A Techno-economic and pricing strategy simulation model of multiple manufacturing companies supplying micro milling.

by

Theunis Gysbert Dirkse-van Schalkwyk

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Supervisor: Prof. A. van der Merwe
Co-supervisor: Prof. D. Dimitrov

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Declaration

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Date: ....March 2017........

Abstract

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T.G. Dirkse van Schalkwyk
Department of Industrial Engineering,
University of Stellenbosch,
Private Bag X1, Matieland 7602, South Africa.

Thesis: PhDEng (Industrial)
March 2017

Micro milling is a fairly new machining technology and is still developing in leaps and bounds. Many new products are also smaller than the products they replace, driven by microprocessing, portability advantages and resource scarcity. This allows micro manufacturing in general and micro milling specifically to increase market share at the expense of traditional manufacturing technologies. Advantages in capital cost, labour, materials volumes and operating costs all add to the attractiveness of micro manufacturing. The ability to manufacture smaller batches economically promotes local manufacture and has a smaller carbon footprint than traditional approaches. It also fits well with the concepts of mass customisation and tailor-made products in the medical implants area. Other, more esoteric concepts, such as cloud storage and design coupled with local manufacture, have impacts to potentially simplify local manufacture and lower overheads.

Such new technology and rapid changes in the market require timely and informed decisions by businesses to become more efficient and stay competitive. Simultaneously, business risk must be considered. A techno-economic feasibility studies or business plans are common ways to support such a complex decision making process. A methodology to do a comprehensive techno-economic feasibility study is described and followed.

The techno-economic feasibility study depends on various aspects such as market demand, a model of a typical business process, generating of potential outcomes through applying simulation and evaluating the simulation output.

By way of a market analysis and literature study, the most advantageous markets to consider for micro milling were identified as medical implants, research and prototyping, small and medium batches of complex 3D shapes, electronics devices and dental accessories.

One way to explore the business potential of new technology and simultaneously consider risks is through simulation. A simulation model of the technology environment was set up and simulated outcomes were used to assess risks versus opportunities. The simulation used in conjunction with the techno-economic feasibility study allowed a thorough investigation of the issues involved, conclusions to be drawn and recommendations to be made.

Some conclusions include the following. Companies which are interested in new technologies should have at least some human resources available to allow technology transfer to be successful. Software and hardware training, time to gain experience and insight into the financial aspects of the new technology will all have an impact on the success of the investment. If the company is already active in the macro milling market, the techno-economic feasibility study shows that such knowledge should be sufficient to allow the company to become more efficient and competitive if they invested in micro milling. The market size, competing companies and minimum required rates of return all have bearing on these decisions. Using a simulation model more completely identifies the probable outcomes, but also shows that the future will not limited to deterministic outcomes.

The market analysis of potential products that can be manufactured using micro milling showed that there is ample space in the manufacturing sector to invest in this technology and that the uptake of the technology is far from saturation. Many of the identified markets are in growth phases and will continue to grow for many years according to forecasts. Some barriers to success include skill requirements, complex process chains, compatibility issues with software and hardware and penetration of high technology markets. Universities are in favourable positions to facilitate some of the technology transfer by using their research capacities wisely.

The simulations showed that the initial market size, required minimum interest rates or hurdle rates, growth rates of the markets, pricing strategy and number of competing companies in the market will have the greatest impact in the choice of investing.

Uittreksel

’n Tegno-ekonomiese en prys-strategie simulasie model van veelvuldige maatskappye wat Mikrofrees vervaardiging voorsien

(A Techno-economic and pricing strategy simulation model of multiple manufacturing companies supplying micro milling.)

T.G. Dirkse van Schalkwyk
Departement Bedryfsingenieurswese,
Universiteit van Stellenbosch,
Privaatsak X1, Matieland 7602, Suid Afrika.

Tesis: PhDIng (Bedryfs)
Maart 2017

Mikro-frees is ’n taamlike nuwe tegnologie en dit ontwikkel steeds vinnig. Baie nuwe produkte op die mark is ook heelwat kleiner as die produk wat hulle vervang, as gevolg van die markkragte soos mikroprosessering, draagbaarheid voordele en hulpbron skaarsheid. Die tendense gee vir mikro-vervaardiging in die algemeen en mikro-frees spesifiek die geleentheid om markaandeel te bekom te koste van tradisionele vervaardigings metodes. Voordele in kapitaalkoste, arbeidkoste, materiaal volumes en bedryfskoste dra alles by tot die aantreklikheid van mikro-frees. Mikro-frees kan ekonomies werk met kleiner lotte en bevorder dus plaaslike vervaardiging en het boonop ’n kleiner koolstof voetspoor as tradisionele vervaardiging modelle. Dit het ook goeie passing met die konsepte van pasmaak massaproduksie en mediese implantate.

Die voordelige areas om te oorweeg is mediese implantate, tandheelkundige bybehore, ontwikkeling en prototipering van klein tot medium lotte wat komplekse 3D vorms benodig.

Nuwe tegnologie en snelle veranderings in die mark noop vervaardigers om intydse en goeddeurdagte besluite te neem om meer effektief asook kompeterend te wees. Terselfdetyd moet risiko’s oorweeg word. Tegno-ekonomiese doenlikheid studies of besigheidsplanne is algemene metodes om sulke komplese besluitneming te ondersteun. ’n Metode om so studie volledig te doen is beskryf en gevolg.

Die tegno-ekonomiese doenlikheid studie word moontlik gemaak deur verskeie aspekte te ondersoek, soos markaanbod en vraag, ’n besigheids model, simulasie van moontlike uitkomstes en deur die simulasie resultate te ondersoek.

Simulasie is een van die maniere om besigheids risiko’s duidelik te maak. In die simulasie is ’n model gebou wat die markaanvraag voortbring en dan vervaardigers die geleentheid gee om te tender vir kontrakte. Vervaardigers moet dus koste berekeninge doen en daarna hulle wins persentasie bysit. Verskeie aspekte beïnvloed die vervaardigers wat veroorsaak dat hulle met verskillende pryse in die mark kom. Die klient besluit dan weer met ’n komplekse stel reëls, wat prys en reputasie insluit, aan wie die kontrak toegeken word. Inligting uit die simulasie saam met die navorsing oor die mark-potensiaal gee dan ’n redelike volledige voorstelling van die geleenthede en risiko’s.

Maatskappye wat wil belê in komplekse tegnologie moet in ag neem dat hulle genoeg spaar kapasiteit in menslike hulpbronne het sodat die leerkurwe van die tegnologie bemeester kan word. Opleiding moet voorsiening maak vir beide hardeware en sagteware aspekte. Om akkurate koste berekenings te kan doen moet die tegnolgie ook leer ken word. Indien die maatskappy reeds bestaande mikro-werk verrig sal dit die oordrag vergemaklik. Die mark volume, kompetisie, minimum opbrengs koerse, groei in die markte en huidige ondervinding sal alles kan bydra tot sukses. Deur simulasie te gebruik word al die uitkomstes sigbaar gemaak en kan die waarskynlikheid van elke uitkoms bepaal word. Dit wys ook duidelik dat die toekoms nie in ’n enkele uitbeelding kan pas nie.

