COMPARISON OF RETURN ON INVESTMENT FOR AN ENTRY LEVEL MICROMILLING MACHINE VERSUS BENCHMARK STATE OF THE ART MACHINES.

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ABSTRACT

Entry level micromilling machines have a substantially reduced capital cost, and lower operating costs associated with them, compared to the state of the art micromilling machines. This paper presents the decision making process and complexity of comparing these two technologies given part requirements, time constraints and part features. Some decisions are trivial, while others require an in-depth understanding of the economics and technical aspects of the technology and the product. Insights gained from research and manufacturing of Micromilled parts are discussed as well as aspects that could impact a techno-economic model. The model aspects are then related to various product sectors each with an estimated market size. One of the outputs of the paper is a business decision framework to guide investors.

1 INTRODUCTION

Computer Numeric Control (CNC) micro milling machines differ extensively on price, functionality and quality, which creates uncertainty for the first time buyer or even seasoned users. With so many options available at such a range of costs it becomes vital to determine what is required in specific applications and to ensure the best return on investment. This study looks at batch volume and one-off production of micro-milled products. The techno-economic model allows comparisons of some real and various estimated costs due to capital repayment, training, software, operations and maintenance.

Various authors define micromilling as related to small machine sizes, tool sizes, work piece sizes and feature sizes [1], [2], [3], [4], [5] and [6]. Simoneau [7] promotes the idea that the difference between conventional and micromilling is the cutting mechanisms or chip forming. In this paper, micromilling is defined as using small milling machines, appropriate for part sizes up to about 300mm on the longest dimension.

The techno-economic model presented in this paper is the result of mostly primary research and manufacturing performed by either the author or under supervision of the author. By analysing requests made to the author "to manufacture parts using micromilling", it is estimated that likely part sizes could be described as a Weibull distribution with Alpha = 2 and Beta = 110. By plotting this distribution in figure 1 it can be seen that approximately 70% of the micro milled parts are expected to be between 50mm and 150mm on the longest dimension. A further restriction is placed on the collet size to be a maximum of 3.175mm. The milling machines in the comparison must be able to machine in any machinable metal. There should also be a cooling and lubrication system that is comparable for the milling machines. This definition of micromilling restricts the machine and tool size to allow a fair comparison to be made.

