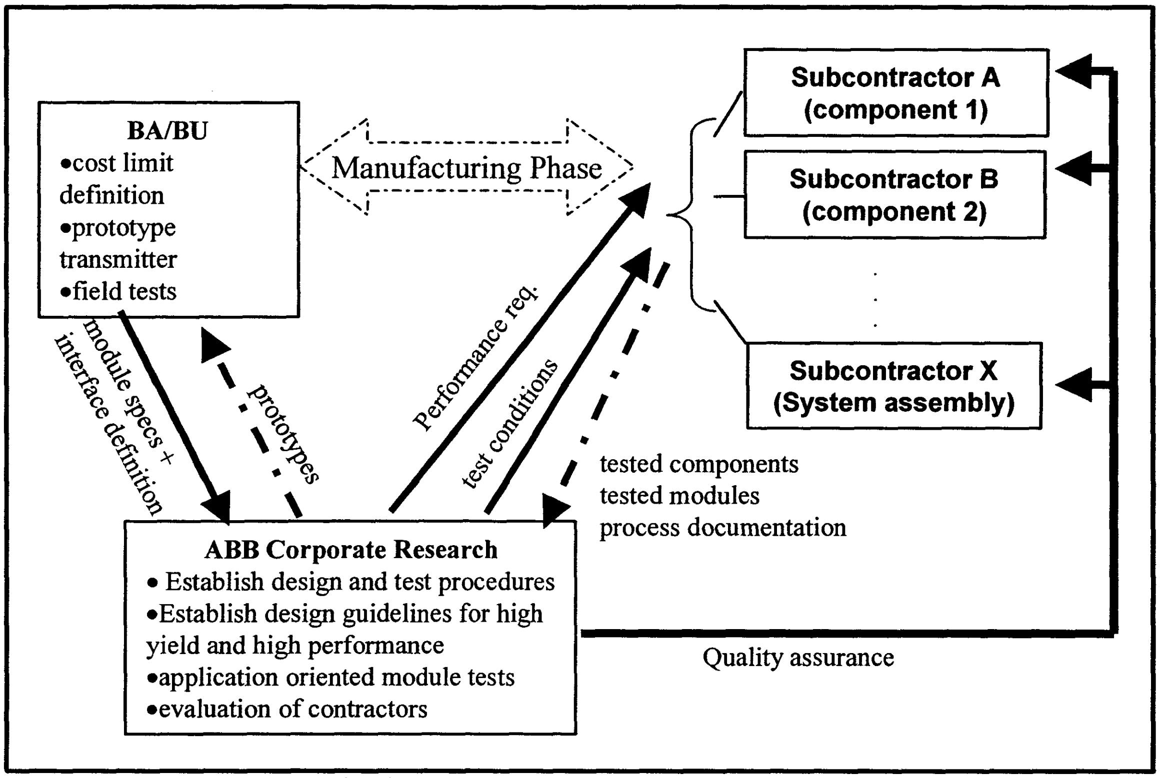

Figure 15: Relationship set-up at the prototyping phase for a single BU under the current system. Note that once the product is in the manufacturing phase, the CRC is basically cut-off from the relationship.(Adapted from [xxxv])

4. Clear lines of responsibility for the relationships need to be determined. The vendors need to perceive a unified effort and voice coming from ABB. Otherwise they will use whatever internal confusion they perceive to their own advantage. Also, and in order to obtain the maximum leverage and potential economies of scale and scope, it is recommendable that the company sets up some type of process or system that will allow it to "see the forest from the trees".

The four milestones described above are not necessarily that complex to achieve. Companies such as Sun Microsystems[xxxvi] have developed the ability to establish and maintain long term relationships with their outsourcing manufacturing partners. Their need for outsourcing of integral, Sun-customized server subsystems has led them to develop a model where they work along with their suppliers through every step of the development process, and by the time the products are rolled out into full production, they feel confident enough about the relationship to allow their suppliers to take over some of the design and modification functions as the product evolves.

6.4.3 The MEMS Competence Center

Under the current Product Development System and following the Gates Process at ABB, ownership of the know-how and technology are passed along to the BU once the product has demonstrated its feasibility. It is up to the BU then to come up with solutions to manufacture and sell the product, with little or no CRC participation. As seen repeatedly in this thesis, MEMS manufacturing and its close relationship to device design and development mean that this process is not necessarily as applicable in this case. Even more so when the added complexity of the relationship with the vendors is added to the mix.