Die mark-analise van moontlike produkte wat vervaardig kan word wys dat daar baie geleenthede is om in mikro-frees tegnologie te belê en dat die gebruik van die tegnologie nog ver van voldoende is. Baie van die mark-sektore wat geïdentifiseer is, is ook in ’n groei-fase en sal so wees vir etlike jare. Die hindernisse tot mark-betreding is in skaars vaardighede, komplekse proses kettings, meewerking van sagteware en hardeware en die binnedring van hoë tegnologie markte. Universiteite is in ’n gunstige posisie om sulke tegnologie oordrag te fasiliteer indien hulle navorsing oordeelkundig aanwend.

Die simulasies het gewys dat oorspronklike mark volume, benodigde minimum opbrengs koerse, mark volume groei koerse, prys-strategie en aantal kompeterende vervaardigers die grootste impak sal hê op die keuse om te investeer.

Acknowledgements

I would like to express my sincere gratitude to the following people and organisations. Stellenbosch University, for allowing me the space to grow at my own pace. Prof. Dimitrov and Prof. van der Merwe who were always ready to advise, even if I was not always there to listen. My family and specially my wife Liz for their unwavering support and love. Finally, my friends at Judo who has kept me motivated to enjoy life.

Dedications

This thesis is dedicated to my mother.

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Abbreviations and Glossary

Abbreviations

- ABC activity-based costing
- AHP analytical hierarchy process
- AI artificial intelligence
- AMTS advanced manufacturing technology strategy
- BMC business model canvas
- CAD computer aided design
- CAM computer aided manufacture
- CFPR consistent fuzzy preference relations
- CIM ceramic injection moulding
- CNC computer numeric control
- CI commonality index
- DES discrete event simulation
- DFM design for manufacture
- DFMA design for manufacture and assembly
- DI differentiation index
- DTF Desk Top Factories
- DTI department of trade and industry
- GC golden circle

- IDE integrated development environment
- ISO international standards organisation
- JIT just in time
- MEMS micro-electromechanical system MM micro milling
- MIM metal injection moulding
- MOH manufacturing overheads
- MRR material removal rate
- NEMS nano-electromechanical systems
- NPV net present value
- PCB printed circuit board
- PCM price-cost margins
- PIM powder injection moulding
- POU point-of-use
- RFQ requests for quotes
- ROI return on investment
- SD system dynamics
- SG and A Selling, General and Administration
- SI set-up index
- SME small medium enterprises
- TEFS techno-economic feasibility study
- TEP techno-economic paradigm
- WTEC world technology evaluation centre

Glossary

- Cutting Force - one component of the machining force, acting along the line of action of the cutting speed.
- Cutting Speed - the relative speed between the cutting edge of a tool and the uncut work material just ahead of the cutting edge.
- Cutting Tool - the portion of a machine tool which has edges designed to shear the work material. The cutting tool is normally replaceable and can be made of different materials such as steel, diamond, carbides, etc depending on the application.
- Edge Sharpness - the radius of the cutting edge of a cutting tool at the intersection of the rake face and the flank surface.
- Feed - the distance a cutting edge moves per revolution of the tool or work piece in machining, used to calculate the volume of material removed, sometime referred to as the tooth loading.
- Feed Rate - the distance a cutting edge moves in a given time, to calculate the feed the rotational speed of the tool or work piece must also be known.
- Fixture - a structure used to securely hold a work piece during machining, the fixture is normally clamped to the machine tool and should not induce deformation into the material to be machined.
- Machine Tool - the entire structure, actuators, feedback devices, and controllers used to hold a work material, the cutting tool, and provide all motions and rigidity to fulfil a machining operation.
- Machining Forces - in general, all the forces and torques on the cutting tool, machine tool, and work piece as a result of material removal.
- Micro-milling - no formal size defines micromilling but is generally in the sub-millimetre range. Milling where the size effect becomes dominant. This will in most cases be where tools smaller than 1mm are used, but additional definitions are discussed later.
- Rake Angle - the angle between the normal to the cutting speed direction and the rake face of a cutting tool, if the rake face tilts toward the incoming work material the sign of the rake angle is negative, rake angle strongly affects the magnitude of the machining forces.

- Resonance - in the study of a dynamic system, resonance occurs when the forcing function, force or displacement, has a frequency equal to the un-damped natural frequency of the system. If there is no damping present in the system to remove energy, the displacement of the system will increase. This build-up of displacement requires time so excessive displacements can be avoided if the input frequency is not allowed to remain equal to the un-damped natural frequency.

- Shear Plane Angle - the approximate plane along which the chip is separated from the work material in a cutting operation, the angle is measured from the line of action of the cutting speed

- Specific Cutting Energy - the experimentally measured amount of energy needed to remove a unit volume of work material, it also has the same units as the power required for a volumetric removal rate of work material, it also has the units of stress or pressure so it is sometimes called cutting pressure

- Thrust Force - the component of the machining forces which is perpendicular to the cutting force and the line of action of the cutting speed, the thrust force normally tries to separate the cutting edge of the tool from the newly generated material surface

- Un-damped Natural Frequency - in the study of a dynamic system, it is the frequency at which the system will prefer to freely vibrate (with no external periodic excitation) due to its mass and elastic characteristics. For a simple spring-mass system with no damping (all materials have some internal damping), the un-damped natural frequency is given by the square root of K / M where K is the spring constant and M is the suspended mass. The un-damped natural frequency is usually referred to as the natural frequency (opposed to the damped natural frequency).

- Size effect: The effect of a constant cutting edge radius and metal grain size vs diminishing tool diameter. It is partly due to the relative change in the cutting edge radius and gives rise to higher stresses in the cutting tool than expected.

Selected simulation terms

- Abstract (Mathematical) Model - is where symbols and logic constitute the model. The symbolism used can be a language or a mathematical notation. A verbal or written description in English is an abstract model.

A simulation model is built in terms of logic and mathematical equations and is an abstract model.