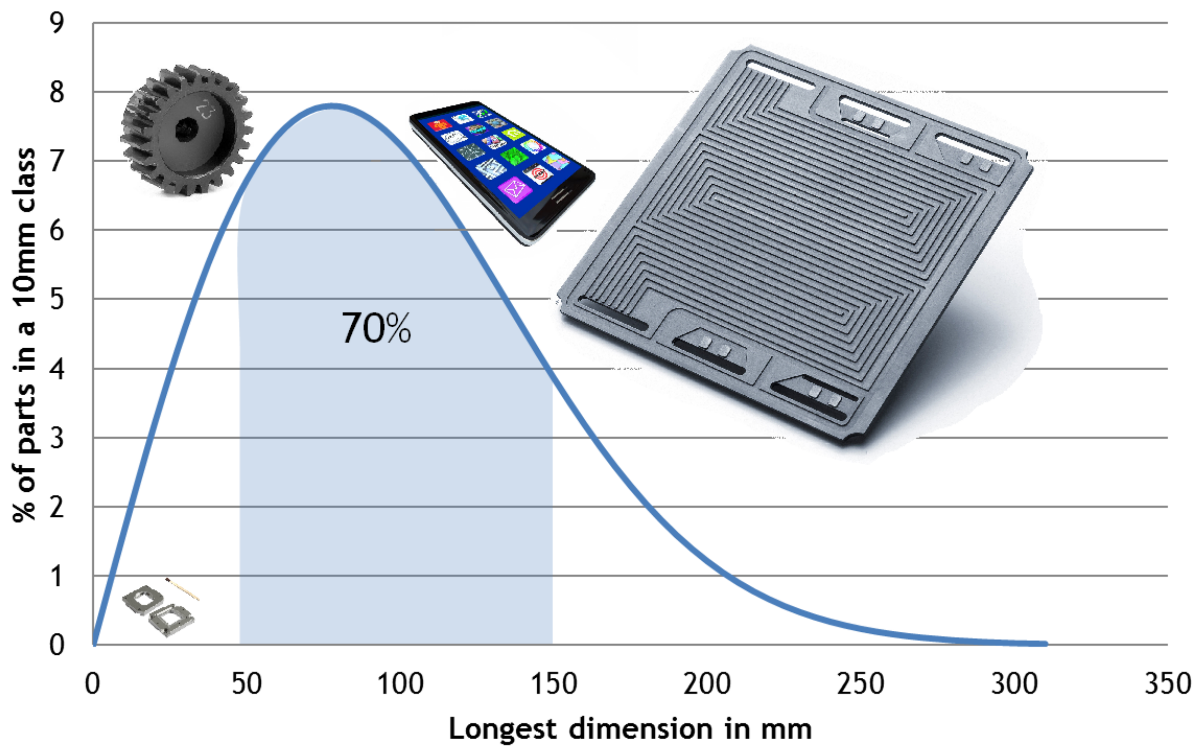

Figure 1: Typical Micromilled part sizes distribution

Micromilling can produce final parts or collaborate in various manufacturing chains, such as moulding, stamping and embossing [1] and [3]. The way that micromilling is used in a specific company will determine the cost and profitability. Enabling multiple uses could increase the utilisation and contribute to recapitalisation.

2 MICROMILLING MACHINES AND ACCESSORIES

CNC Micromilling machines require various supporting functions to be present. These functions include clamping the work piece, providing work piece zero positions, moving the cutting tool relative to the work piece, rotating the cutting tool, lubricating and cooling the cutting tool, changing cutting tools and protecting the environment and operator from harm [1] and [3].

By visiting manufacturers, reading through their brochures or visiting their web-pages, it is evident that various micro mills have different levels of sophistication with regards to the listed functionality. On top of the listed functionalities, add-on tools can be used or operator ingenuity must compensate if lacking.

2.1 Workflow of a micromilling process

According to the author's experience, the typical CNC micromilling workflow will follow a variation of the processes in figure 2. Other authors [8] and [9] have published similar workflows.

Figure 2 : Typical CNC workflow

In this workflow it is assumed that the first two processes are not dependent on the milling machine used, and will be essentially similar for all milling machines in the model. Software is used throughout the workflow, and will be addressed at a philosophical level only. The workflow processes are discussed in more detail below.

2.1.1 Software considerations

Most customers will expect the manufacturer to improve or adapt the final CAD design and do the required transformations to produce a file or code to control their micro mill. There are numerous software solutions to do this; some are free, open source and others commercial systems ranging in prices from R1000 to R50 000 per licence, sometimes valid for only one year.

If your main business is designing of complex and integrated mechanical and mechatronics systems, then comprehensive commercial software solutions could prove to be indispensable for the added benefits of flow, strength or thermodynamic analysis, and dynamic aspects of the design. However, extensive training and highly skilled personnel are required for this type of business.

In the business of manufacturing, simpler solutions, such as dedicated tool path generators or open source solutions could prove cheaper and more efficient. From a practical point of view, it is the author's preference to use the least complex software solution that will do the job.

For sustainability some believe that open file formats are non-negotiable, since the re-use of files and data are ensured [10], [11], [12] and [13]. If files or data are stored on proprietary systems, there could be many reasons why the data could be lost without a method to recover it. These include specific companies that fail in the marketplace, software version changes that are not backwards compatible or when a company decides to switch to a competing product and cannot convert its own data.

> *"The metadata schemas, standards, and architectures must themselves be sustainable, and open and well described, so that their purpose and essence can be mapped and transformed to support the new systems that will emerge"* [10].

Arms [12] lists seven sustainability factors that could influence your data or files at some future date namely disclosure, adoption, transparency, self-documentation, external dependencies, impact of patents and technical protection mechanisms. Most of these factors will be problematic when using proprietary software and file formats, since many proprietary software systems do not disclose their file structures, are not transparent, use technical protection mechanisms and foster dependence on their expertise.

2.1.2 Processes in the workflow that is expected to have comparable cost and resource requirements

Essentially, comparable work will be required for the Order, Design, Rough stock, Consumables and Finishing processes, regardless of the specific micro mill used. For this reason these topics are not discussed further in this paper.

2.1.3 Setup of the machine for individual products

Every product manufactured on the micro mill has a unique setup, which must be repeated before the product can be milled. For products that are made in volume, special jigs and standardised setup procedures could be used to save on setup times [1] and [3].