In the case of MEMS, the relationship that is set up with a vendor at the beginning of a research project remains in place all the way through final production release and product roll-out. Management of this relationship will be the key to success for ABB. It must insure that the relationship remains fruitful and of value to both partners, and that very clear-cut roles and responsibilities for all the functions (BU, CRC, vendors) involved are set up from the beginning, and well maintained. Also, once several relationships are set up for the different products that ABB has in the pipeline, a decision has to be made as to how they will be managed in conjunction.

In a company as decentralized as ABB, the risk is very real that a web of relationships will develop on its own where different BU's unknowingly have contracts with the same vendor, for example, and that the vendor will use this situation to its own advantage. Furthermore, given the relatively low level of proficiency in MEMS technologies that the BU's posses, the building of MEMS skills within the BU will be of primordial importance, as they will otherwise increase ABB's dependency for knowledge on their vendors. Finally, the flatness of ABB's internal structure could translate into a lack of oversight about all the different relationships established over the years, which could then hamper the company's ability to extract economies of scale and/or scope from its variety of MEMS-enabled products and the relationships with several vendors.

A potential, recommended solution to this dilemma is the creation of a so-called MEMS Competence Center (Figure 16). This organization would be ultimately responsible for setting the strategy and tactics of MEMS development and manufacturing at ABB. MEMS is a very complex subject. It takes years of education and practical exposure to reach a sufficient level of expertise. The development projects take long enough that it is hard to maintain the institutional "memory" that will be the most important asset in managing the network of relationships with the vendors. Also, and given the size of the MEMS initiative (not more than 20 projects are active today), it is doubtful that an effort to disseminate know-how to the BU's will be effective in the long run. Instead of focusing internally and having to grapple with an added complexity, the BU's should be able to focus on their customers.

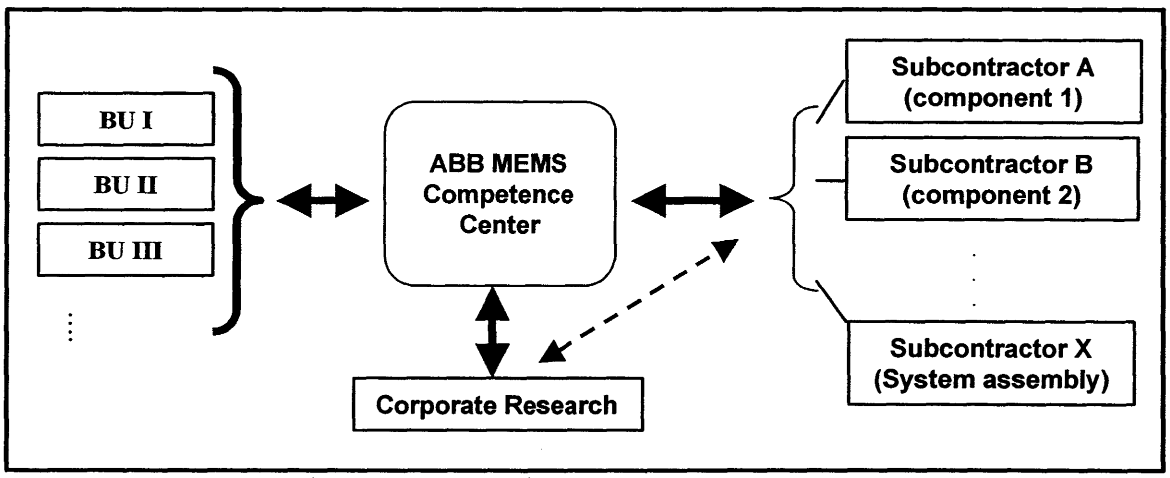

Figure 16: The role of the MEMS Competence Center.

The MEMS Competence Center would then become the depositary of the knowledge base developed at the CRC and BU level, as well as the main interface between the BU and the vendors. In fact, the Competence Center could be set up as a profit center where they would "sell" the MEMS components to the BU's at a negotiated transfer price, and provide support in terms of design and performance specification changes. The Competence Center would in turn buy services from the vendors (and, as needed, from Corporate Research).