- Accuracy - is the degree to which the model or simulated results represent reality.
- Analytical Model - is solved by using the deductive reasoning of mathematical theory. An M/M/1 queuing model, a Linear Programming model, a Mixed Integer Linear Programming model, a non-linear optimization model are examples of analytical models.
- Architecture - is the structure of components, their relationships, and the principles and guidelines governing their design and evolution over time.
- Architecture versus Design - A design is an instantiation of an architecture similar to how an object is an instantiation from a class.
- Artificial Intelligence (AI) - is a kind of simulation that involves a model intended to represent human intelligence or knowledge. An AI-based simulation model typically mimics human intelligence such as reasoning, learning, perception, planning, language comprehension, problem-solving, and decision making. Rule-based knowledge representation is commonly used for building AI-based simulation models. An Expert System is also a kind of simulation of some knowledge, typically constructed using rule-based knowledge representation.
- Conceptual Model - is a repository of high-level conceptual constructs and knowledge specified in a variety of communicative forms intended to assist in the design.
- Coupling of sub-models - is the degree of dependency between sub-models.
- Descriptive Model - is a model which describes the behaviour of a system without any value judgement on the 'goodness' or 'badness' of such behaviour. All simulation models start out as descriptive models.
- Discrete System - is a system in which the changes are predominantly discontinuous such as a factory system.
- Functional Requirements - include statements of services the model should provide, how the model should react to particular inputs and how the model should behave in particular situations. Functional requirements are requirements about the input-output transformations of the simulation model.

- Functionality - is the degree to which the model completely captures all of the desired functional modules that need to be present.
- Garbage-in garbage-out - refers to a simulation with insufficient credibility.
- Intended Use - refers to the explicitly and clearly defined purpose for which the simulation model is intended for use.
- IV&V is Independent Verification and Validation.
- Linear Models - describes relationships in linear form.
- Model - is a representation and abstraction of anything such as a real system, a proposed system, a futuristic system design, an entity, a phenomenon, or an idea.
- Model Builder's Risk - is the probability of committing the Type I Error. See below Type I Error.
- Model User's Risk - is the probability of committing the Type II Error. See below Type II Error.
- Monte Carlo - models and simulations use statistical random sampling. The model typically does not represent time-varying relationships but it may be added by using a mixed model concept. Monte Carlo is typically used in disciplines such as Chemistry, Computational Engineering, Financial Probabilistic Modelling, Mathematics, Nuclear Engineering, (Computational, Nuclear, Statistical) Physics, and Reliability Engineering.
- Pseudo-Random Number Generation - refers to the generation of random numbers in a way that is reproducible by using a starting value called seed. Pseudo implies that the numbers are not truly random, but satisfy statistical properties for randomness.
- R-studio - is the Integrated development environment (IDE) that was used for writing and debugging code.
- Random Variable - is a real-valued function that maps a sample space into the real line (numbers).
- Random Variate - is a particular outcome or sample value of a random variable.
- Self-Driven Simulation - uses random numbers in sampling from probability distributions so as to drive the model.

- Simulation - process that represent some reality by virtue of distributions, logic structures, imitation or mimicry. To Simulate, according to Webster's Dictionary, is: 'To feign, to attain the essence of without the reality' To Simulate, in simple terms, implies to imitate or mimic. Simulation is the act of executing, experimenting with or exercising a model for a specific objective such as acquisition, analysis (problem solving), education, entertainment, research, or training.

- Stochastic Activity - is an activity which varies randomly.

- System Dynamics - uses a model representing cause-and-effect relationships in terms of causal-loop diagrams, flow diagrams with levels and rates, and equations. The equations are used for simulating system behaviour.

- Time Flow Mechanism - is that portion of a simulation that advances time in the simulation, and provides synchronization of the various parts of the simulation.

- Transient Model - is where behaviour changes with respect to time.

- Type I Error - is the error of rejecting the credibility of a model when in fact the model is sufficiently credible.

- Type II Error - is the error of accepting the credibility of a model when in fact the model is not sufficiently credible.

- Type III Error - is the error of solving the wrong problem. It is committed when the formulated problem does not completely contain the actual problem.

- Usability - is the degree to which the simulation application can easily be employed for its intended use.

- Validity - is the degree of behavioural or representational accuracy.

- Validation - deals with the assessment of behavioural or representational accuracy of the model and addresses the question: Are we creating the right model?

- Verification - deals with the assessment of transformational accuracy of the model and addresses the question: Are we creating the model correctly?

Selected economics and business terms

- Bank Rate: The bank rate is the annual rate of interest charged by a national bank on its loans to financial institutions.

- Business Model - the description or model of how a company generates its revenue.

- Capital Cost - Depreciable assets (such as building, machinery, and equipment) cannot be deducted by businesses as a single, one-time item for tax purposes. Instead, a percentage is deducted each tax year over a prescribed number of years. The CCA is the percentage allowed each year.

- Consumer Price Index (CPI) - The CPI provides a broad measure of the cost of living. The CPI tracks the prices for some 600 of the most commonly bought goods and services.

- Constant Rand - Amounts from other time periods that have been converted into present-day Rand by removing the effects of inflation.

- Discount rate - The rate charged by the Federal Reserve Bank on loans. Could also be used in a general sense of a rate to use for any specific company or person.

- Econometrics - A branch of economics that applies statistical analysis to economic theories.

- Elasticity - A measure of the responsiveness of changes in one variable to changes in another. For example, if the price of a good rises, the demand for that good may fall. If the price increases by 1 per cent and sales fall by more than 1 per cent, demand for the good is said to be elastic. If sales fall by less than 1 per cent, demand for the good is inelastic. excess capacity - The amount of 'plant and equipment' not in use. The more excess capacity, the less inflationary pressure.

- Gini Index - Measures income inequality. Zero equals perfect equality, 100 equals perfect inequality. The greater the difference in income between the lowest- and highest-paid sectors of a society, the higher the index number.

- NOPAT (net operating profit after tax) - What a company would earn if it had no debt. Equals operating income minus taxes.

- Percentile - Refers to a 1/100th increment. So, the top percentile of income earners is the top 1 percent.

- Real - Refers to totals that have been adjusted to correct for inflation or other fluctuations so as to reflect volume changes. As in real wages or real GDP. Constant or chained values are examples of this adjustment. The real interest rate is the interest rate less the expected rate of inflation.

- Techno-economic Model - a model that tries to mimic the information from a Techno-economic study.

- Techno-economic study - research where opportunities and threats inherent in new technology are identified, explored and evaluated for business use.

Chapter 1

Research scope and background

1.1 Introduction

For business, a recurring problem is the exponentially increasing speed with which technological and economic changes occur. This was described first in 1965 and reprinted by Moore (2006) regarding integrated circuits and later published for various other fields by Dennard *et al.* (1974), Walter (2005) and Carlson (2003) among others. Due to technological and economic changes, businesses require quick and informed decisions to boost efficiency and competitiveness, while having a deep understanding of their business risk. A techno-economic study or analysis provides a structure to a thorough investigation of the issues involved and enables a more informed course of action. Alternatives to a techno-economic study are discussed in Chapter 3.

One such technology that is considered to be of strategic importance from AMTS (2007), Bissacco (2004) and DeVor *et al.* (2004) is micro milling. Prominent aspects of the technology will be described in Chapter 2.