2.1.3.1 Cutting tool setup

Normally the first step in the setup is making sure the correct tool is mounted in the spindle. This could be done manually, and at the same time the operator should set the spindle speed to an appropriate value for the cutting parameters required. In more expensive machines this might be controlled by the cutting file via software. It probably takes the same time to set the speed in the software, as setting the speed on the spindle controller manually. For batch production the software control method will save more time, since the setting is done once only in the file and executed as required.

2.1.3.2 Work holding

Normally the next step in the setup is providing work holding for the work piece. This could be done using mechanical systems such as a vice, direct mounting, and parallels or v-blocks with step blocks. For faster production, vacuum and magnetic clamping are used extensively. New research has shown [14] that even natural adhesive forces namely electrostatic, surface tension and van-der-Waals forces could have application in micromilling work holding. Some automated systems might save time on this setup aspect, but it will not be significant for single items in the larger scheme of costs. When batch and mass volume production is considered, the state of affairs could change significantly. Mass production will not be considered further since that area deserves a study on its own. For batch production there are strategic options that could provide large time savings. The most noteworthy of these include batching of multiple products on a single milling program and pallet mounting [15]. Batch production of less than 50 items also comprises about 70% of engineering output [15].

2.1.3.3 Work piece zero position

More expensive milling machines will have built-in systems for setting the Zero positions of the X- and Y-axis of the work piece, faster than the operator could do manually. It would also have automated cutting tool setup, to ensure the Z-axis zero position or offset is done very accurately. This could prove invaluable on work pieces where the absolute position of the Z-machined surfaces have tight tolerances. For one-off products the effect of setting the work piece zero position will consume a larger percentage of the total time than for batch production, where this is standardised across batches. When using a pallet system it is also possible to increase the utilisation of the milling machine, since the setup can be done in parallel while another batch is milled.

2.1.3.4 Load cutting file

The final step in the setup is to load the correct cutting file, normally a file containing g-code.

2.1.4 The milling process

The milling process can be split in rough cuts, intermediate cuts and final cuts as required. Each cut could require a specific size and geometry of cutting tool.

2.1.4.1 Cooling and lubrication

During milling, many materials might require cooling and lubrication to achieve an optimal material removal rate (MRR). A popular traditional cooling is flood cooling, but Minimum Quantity Lubrication (MQL) such as mist cooling or micro-flood are gaining popularity [16], [17], [18] and [19]. The foremost reasons are occupational health, economic and environmental concerns. Marksberry [16], Sreejith [17] and Li [20] claim that lubrication costs are significant and higher than labour and overheads. In occupational health, respiratory and skin disorders are major complaints; however, there are also risks of airborne lubricants that present problems similar to aerosols. Cooling and lubrication also influences the surface and subsurface changes in the work piece, with possible work-hardening and micro-cracks, stresses and dimensional inaccuracies [17], [18] and [19].

Dry machining is also possible, but would in general require a larger number of cutting tools due to excessive wear. It is however highly dependent on the cutting tool and the material being cut.

2.1.4.2 Rough cuts

For rough cuts, the material removal rate is one of the foremost considerations. Various methods have been used to optimise the removal rate, such as genetic algorithms, cutting force calculations [21], [22], [23], [24] and experimental studies [25]. To increase material removal rate we may either increase the depth of cut, the step over distance or feed speed. If this is done at a constant spindle speed, the chip and forces on the cutting tool becomes larger. At the same time, there is a resultant increase required to the spindle energy requirements. For this reason the maximum spindle torque at various rotating speeds can become a limit to material removal rate. In the section discussing lubrication it also became clear that choosing the correct lubrication method will influence the material removal rate.

2.1.4.3 Intermediate cuts

Intermediate cuts might be required for a variety of reasons. These include inside radius requirements, deeper cuts that could not be done with the roughing tool and similar geometric situations. These intermediate cuts are still doing roughing work, but with specialised roughing tools that are either of a smaller radius, longer or deeper reach or of a different type to the optimal first roughing tool.

2.1.4.4 Tool changes

The major difference between using an entry level micromilling machine compared to the state of the art micromilling machines would be tool changing and setup times. On almost all state of the art micro mills, the cutting tools will be changed automatically, and the Z-position of the cutter tip will be set automatically. Such tool changes will take less than five seconds in many cases and can be seen to have an almost zero effect on cost. On entry level micro mills, each tool change has to wait until an operator is present to do the change and then it will take about one minute to change the tool, and another two minutes to set a new zero position [26].The wait time for the operator is an unknown, since that depends on whether the operator is operating multiple machines and processes. This complicates the comparison process and adds complexity to managing entry level micromilling machines.