If the incentives structure for the Competence Center is set up correctly, they can be held responsible for the whole life-cycle of the MEMS-enabled products. It would provide both the BU's and the vendors with a single point of contact for MEMS at ABB, which, when set-up with enough care and the right combination of people, could increase efficiency by unburdening the BU's while keeping a tighter control on the vendor relationships.

This independent structure would give the Competence Center an incentive for effectiveness, as well as create a strong, vibrant MEMS organization within ABB. By being solely responsible for the relationships with the vendors, and as a virtue of being a single organization, the Competence Center would be then better positioned to tackle the challenges mentioned at the beginning of this section. This Competence Center could be partially staffed with current members of the CRC teams in charge of MEMS development, and with Technology Mangers from the BU's interested in enabling their product lines with MEMS devices.

A basic way to measure or benchmark the efficiency and competitiveness of this MEMS Competence Center would be to set a goal for it to sell some of its basic products (and maybe even services) outside ABB, making sure it was not aiding a competitor, of course. This would also start ABB in the direction of being a standard-setter in their industry. Plus, the BU's can be given the option of sourcing their MEMS-parts externally, if they find partners that offer them a better, complete solution for their MEMS initiatives, also increasing the pressure on the MEMS Competence Center to be competitive vs. the marketplace.

7 Factors for success and potential pitfalls going forward for ABB

Regardless of the final structure that ABB chooses in order to tackle the challenges in manufacturing MEMS, there are some considerations that need to be taken into account. This chapter reviews those considerations, both factors for success as well as potential pitfalls.

7.1 *Why it should go really well*

There are several reasons to be optimistic about the prospects of MEMS at ABB. Starting with the caliber of the people involved in this initiative. The main push for this technology is centered around the CRC in Ladenburg, Germany. The people in charge all have obtained advanced graduate degrees, some of them centered on specific areas of MEMS development. They have demonstrated leadership qualities and a deep understanding of the actions needed to make MEMS a reality at ABB. They also share a strong belief in the promise of this new technology, which by itself lends a lot of credibility to their efforts. Finally, the Program Manager for MEMS has a very clear, tight understanding of how to make this initiative work, and under his stewardship the first products should be rolled out at the end of 2002.

Also, MEMS technology itself promises to become an extraordinary source of competitive advantage for some of ABB's products. Due to proprietary information considerations, this thesis does not discuss the details of the products currently under development. Still, some of them can be mentioned without revealing critical data. For example, the project under development that shows the most promise entails a new, radical solution to a customer need in the Process Industries BA. If the research work is successful and the new platform is adopted, the new product will occupy less than 5% of the volume of the current equipment, require less than 25% of the power supply, will be permanently pre-calibrated at the factory for precision and will require absolutely no use of external chemicals (instead, customers will only need to change a disposable cartridge every few months). The life-cycle costs for the customer of this new solution should be less than half of what the current solution entails.

Another reason why MEMS at ABB could prove to be a major stepping stone is the nature of MEMS technology itself, and its current evolutionary stage. True, there is low standardization in the industry and manufacturing is a key barrier to entry. But still, it is expectable that over the next few years[xxxvii] the industry will mature to a degree where MEMS become ubiquitous. The companies that manage to position themselves at the forefront of this revolution should be rewarded handsomely in the near to mid-term future. ABB even has a window of opportunity to become the standard setter in some of the analyzer markets if it manages bring its products to market fast enough.

Furthermore, there is an opportunity to capitalize on ABB's name and credibility as a way to achieve the margins that should allow them to overcome the inefficiencies of low volume. In order to achieve this and extract the maximum possible surplus from the market, ABB needs to insure that it is the first-mover into the market.

In terms of management of the technology, ABB has taken a step in the right direction by launching the ADAMM project. This should enable the company to give a holistic approach to this initiative, from initial idea all the way to the full production phase. It should allow ABB to front-end-load much of the work needed around the development of critical elements of its knowledge base, such as supplier selection criteria, quality assurance procedures and homogenized testing standards. Most importantly, it will give ABB a head start in the development of modular component and process libraries, which could then serve as the cornerstone for the MEMS Competence Center.