1.1.1 Technology life cycle

The whole micro manufacturing life cycle seen in figure 1.1 is currently nearing the gap as defined by Moore (2004), and while visionaries have adopted the technology, the pragmatists still require some convincing in South African Industries. However, the life cycle shown is an aggregation of various sub-life cycles as will be shown next. In many complex *developing* technologies, there are dependencies that must be integrated manually by the user. This means that the user cannot just buy an off-the-shelf experience and that various technologies must be mastered to get into the market. These inter-dependant technologies also each have its own life-cycle similar to figure 1.1. Further complicating the matter is the fact that the life-cycles might not be perfectly synchronised as to the

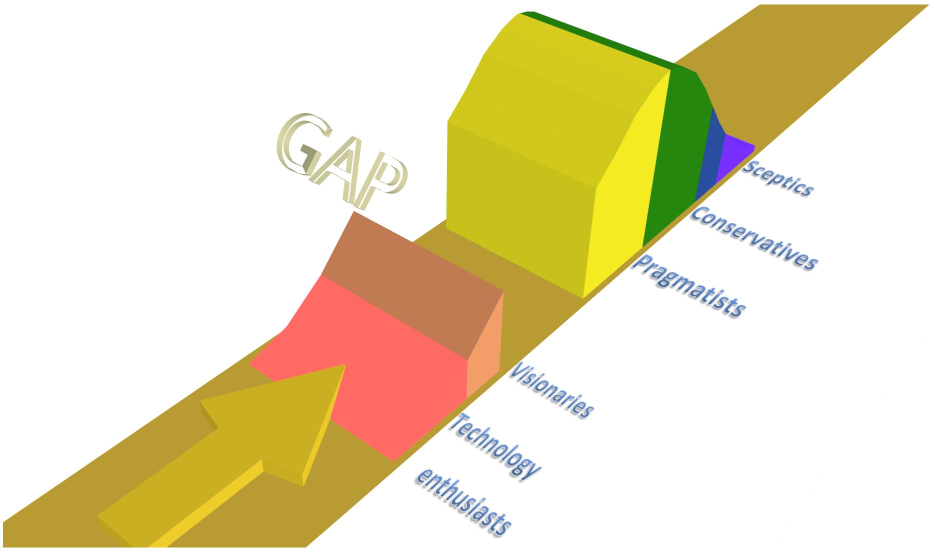


Figure 1.1: Technology adoption life cycle as described by Moore (2004), adapted for the research

maturity of the technology. All of these issues thus complicates the acceptance and use of new technologies in the market. In the case of micro milling, the various life-cycles and maturities that are most visible is that of machine tools, cutting tools, work holding, materials adapted for micro manufacturing, software, metrology and design. This results in having to master at least 7 technology areas to ensure consistent success. While a technology is in the developing stages before reaching maturity, the skill level of managing such technologies require at least a graduate engineer or similarly qualified technologist and some specialised training by companies who develop these systems. Such specialised personnel adds to the cost of technology acquisition.

Once these inter-dependent technologies are packaged for consumers in a single product that integrates the experience, the conservative users will join in using the technology and the skills level of operating the technology drops sharply. This is however still some way off for the micro milling technologies.

1.2 Structure of this research

This research developed a techno-economic model from a wide variety of disciplines and literature. The model includes significant contributors to machining cost and specifies the capabilities of the micro milling processes, for the South African context. Using the techno-economic model, it is then possible to perform the techno-economic study. More detail regarding techno-economic models are given in Chapter 2. The techno-economic model is based on a Business Model and this idea is discussed in more detail in Chapter 2. Regarding terminology, it is worth noting that a *Business Model* is quite distinct from a *business plan*, which describes the course of action a company plans to take. Porter ((2000) and Shafer (2005) describes a *Business Model* as the description or model of how a company generates its revenue. A techno-economic study must thus take cognisance of the *Business Model*, but is considered to be more general and less detailed than a *business plan*, which is most often tailored to a specific company. The opportunities and threats inherent in this new technology are identified, explored and included in this study. The price model is validated using various manufactured components, including a case study in fuel cell plate manufacture, the medical sector, and components manufactured for research at Stellenbosch University. Micro milling *technology* is scrutinised regards design aspects, materials, technologies, processes, metrology, sensors, control, potential and existing application sectors. *Economic* aspects of micro milling that are examined include capital investment, availability and cost of training, personnel, markets, various material costs, income potential and environmental cost.

1.3 Problem statement

It is challenging for companies to accurately predict the income potential of new technologies. These predictions are often done via a business plan, techno-economic evaluation or feasibility study. It is however often difficult for small and medium sized companies to release resources to evaluate new technology for their business. There are many unknown factors and obtaining reliable information about operating, costs, skill requirements and similar aspects are difficult. Apart from these obvious problems, the company also do not know if they will sell or get contracts based on the new technology. For this reason, small and medium sized manufacturing companies often lag considerably behind the technology curve, resulting in a reduced ability to compete with larger firms. Micro milling as a developing technology is relatively unfamiliar and presents unknown risks to companies who might be interested in acquiring the technology.

1.4 Objectives

The research attempts to provide a techno-economic model for small and medium sized manufacturing companies who need to make investment decisions about a specific new technology. The functional requirements call for a techno-economic model that should provide capabilities to adapt to and assign localised costs, attribute market share and simulate a marketplace where contracts are awarded to the company or its competitors. To make the model useful, it is implemented in R (RCoreTeam, 2014), which is freely available as Open Source software. The model is implemented as a Monte Carlo simulation, which generates the expected ranges of outcomes that are likely. The outputs of the simulation should be made visible in the form of tables and graphs, and the likelihood of the individual outcomes or ranges should be estimated. These likelihoods must then be expressed as the risks that one may encounter.

Although the model is meant to be a general model for simulating requests for quotes (RFQ's), awarding of contracts and assigning of costs, it is implemented in a specific case study where micro milling is the technology of choice. Thus micro milling markets were analysed in detail to provide the data that is needed for the model. The modelling process is discussed in more detail in Chapter 3. The main objective of a simulation study Law (2009) is to gain insight. In the case of this research it is to gain insight into the way high technology manufacturing companies may gauge their risk when deciding to acquire new technologies. Specific scenarios that could be explored through simulation may answer questions such as the following.

1. How many companies may survive for a given market size?
2. How does reputation influence the sales volumes?
3. How do random or unknown aspects of cost and sales influence cash flow?
4. How do random or unknown aspects of cost and sales influence cash balance and break even?
5. How do random or unknown aspects of cost and sales influence profit?

The performance measures that will be used include "number of months to break even" at various capital cost rates. Also, other common measures such as Return on Investment (ROI) and Net Present Value (NPV) are calculated. Data and graphs of relevant simulation output are presented and discussed.