2.1.4.5 Final cut

The final cut in the milling process has to give a surface finish that conforms to the specifications. The surface finish is specified by smoothness and could also include work-hardening type specifications including allowable residual stresses. To ensure a high smoothness finish with micro tools, it is required that high spindle speeds can be achieved. For the benchmark comparison, it was required that the micro mills must have a spindle that can rotate at speeds up to 60 000 rpm.

2.1.5 Overheads

Some important overheads not included in the above discussion include energy cost, training requirements and maintenance. Since the current comparison is on machines with a similar power output, the energy requirements should be substantially similar. It would in any case be nonsense to compare the energy requirements in the general case for all micro mills. For this reason the energy cost is not considered further.

However the cost for training and maintenance will be of interest. In the case of state of the art micro mills there are costs that are locked into the system at the time of purchase, in the form of company specific software as well as high skills requirements from the operating personnel. This means that in general the additional requirements for state of the art micro mills will add additional overheads to the process. These costs will differ from company to company and were estimated using real training costs and software costs.

3 PRACTICAL MODEL FOR TECHNO-ECONOMIC EVALUATION OF MICRO MILLS

A reasonable comprehensive cost model to allow product pricing of micro milled items is presented. The model has nine major parts, specifically capital, training, software, order, design, rough stock, consumables, operating and overheads. In previous work Essmann [26] showed that finding the optimal machining parameters could be a multi-objective problem. Essmann solved these problems by applying a Simulated Annealing Algorithm. Other types of genetic algorithms could also be applied with success. Figure 3 illustrates the author’s understanding of cost in terms of when it is committed versus when it is incurred over the product life. The dotted line is the traditional view of this graph applied to product manufacturing and it can be seen that as much as 80% of total product cost is already committed in the design stage. The upper line labelled “Technology buying Cost fixing” shows that this tendency is highly reinforced for buying technology. Thus, when buying a specific technology to manufacture products, the cost is committed very early in the timeline, specifically at the time when you buy the machine. Once the capital is spent, the ability to influence cost is reduced. The lower line labelled “Actual Cost at the time” (assuming the capital to purchase was borrowed) shows that the real costs are actually accrued at this time. This makes the choice of technology critical.