Finally, there is some promise in the European model of manufacturing clusters, which could also prove to be of great advantage to ABB. One of the reasons why foundry clusters are favored in Europe is geographical proximity, where most of the "fabs" are at the most one day away by truck from each other. This could actually enable ABB's tactic of distributing its production across several vendors, where each realizes a different set of process steps on the wafers, which are in turn transported between facilities in sealed boxes of 10 to 20 wafers. This could prove to be workable, especially given the projected low-volume of production.

7.2 Why it could go wrong

ABB needs to be acutely aware of a number of factors that could potentially derail its efforts at enabling part of its product line with MEMS technology. MEMS development is a difficult endeavor, which can not be taken lightly. The current development stage of the technology itself means that there are many potential pitfalls on the road ahead for any company.

The main risk lies in the lack of clear understanding by management about the nature of the new technology. It is imperative that upper management develops a clearer understanding of the complexities in MEMS development. The decision to outsource should be open for revision once a few products have demonstrated their mettle in the marketplace, for example. Upper management needs to be aware of the close relationship between development and manufacturing, and the needed organizational structures that must be set up for the initiative to be successful.

Another source of risk is in the explosion of projects that are not closely related to each other in nature, and therefore cause the company to miss opportunities in potential economies of scope. Given ABB's decentralized structure, the de-aggregation of efforts within ABB is a very real possibility that must be avoided. Even more so given the importance of developing standard structures and modules for ABB. Low volume is the key obstacle for MEMS development at ABB. It must therefore look for ways to aggregate some of its projects in ways that make up at least a little piece of that volume.

Under the current development model, ABB is utilizing the design and development services of universities and research institutes, with the goal in mind of then transferring the development of the resulting device idea to a commercial fab for process development. This may very well be one step too many. There are some advantages to working with universities and research institutes in that they are less constrained in their idea creation and will probably be more willing to push the edges of what is achievable with MEMS. If, however, the solution envisioned by the university or research institute proves to be unworkable for a commercial fab, all the valuable effort will have been wasted. The commercial vendors should be involved very early in the process and manufacturability concerns should be at the forefront of the design process.

Which points to another source of uncertainty. Currently, there is no well defined and accepted model for management of Intellectual Property. ABB is doing an extraordinary and successful effort at patenting every step of the development process. However, when it comes to development of the fabrication process, the question of who owns what pieces of the IP is still open at this point. This is very important because a key element of competitive advantage for ABB will be to insure that it has exclusivity in the development of special processes for its products. It must eliminate the possibility of a vendor transferring know-how gained in a process developed for ABB to a competitor.

Parallel to the definition of the ownership of intellectual "property limits", it is important to determine who will take care of the engineering and risk of manufacturing process development, who will pay for it, and how it will be kept under ABB's control. Vendors will probably be interested in ABB's business not simply in exchange for a contract and payment, but also because each contract gives them an opportunity to climb up the learning curve and use some of the development work for their own or some other client's purposes. ABB needs to define how much of that it is willing to give up in exchange for outsourcing its production.

Given the intertwined nature of development and fabrication, ABB runs the risk of becoming "wedded" to a specific fab. This is a very dangerous situation given the integral nature of the MEMS subsystems in the envisioned products. A straightforward solution would seem to be to develop second-source vendors early on, but it will be very difficult for find two vendors willing to provide the exact same process flow for a product. This would seem to point to the need for flexible designs that achieve the same performance characteristics with a few differences in final layout, so that they can be adapted from one vendor's fabrication process to the other with a little more ease.

Finally, if the company decides not to implement or develop a MEMS Competence Center, it must focus on establishing a clear procedure for the delivery or transfer of the relationships with its vendor to the BU's. This delivery would then start with the very early involvement of BU technologists, who need to become familiar with the specific "idiosyncrasies" of the MEMS world, and who must be able to carry the burden of managing this high-tech product and its need of fabrication knowledge.

8 Concluding remarks

MEMS is a very challenging and exciting new field with a lot of promise for ABB. From the point of view of its customers, the type of solutions that the company could potentially offer in the sensors and analyzers marketplace is extraordinary. The potential reductions in size and power requirements, coupled with the expected increases in sensor performance point towards a breakthrough improvement in their product line. Also, it is to be expected that if ABB does not incorporate this technology into its offerings for the sensor market, sooner or later one of their competitors will.