1.5 Scope and scope exclusions

Large local companies and multinationals are excluded from this study due to the dissimilar environment and operating realities they are exposed to. Doing a similar study as the current thesis, for a large multinational, would entail analysing whole clusters of companies, their suppliers and global markets, placing the research outside of a single academic study and into the realm of a large international project. For example, Quinn (2013) shows that large companies can get substantially higher value by outsourcing their non-core activities to specialists with greater knowledge depth, sophisticated software and highly trained personnel. The same specialists do not see small to medium sized companies as viable clients since they would have to service many small companies, each with its specialised set of problems, and therefore a lower efficiency of service would result. For these reasons, this study is focussed on small to medium sized South African companies, who typically do not outsource core activities. The model attempts to replicate the market environment and competitive bidding between companies who might reasonably acquire similar micro milling technologies, but who might make different strategic choices. Since the complexity of the research problem is relatively high, a practically complete and accurate model including all the required data, would involve a team of researchers and multiple studies. It is however reasonable for a single researcher to get a structure and methodology of such a model in place and allow future research to build on this.

The scope of the data in the model is further limited to theoretical distributions and their derivatives, since no data exists for the problem. The system configurations to be modelled will be limited to less than ten sectors that require manufacturing, less than twenty companies who request quotes and less than ten manufacturing companies who compete for tenders. The simulation will span 4 years of results as the baseline, since the technology is expected to reach payback within four years. The simulation will be run however for between 3 and 10 years to test the sensitivity of the model.

The model will not be calibrated completely for a representation of the current reality, though such a project would be possible with the support of industry stakeholders. To calibrate the model completely would require a commercial project with very high costs in man-years and industry participation.

1.6 Research design and methodology

The research will comprise of the following aspects:

1. Reviewing previous work and literature.
2. Adapting and applying some of the literature study results to better describe the current problem and identify potential methodologies to enhance insight into the problem.
3. Describing the Techno-economic and pricing strategy model in general terms. During this process, conceptual validation is performed using a structured walk-through. Where errors or omissions are discovered, the

conceptual model is updated before proceeding to programming. The conceptual validation is repeated for step 4.

4. Describing the Techno-economic and pricing strategy model in simulation and modelling terms.

5. Writing code in R for simulation runs. During this phase the model is run multiple times to add features, debug code and check results for consistency. Once the model is programmed, validity is checked. Results validation from actual companies provide the most rigid validation. If actual results are unavailable, the analyst and stakeholders check the simulation results for reasonableness to satisfy face validity. Some aspects of the price and cost models are also validated using actual manufactured parts.

6. Sensitivity analyses are performed using the simulation model to determine critical variables and parameters that could have the greatest effect on the performance measures.

7. Finally, the results of the simulation runs are studied, analysed and discussed.

The literature review is interspersed with the author's comments as to how it may be used to support aspects of the design or methodology. Previous work in the scope of this study are sparse. However the research design process will follow commonly accepted model building principles as listed by Law (2009). The figure 1.2 from Law (2009) illustrates the relationships between the various aspects.

Once the scope of the model is fixed, the collection of information on the system layout and operating procedures may commence. This involves collecting data to specify model parameters and probability distributions. The model assumptions, algorithms and data summaries should be documented in a written conceptual model. The level of detail in this conceptual model, as well as the data and algorithms depends on:

1. Project objectives

2. Performance measures of interest

3. Data availability

4. Credibility concerns and computer constraints

5. Opinions of stakeholders, time and money constraints

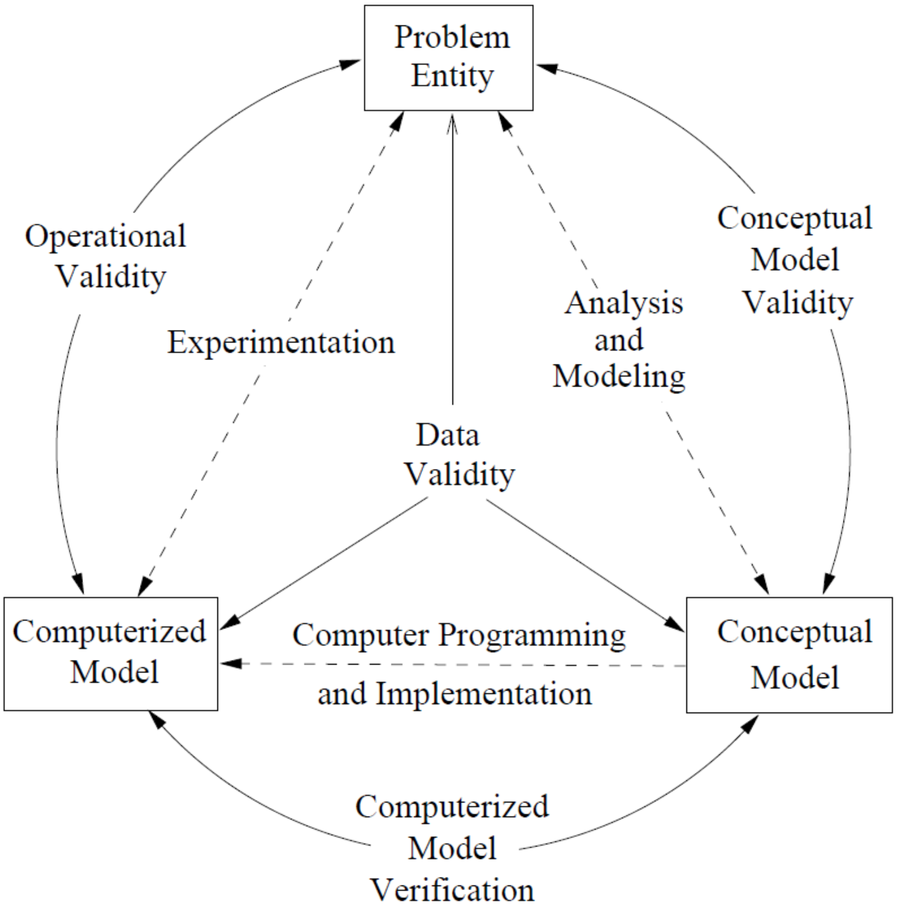


Figure 1.2: Law's understanding of how reality and model are linked in a the development cycle (Law, 2009)

One has to keep in mind there is seldom a one-to-one correspondence between the model and the system.

The next step is conceptual model validation. This can be done by a structured walk-through of the conceptual model. If errors or omissions are discovered in the conceptual model, which is almost always the case, then the conceptual model must be updated before proceeding to programming. For instance, during a presentation of version 1 of the conceptual model, a concern was raised that the model does not consider the marketplace as a competitive environment where multiple companies compete for limited work. This and other identified aspects such as company reputation and utilisation were then added to the model.

After the conceptual model is validated, programming the model may commence. This is done either in a commercial simulation-software product or in a general-purpose programming language. In the case of this research the open source statistical language R was used. The model is run multiple times during the development cycle to add features, debug code and check results for consistency.