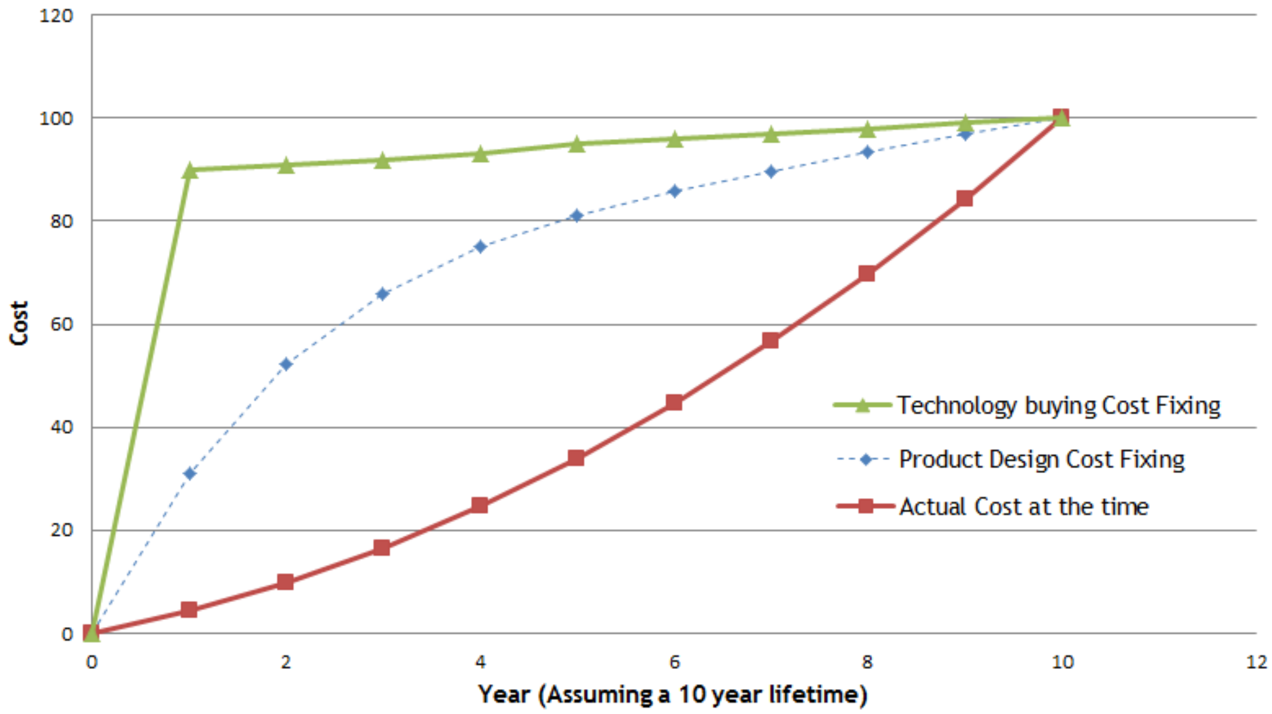

Figure 3: The nature of cost committed versus actual cost at the time

Cost is however only one aspect of the model, since profit is the only mechanism to generate a positive return on investment. The second aspect of the model includes the drivers of sales as market size, number of competing suppliers to the market and market share. The market size and number of competing suppliers are estimated from government statistics, while market share that the specific company may attain is quite fickle and is left as a user variable in the model.

3.1 General assignment of cost

In the model all costs must be assigned to products that are manufactured on the micro mill. The assignment of costs to products can be done using several approaches. The cost assignment methods that will be considered are direct cost and unit cost.

3.1.1 Direct cost

Direct cost, as the name suggests, tries to assign real and directly attributable costs to each product. In many cases it is not possible to know these costs in detail, specifically not if the micro mill is a new product with no historical data available. This means that most costs cannot be assigned using this method. The costs that could be assigned, given proper measuring systems are in place, include material used, real energy use, real operator hours, cutting tools used and lubrication.

3.1.2 Unit cost

For costs that are difficult to measure it is possible to use either hour-based or volume-based unit costs. In many companies, direct energy use is not measured at every machine or process, similar for things such as lubrication, personnel time or even cutting tools. It is however possible to assign average cost based on historical use of resources in such cases.

3.2 Specific assignment of cost

In the next section some specific costs are discussed, estimated and assigned. The reader is reminded of some requirements; specifically the restriction on the collet size to be a maximum of 3.175mm and that the mill must be able to machine in any machinable metal. A minimum quantity lubrication system should be present. Repeatability below 10µm is required and axial movement increment of 2µm or less. Other differences between the micro mills will be considered in the various following sections.

3.2.1 Capital to purchase

To calculate return on investment, it is required to factor in the risk of the investment in the interest or required return rate. For items in the category of manufacturing tools, an acceptable rate could be 15% return over a lifetime of 10 years. Since technology changes quickly, looking at a machine payback period of longer than 10 years is considered unrealistic. The real or quoted capital cost will be used in the model. An average price for an entry level micro mill (given the required specification) ranged from R190 000 to R300 000. These mills generally do not have tool changers, especially at the lower end of the spectrum. For the purposes of this comparison it is estimated that an average capital outlay would be R240 000. Given a 10 year repayment period at 15 % interest, this gives a required contribution of about R48 000 per year.

High end micro mills are available in a variety of machines, typically ranging in cost from R1 million to R2 million. The wide range can be attributed to perceived quality of these tools in the marketplace, which is mostly underpinned by real quality in these products. A large factor in the costs of these mills could also be in the systems that they could contain, such as automated temperature control or compensation, safety systems and higher accuracy or power. Assuming a capital cost of R1.5 million and given a 10 year repayment period at 15 % interest, yields a required contribution of about R300 000 per year.

Comparing such widely different systems might create unease. However, in the marketplace, these widely different systems are all touted as micro milling systems and therefore some part comparison is possible, while also stressing the differences. This could improve the decision making process of a potential investor in these technologies and prevent a potentially ruinous investment.

3.2.2 Training and software

Part and parcel of the market leading state of the art micro mills, are specialised training and software requirements. This is inherent and was shown in figure 3 previously that when you buy the technology you commit most of the lifetime expenses. It stands to reason that if you are willing to spend R1.5 million on a micro mill, then you will want to protect the investment and maximise its profitability. To do this you will require some of the best operators, trained in high-productivity software to optimise your product quality and throughput. From current experience these costs will be repeated over the lifetime of the investment. A conservative estimate of additional yearly cost (above the entry level micro mill) is about 5% to 10% of the initial capital cost. At 7% this will add a yearly cost of R100 000 to a R1.5 million micro mill.