The current development stage in the technology means that ABB has to make a number of strategic and tactical decisions concerning how exactly they will reap the bigger benefits from this new technology. More precisely, ABB needs to constantly be aware that:

MEMS manufacturing is difficult. It requires a high degree of fabrication expertise, as well as the conjoint work of highly skilled scientists in several diverse disciplines (i.e. as diverse as fluid mechanics and electrical engineering). The group of processes required to successfully manufacture a device is very complex and difficult to control. It is highly iterative, and no quality assurance standards have been developed throughout the industry. Furthermore, there are no libraries of standardized modules (such as is the case for ASIC's) and structures that can be used as a reference. Each new product poses a new, unique manufacturing challenge. Manufacturing is the main barrier to entry in MEMS, and will probably remain so in the foreseeable future.

MEMS development and manufacturing can not separated from each other. Given the low level of standardization in industry, and the experimental nature of some of the existing processes, it is fabrication that will constrain the limits of achievable designs. Design of MEMS devices is a highly iterative process that cycles between idea development and manufacturing considerations. The main consequence of this is that the process sequence usually will drive the design, and not vice-versa. This has important implications for both the development and the implementation phase. Manufacturability determines the design, and any changes in the fabrication process will affect the design. Inversely, any changes in design have to be revised for manufacturability.

The market for foundry services is not yet mature. The marketplace at this point does not pass the litmus test of modularization and standardization of devices and processes that would make the decision to outsource a clear recipe for success. MEMS fabrication is in many ways still in the craftsmanship stage. Designs are not easily transferable between different foundries. Homogenized quality standards are non-existent. Each vendor has different capabilities, and very few or none offer the whole range of processes available in industry.

Vendors need to be evaluated on their capacity to provide the complete process sequences for a design. The main challenge for MEMS manufacturing is the capacity to manufacture devices integrally within a single fab. And it is the sequence of processes that determines whether a fab can produce a design, not the ability to perform certain process steps separately. A way to tackle this problem is to develop standardized test structures that incorporate the elements with the highest relevance for ABB's projects, as well as quality criteria for the functionality of the resulting device. This standardized test structure can then be submitted for fabrication to a potential vendor, who in turn will develop the whole process sequence. This could provide ABB with a uniform benchmark against which to measure its vendors. Also, it would bypass the trap of looking at single process-steps that can be achieved by a vendor and then finding out that they are unable to process the whole sequence needed by ABB when they are awarded the contract.

The Supply-Chain must be designed promptly. Given the peculiar difficulties of developing MEMS-enabled products and the uncertainty surrounding the viability of the outsourced manufacturing service vendor market, a clear Supply-Chain strategy needs to be delineated in the short term. In order to do this, ABB needs to look at both external and internal tactical considerations. It must decide what type of partnership it will establish with its manufacturing partners and how it plans to extract the most value from them by aligning its internal structures correspondingly. A decision on the creation of a MEMS Competence Center should be taken before the first product is rolled out into the market.

Management of the relationships with vendors will be the key to success. The nature and evolution of its relationships with the vendors need to be well understood and managed. In a decentralized company such as ABB, the risk is high that the network of relationships with the vendors will acquire a life of its own, which could result in inefficiencies that could derail the initiative. Also, the main competitive advantage for any company in the MEMS field may lay in its ability to handle the interaction between development and manufacturing, and given ABB's decision to outsource manufacturing, it still needs to maintain a tight control of its production. Otherwise it will find itself in a very weak position strategically, where it becomes dependent on its vendors and is unable to leverage the size and scope of the MEMS initiative. In the worst case scenario, it could find itself stripped of its product pipeline because its vendors are bought out by competitors.

A set of internal standards and procedures for MEMS needs to be developed. ABB stands a lot to gain from the fact that due to both its size and the scope of the markets it serves, it is able to pursue several MEMS projects in parallel. These projects need to be utilized in the creation of internal standardized structures and subsystems, as well as fabrication sequences. This will enable ABB to obtain a tighter grip on the technology, and streamline future efforts at MEMS development. If ABB manages to find ways to aggregate these product ideas into a coherent technology roadmap, it will be in a better position to make decisions on which vendors are of relevance, and how to find synergies between the vendor's knowledge base and its own.

With precise execution of a carefully designed Supply-Chain strategy, ABB stands poised to overcome these obstacles and become a powerful presence in the world of MEMS.

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