Once the model is programmed, the simulation model is validated. If there is an existing system, and data, then the most direct method is to compare model performance measures with the comparable performance measures collected from the actual system. This is called results validation, but is seldom available. Regardless of if there is an existing system, the simulation analyst and stakeholders should check the simulation results for reasonableness. If the results are consistent with how they perceive the system should operate, then the simulation model is said to have face validity. Some aspects of the model may be validated from previous research, and should be consistent with experimental results or data from literature. Histograms may be used to check the output of probability density or mass functions versus what are expected.

Sensitivity analyses should be performed on the simulation model to determine critical variables and parameters that could have the greatest effect on the performance measures. These variables and parameters must be modelled even more accurately. Interest rates are generally considered to be one such a group of variables, since they influence the time value of money directly. Other examples of factors that could be investigated by a sensitivity analysis include the choice of probability distributions, entities moving through the simulated system and the level of detail for a subsystem.

When the simulation model is verified to give reasonable results, it is time to design, run and analyse simulation experiments. For each system configuration of interest, run length, warm-up period (if applicable) and the number of independent model replications are specified. From analysis of the results it may also be decided if additional experiments are required.

Finally the output of the simulation study should be presented including data output, graphs, risks and potential outcomes. Time plots show the dynamic long-run behaviour of the system, while animations could show the short-term dynamic behaviours of systems.

1.7 Background to micro milling

Figure 1.3 gives an overview of various world scales, adapted from Coetzee and Dimitrov (2007). Though micro milling is discussed and used in this model, meso-scale products also sometimes require micro-scale work, such as small features for clips, pins and more. These meso-scale products are included as part of the markets for micro milling.

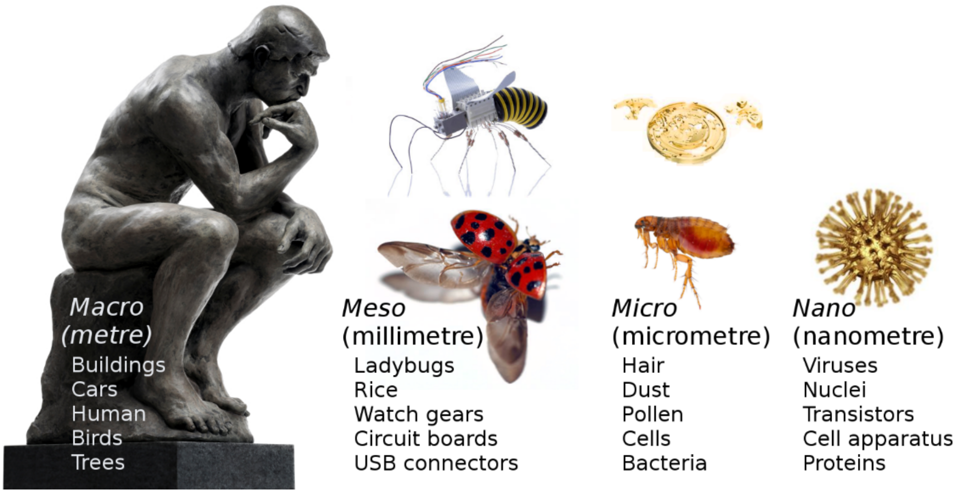


Figure 1.3: An overview of various world scales adapted from Coetzee and Dimitrov (2007)

Micro milling is a subclass of micro manufacturing and more specifically of micro machining. Micro milling is focused on the physical removal of material using a cutting tool. Micro manufacturing focuses on the emerging global trend toward the miniaturization of manufacturing processes, equipment and systems for micro scale components and products, i.e., "Small Equipment for Small Parts." It encompasses the creation of miniaturized units or hybrid processes integrated with metrology, material handling and assembly to create micro-factories capable of producing micro-precision products in a fully automated manner at low cost. The first major international study in this field, the WTEC panel report (Ehmann *et al.*, 2004), investigated both the state-of-the-art as well as emerging technologies from micro manufacturing. The report describes various scientific, technological, and commercialization perspectives across key industrial sectors in the U.S., Asia and Europe including medical, electronics, aerospace, and consumer products. Some of the WTEC panel's main conclusions are that micro manufacturing will become a disruptive technology and that countries need to support research in micro manufacturing to ensure future competitiveness in manufacturing.

Micro milling is defined by various authors (Aramcharoen *et al.*, 2008; DeVor *et al.*, 2004; Dae Jin Yun and Park, 2008; Ehmann, 2006; Gafford, 2010; Heamawatanachai and Bamberg, 2010) related to machine size, tool size, workpiece size and feature size. Masuzawa (2000) first related micro milling to the micrometer, meaning the machining of dimensions between 1 and 999 μm.

However Masuzawa (2000) later suggested that a more flexible approach considering factors such as the personal viewpoint, era, machining method and material might be better suited. Dornfeld *et al.* (2006) argued micro machining happens when cutting with tool engagements less than 1 mm. Meanwhile, Chae *et al.* (2006) had an inclusive definition of machining miniature products with features whose size range from micrometres to a few millimetres.

Because of the size effect introduced by micro machining, it can be argued that the definition by Simoneau *et al.* (2006) correctly advocates that the difference between conventional and micro machining should embrace factors influencing the cutting mechanisms. This size effect comes into play essentially when either or both of the following conditions arise. Condition one relates to the cutting edge of the tool that becomes large in relation to the tool diameter. For instance, Bissacco (2004) used a scanning electron microscope (SEM) to measure various geometry features on flat end mills as well as on ball nose mills with diameters ranging from 0.2 mm to 1.0 mm as an aid to determine when micro milling takes place. To expand on this idea, keep in mind that regardless of the tool diameter, the cutting edge was measured by Bissacco (2004) to be about 2.9 μm with a standard deviation of about 500 nanometre. Due to the relative large cutting edge in smaller tools, the tools effectively become less sharp at smaller tool sizes. Both the shear stresses and the bending stresses are thus larger in smaller tools due to this aspect and the next condition as expanded on in section 3.5. The second condition that causes the size effect has to do with cutting through individual metal grains and boundaries between the grains in a sequential time-line. Due to changes in the material properties in different grains, the cutting process will be discontinuous with added forces that are generated.

In this thesis, if size effects impact the cutting mechanism to any extent that makes conventional cutting calculations or assumptions inaccurate, then micro milling is assumed. This allows for products from various sectors that have sizes ranging from sub-millimetre to tens of centimetres with features that require micro milling accuracy or tools to be used. This means effectively that the definition of Simoneau *et al.* (2006) is adopted for the thesis.