3.2.3 Material and consumables used

The real rough stock material and consumables prices are used. The cost is the same for all micro mill machines.

3.2.4 Setup, finishing and overhead cost

Experimental data is measured and averages are calculated to be used in hour-based unit costs [26]. These costs are different for the compared technologies due to the differences explained in section 2.1, such as different operator wages and time spent by the operator.

3.2.5 Milling Cost due to operator hours and cutting tools

Historical data is logged for cutting graphite-composites and the averages can be used in volume-based unit costs [26]. For the cutting of aluminium, published data is available for a similar estimation of average cost [17]. Similar to setup costs, these costs are different for the compared technologies. A major contributor to the differences is using optimised software that gives proper cutting parameters and increased throughput. The effect of this is highly variable but estimated from previous research to be in the order of 30% to 50% savings in milling time as well as doubling of cutter tool life [27], [28], [29] and [30].

3.3 Sales estimation

The company sales are dependent on the total market size, the number of competing suppliers to the market and market share. For this reason it is logical to investigate the potential market segments that are currently using micromilling processes.

3.3.1 Market size

The model must be supplied with the most recent and best estimate of market size. Typically the only sources of such information are government statistics and competitiveness reports. The markets that are considered as examples for this study are the medical implant and automotive sectors.

3.3.1.1 Medical

Hip replacement average estimates was 13 procedures per year per 10 000 inhabitants in the late 1990's, with estimated annual growth of about 5% [31]. The global dental implant market was estimated to be about €1 billion in 2005 and was estimated to grow to €2.4 by the year 2010. At the time, around 600 000 dental implants were used annually in the world. The implant industry was made up of four or five large companies and maybe 200 smaller manufacturers [32]. In the USA there were about 370 000 hip replacements and 380 000 knee replacements in 2005. The estimated cost of the individual procedures were $14 500 per hip and $13 200 per knee [33].

Using available data from knee replacements as an example, the following process could be used to estimate figures for South Africa. Using data from Kurtz et al [34] and the global competitiveness report of 2010-2011 [35] it was possible to derive a relationship between real knee replacements, obesity and three of the factors of the competitiveness report. The factors used were health, innovation readiness, income per capita and obesity [36]. There are 18 countries' real data shown in figure 4 (number 2 to 19 on the x-axis), with South Africa added to the graph as number 1 ("Real Value" for South Africa on this graph was set to be equal to the Predicted Value, since no real data is shared by the industry in South Africa). The best predictive values, with an R^2 value of 0.846 were found using the following equation (with the two outliers removed the R^2 improves to 0.944):

$$(H^{2.59} \times I^{0.926} \times \$^{0.607} \times Ob^{0.457}) \times 0.008 = \#\, of\ knee\ replacements\ per\ 100\,000 \qquad \textbf{(1)}$$

Where H is the Health score [35],
I is the Innovation readiness score [35],
$ is the income per capita in 1000's of dollars [35] and
Ob is percentage of obese people in the country [36].