1.7.1 Products and sectors for micro manufacturing

Micro manufacturing includes the fabrication of micro systems such as micro reactors, micro fluidic devices and micro scaled machines, whose outer dimensions are measured in millimetres or centimetres, and whose inner surfaces are configured with pores or channels that have dimensions measured in micrometers (AMTS, 2007). Emerging markets that require micro milling are described by various authors including Luo *et al.* (2005), Alting *et al.* (2003), Yan *et al.* (2004) and Masuzawa (2000). Opportunities and threats that are always present in disruptive technologies are possible driving forces to advance micro manufacturing. Emerging miniaturization technologies are driving developments in micro-scale processes, machines and metrology to meet needs related to part size, feature definition, accuracy and precision, and materials developments. To stem the hollowing out of their manufacturing base, the governments of many developed countries have made significant investments (AMTS, 2007) in the miniaturization of new products (specifically the lithographic-based processes such as micro-electromechanical systems -MEMS and nano-electromechanical systems - NEMS) and the miniaturization of manufacturing tools (for example, Desk Top Factories (DTFs)). These efforts are intended to regain a manufacturing edge. To illustrate this point, Olympus' Haruo Ogawa (the leader of Japan's MEMS team) says that MEMS may help rebuild Japan's power as a manufacturing nation (AMTS, 2007). Sankyo Seiki believes that its DTFs might revive manufacturing in Japan (AMTS, 2007). In Korea the government started a new DTF project in 2005 (Ehmann, 2006).

1.7.2 Manufacturing processes

A widely adopted classification by Swift and Booker (2003) lists casting, cutting, forming and fabrication as the major manufacturing processes. A slightly more recent classification by Kalpakjian *et al.* (2008) expands the list to include joining, sheet metal, polymer processing and bulk deformation processes. These traditional classifications do not cover all manufacturing processes and Zhu *et al.* (2013) suggests five categorises, namely joining, dividing, subtractive, transformative and additive technologies. However, a manufacturing chain of processes often involve two, three or even all types of processes to manufacture the final part. As an example, a injection mould might be manufactured using a Selective Laser Melting (additive) process, with a final surface machining on a milling machine (subtractive). For mass production, the process of casting metal or injection moulding of plastic parts are common. To manufacture the mould, in almost all cases machining and milling would play a part, if not the major part.

This study is only concerned with subtractive technology, specifically micro milling and some hybrid processes such as injection moulding that uses milling to create the required tools.

In this Chapter the scope of the research was defined and an introduction was given to the research problem.

Chapter 2

The techno-economic study

2.1 Introduction

This Chapter describes the methods (Arunraj *et al.*, 2013) (Kala and Omishore, 2005) commonly used by businesses to evaluate if or when they should invest in new technologies. Most businesses use a common strategy to execute the detail:

- Begin with a preliminary investigation of the current business model of the specific company and the new technology, that gathers as much detail as possible with the resources available. Competitors in the market are identified and investigated. The market is researched to determine its size and growth potential.

- Analyse the data gathered in the previous step to show flows of information, resources, money, time frames and where decisions are made.

- Using the information from the previous two steps, formulate the model or mathematical representation of the system that can be used to either gain direct insight or may be developed further to become a fuzzy set (Abdel-Kader *et al.*, 2001) or simulation model. Various authors including Arunraj *et al.* (2013) and Kala and Omishore (2005) have compared fuzzy set theory and Monte Carlo simulation and found that for complex systems simulation is more useful and accurate. If simulation is not done, then the same process is normally followed but substituting a *sensitivity analysis* for simulation. Both simulation or sensitivity models will contain logic to represent flows of money, information and resources over time in some format.

- When employing a simulation model, users run the simulation a large number of times to ensure they are confident of predicting outcomes with a reasonable certainty.

- The outputs of the simulation runs or *sensitivity analysis* are then presented in various numerical and graphical formats so that these may be analysed, interpreted and could lead to more informed decisions regarding investing in the new technology.

The reader should take care to distinguish that there are three steps that contain analyses (including *sensitivity analysis* in the last step). In step 2 the preliminary data, flows and logic to build the model are analysed, while in the last step the outputs from our model are analysed to inform our decisions.

During the simulation output analysis, the analyst attempts to identify the relationships or effects of critical input parameters on the output, regarding probabilities or risk distribution on expenditure, income, profit or other relevant aspects of the business.

Technology development is on an accelerating curve and requires agile and informed business decisions that are cognisant of efficiency, strengths, weaknesses, opportunities and threats (SWOT) of new technology. A techno-economic feasibility study (TEFS) includes any relevant technical, market, operational and financial information to assist in making decisions about technology investment and market- and operational strategies regarding the technology.

2.2 Economic modelling considerations

2.2.1 Introduction

Economic modelling can be interpreted to have various definitions including the following one from Merriam-Webster (Dictionary, 1996):

- A process in which computers use a set of ideas and numbers to describe the past, present, or future state of something (such as an economy or a business).

More general of course, modelling existed before computers did and the idea of representing some reality state of the economy or part of it with sets of ideas and numbers can be considered Economic modelling. In the case of this dissertation the Economic modelling is indeed executed using software simulation and a computer, and data from various sources as discussed in Chapter 6.

A high level of detail in a simulation will normally increase the accuracy of the model, but could also lead to a false sense of certainty, especially if the data used in the simulation are limited in geographical, technology specific, time period or similar attributes. So while the modelling might be generic enough to describe various scenarios, the data in this dissertation will be specific to a narrowly defined case and as such only accurate for the case presented and as far as the data can be verified.

The following paragraphs introduces previous research in economic modelling and give some insight on what areas to consider.

Fuzzy set theory and the analytic hierarchy process are used (Abdel-Kader *et al.*, 2001) in a conceptual framework that combines the three dimensions of risk, financial return and non-financial factors. The authors argue that traditional investment models such as return on investment, payback and internal rate of return emphasize quantitative, financial analysis but fail to capture many of the intangible benefits that should flow from AMT investments such as greater manufacturing flexibility, improved product quality and better employee morale. They further argue that the high risk inherent in new technologies often leads to the use of arbitrarily high hurdle discount rates. Various other authors also describe financial, business or economic models to guide strategic planning (Jones, 1996), investment (Butler, 2012), prioritising (Bardhan *et al.*, 2004), open collaboration (Bicking and Wimmer, 2011), innovation (Calantone *et al.*, 2006) and risk (Butler, 2012). Focussing more on the topic at hand, investment into high or new technologies are addressed by (Findlay, 1978*a*), by drawing on two previous authors, Richard Nelson (1959) and Edwin Mansfield (1968).

2.3 Definition of a techno-economic feasibility study (TEFS)

Considering previous research (Perez, 2009; Fokiali and Moustakas, 2009; Sinek, 2009; Osterwalder and Pigneur., 2010; Shafer, 2005; Faber *et al.*, 2007), at a high level the definition of a TEFS can be argued to be: "Researching and quantifying opportunities and potential benefits versus costs and risks of technology acquisition".