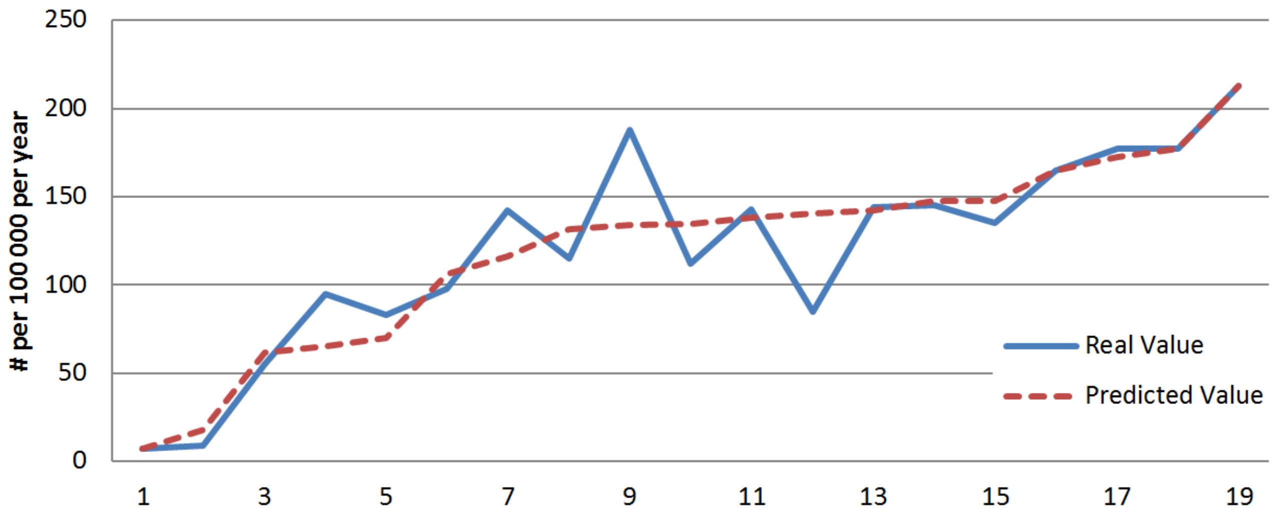

Figure 4 : Real and predicted number of knee replacements per 100 000 people per year

Estimating the market size in South Africa for the year 2011 using equation 1 gives 3614 knee implants and assuming a growth of 8% it may increase to 4215 knee implants in 2013. An estimate from personal communications within the industry suggests the number of knee implants in South Africa is higher, possibly 10 000 to 12 000 per year. It is claimed that up to 50% of the knee replacement cost is in implant cost [33]. Assuming a conservative R20 000 for the implant in South Africa, the total cost of 10 000 knee implants are estimated to be R200 million.

In 2009 there were about 30% more hip than knee replacements done in countries belonging to the Organisation for Economic Co-operation and Development (OECD) [36]. Knee replacements are however gaining ground in the past few years [36]. Repeating the previous calculations for hip replacements, the total cost of 13 000 hip implants are estimated to be R260 million. Dental implants are a lot cheaper and the total cost of all dental implants is estimated to be less than R30 million in South Africa [37].

The global bio-microsystems medical implant market, including accessories and supplies, was estimated at $16.3 billion (R146 billion) in 2012 and is projected to grow to $24.8 billion (R221 billion) by 2016 [37]. In bio-microsystems, devices such as biosensors, micro-arrays, DNA chips, lab on chips, cell chips, bioMEMS, and total analysis systems are used [38].

3.3.1.2 Automotive

Micromilling has several possible roles to play in manufacturing automotive parts. Direct milling of some smaller metal parts is possible, though the more significant application would be making moulds for injection moulding of plastic parts, sintering or stamping of metal parts.

Sales of motor parts and accessories for motor vehicles and their engines were R63 866 million in 2012 [39]. Since South Africa also exports motor vehicles, the overall vehicle production in South Africa could be a more useful measure, and this is expected to reach about 650 000 units in 2013 up from 539 424 units in 2012 [40].

The four ‘Pillars’ of the Automotive Production and Development Programme (APDP) will influence the automotive industry from 2013 [41]. It could also act as an added incentive for investment in micro mill technology. The Pillars are:

1. Import and customs duties of 20%
2. The Volume Assembly Allowance (VAA) for volumes above 50 000 per year

3. The Production Incentive (PI)
4. The Automotive Investment Scheme (AIS)

To qualify for the AIS at least 25%, or R10 million, of a company's automotive turnover should be local and, or, export sales to original equipment manufacturers. These incentives provide strong incentives for investors in the automotive sector, since most manufacturers have less than 50% local content.

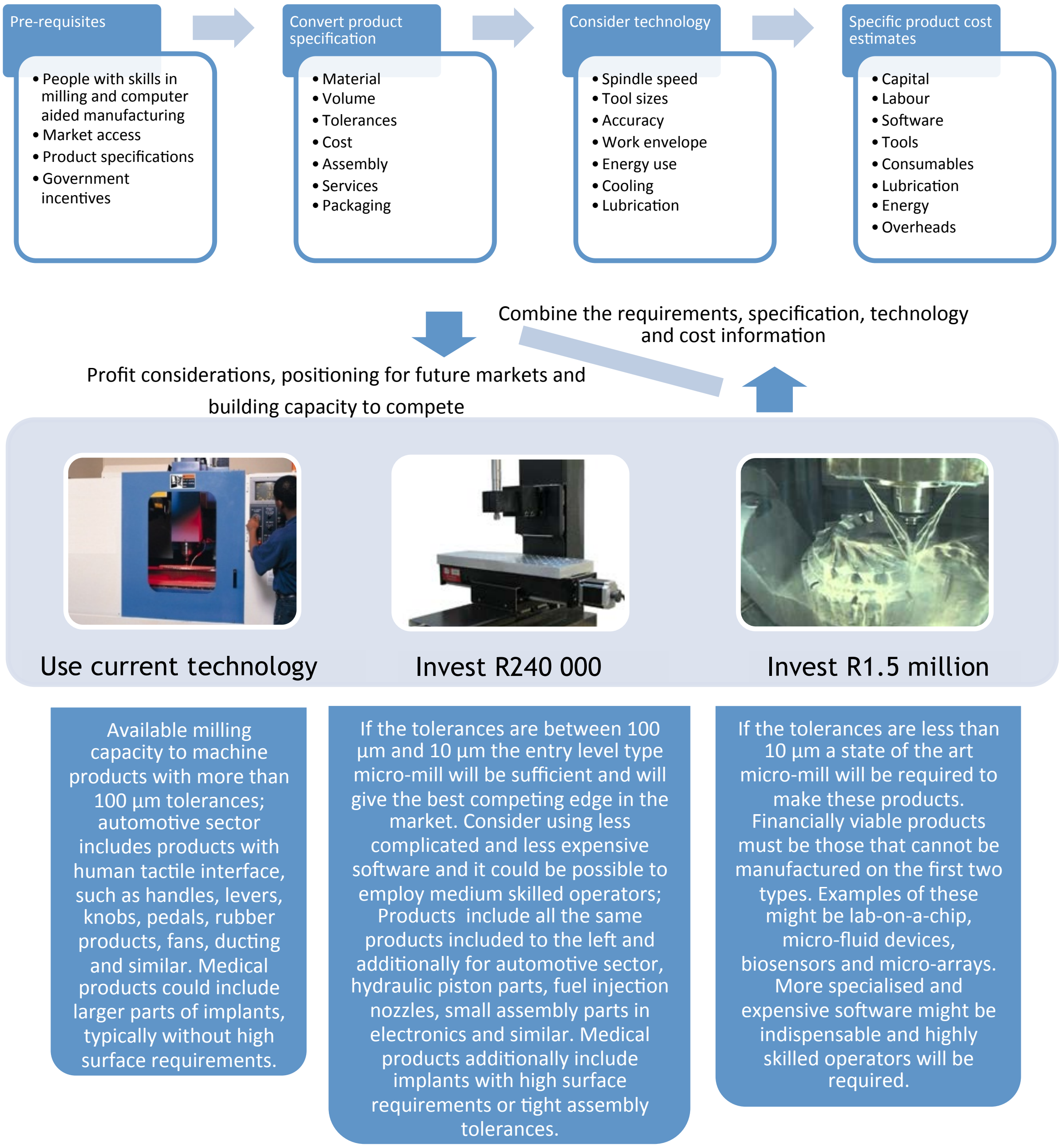

Figure 5 : Business desicion framework for Techno-Economic model

4 MICRO MILL BUSINESS DECISION FRAMEWORK

Previous research suggests possible reasons for investing in micro machining [1], [3] and [42]. These include smaller business sizes or lower throughput, more affordable start-ups, the ability to change technology more frequently, lower maintenance and insurance costs and reduced floor space requirements. To ensure a profitable business however, it is not enough to only understand these strategic reasons. The most important decision will be to choose a micro mill that is capable of delivering the requirements of the market, but no more. Additional capability will cost dearly, and is normally associated with additional operating expenses as well, which drives the price of the products to be only viable for high technology or exotic products. Knowing exactly what your specific market requires in their products will be crucial to choosing the correct micro milling technology and support levels. This will ensure a competitive price, potential market share and a reasonable return on the investment. The pertinent areas to consider before buying technology and possible opportunities in the markets are identified and shown in figure 5.

5 CONCLUSION

It was shown that there are large and somewhat untapped markets for micromilling in South Africa. Many products that are imported for the automotive and medical sectors can be manufactured using micromilling as part of the manufacturing chain. It is fundamental to understand the market and product requirements before choosing the appropriate technology. Additional considerations, including incentives from government, were identified for those interested in investing in micro mill technology. Thinking about those considerations in detail will help investors to choose the appropriate technology and limit the risks of overinvesting in too sophisticated technologies. In those specific cases where state of the art technologies are required, the model shows that significantly more investment will be required and higher operating costs will be experienced. Due to a highly specialised market, subsequent higher financial and technological risks can also be expected.

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