Delving into the definition, *researching* refers to either primary research in the form of experiments and questionnaires, or secondary research such as books, articles and technology reports. Further, *quantifying opportunities* includes a plethora of terms such as throughput, markets, sector sizes, sales estimates, products, import replacement, profit margins and government subsidies and policies. Each term must be quantified using typically a number and unit; for example, the global bio-micro-systems medical implant market, including accessories and supplies, was projected to grow to R221 billion for the year 2016 (Merx *et al.*, 2003). These *quantifying opportunities* will be explored in more detail in Chapter 4.

Next, the potential benefits in most cases will be income generated by using the new technology at some estimated or calculated cost to the company. When the cost is subtracted from the income, the profit before tax is found.

Finally, since none of the above values that are used are known and fixed quantities, they will be represented in the model as distributions, and as such may take on various values during a sensitivity analysis or simulation. This leads to various potential outcomes, each with an estimated probability of occurring and allows us to define the risk inherent in the technology acquisition.

2.4 Business analysis and modelling

Feasibility, business, technology and economic analyses, are often classified as either a *macro-study or micro-study* with the following in mind.

Analysis and modelling can be applied to various levels of thinking, such as the *overarching analysis* of a country's use of and strategy with their finances, workforce, resources and technology; including broad studies on existing and emerging markets and current and expected technology developments and adaptation to industry. Such a macro-analysis could lead to policy frameworks regarding resource exploitation and to programs that assist industry with skills transfer and funding in strategic projects.

In *Innovation Economics - The Race for Global Advantage*, Atkinson and Ezell (2012) describe how government policy should use innovations and push these to commercialise them using the four pillars of:

1. Technology
2. Tax
3. Trade
4. Talent

Atkinson and Ezell (2012) state that government must encourage business investment in innovation by policies that reward innovation, talent training and commercialisation. However, such an analysis or the model that underpins it is the domain of governments and is seldom contemplated by businesses. The macro level of analysis and modelling *is not entered into* during this study, although isolated comments might relate to it.

A *second level* of thinking, but still seen as macro-analysis, might look at analysis in a *specific sector*, such as medical, energy or transport. Once again, this might lead to policy initiatives to grow the specific sector. Some research is directed to this topic and commented on, but it is considered outside the scope of of this study.

A *third level*, called micro-analysis might look at a *specific company*, with limited skills, funding and accessibility to markets. These analyses are based on the value that the company can add to its product or service offering, income it may generate, risks and costs estimates.

Businesses may again have various levels of detail in plans, reports, models, analyses and data that they use to assist with choosing an informed course of action. Apart from the techno-economic evaluation, there are two similar methods that are often used, namely the feasibility study and the business plan. To generate a techno-economic evaluation, feasibility study or a business plan, a model or abstract description of reality or *as-is* is required. In the case of a new technology, there is currently no reality and a model or abstraction of the required reality or *to-be* is generated. Once the model is described adequately, it may be used generate the outputs to perform analyses on. For instance, Blank (2005) says that the business model of a company should be a one-page description that includes all the flows between the company and the clients, including costs and income cash flows. However to get to that one page description is all but trivial. In the marketplace things get more complicated due to competitive bidding for tenders, and how these tenders are awarded. The economic evaluation of the technology is also dependant on the sales that may be generated, which is of course not known in advance.

Case studies listed during this report relate to modelling and analysis of a single technology namely micro milling. Also, acquire a new technology, the art of technology transfer which includes finding the correct partners and training is critical.

2.4.1 Technology transfer to business application

As a small introductory case study, during 2003, Zyvex in Richardson, Texas, introduced more than ten new products in the nanotechnology environment (Cellucci and Folaron, 2004). Zyvex COO Thomas Cellucci and the Director of Product Development, Robert Folaron claim that such technology transfer success hinges greatly on the creation and execution of a well-defined new offering development strategy. The first stage of this strategy is the concept feasibility and evaluation, which is proven by researching the scope and investment into technologies that are required, estimating the resources and training requirements, forming multi-disciplinary teams and estimating sales and returns.

In Zyvex, the Sales and Marketing members define the potential offer to the market in terms of features, benefits and reasons to buy. They also estimate the market size by considering potential growth trends and identify potential customers and competitors.

The Zyvex Manufacturing, Finance and Operations teams estimate and specify the required capital, technologies, manufacturing processes, and materials and suppliers. The Research Team investigates relevant intellectual property and defines complimentary technology transfer requirements.

From the Zyvex case study, some aspects of modelling may be inferred already. Capital costs of technology and training, operational and resource cost must be compared to predicted sales and income. Detailed manufacturing processes, and materials and suppliers must be modelled to allow estimated costs to be easily calculated per request for service or product. From the previous information the model should create cash flows, cash balances, net present values and calculate returns.

Various researchers Findlay (1978*b*); Krugman (1979); Chen and Small (1994); Gehani (2007) have described how road-maps and other tools may be used to introduce and commercialise technologies.

Findlay (1978*b*) constructs a dynamic model which captures aspects of the way in which the transfer of technology takes place, including the role of direct foreign investment. Included in his model are parameters to describe the level of development of the regions involved in the technology transfer and the degree to which the receiving region is open to direct foreign investment. Also considered are the relative growth rates of foreign and domestic capital. Findlay also includes the effects of changes in various parameters such as the tax rates applicable.

Krugman (1979), while at Yale, developed a general-equilibrium model of product cycle trade. He describes two countries, an innovating North and a non-innovating South. Technology transfer allows the South to master the technology and manufacture it at a lower cost. The technology transfer lag gives rise to trade, with the North exporting newly developed expensive products and importing cheaper old products.

To successfully implement advanced technology, Chen and Small (1994) listed various integrated planning requirements and uses a survey and data about the success of each project to gauge the effect of each. The most important considerations on the list are multi-disciplinary planning and implementation teams, financial and strategic investment appraisal, matching the technology to business requirements, development of performance measures and having knowledgeable project managers. It is of course difficult to encapsulate all the requirements into a single and comprehensive model, but the simulation performed during this study attempted to include financial appraisal and performance measurement from the list by Chen and Small (1994).

Other authors Yusuff *et al.* (2001) presented the analytical hierarchy process (AHP) for forecasting the success of advanced manufacturing technology implementations. Their AHP is based on seven influential factors, including a committed and informed executive and operating sponsor, think-tank linkage, alignment and integration of business and organisational fit, user commitment and support. Chang and Wang (2009) later duplicates the previous case study, but uses consistent fuzzy preference relations (CFPR) to determine a similar outcome. They further ascertain that the comparative results show that consistent fuzzy preference relations is computationally more efficient than the analytic hierarchy process.

When considering the introduction of new technology in a specific region, it is also useful to compare the region to other economies, regarding technology readiness, infrastructure, business sophistication and such metrics. In figure 2.1 adapted from (Hellebrandt *et al.*, 2015) it is clear that South Africa is the best equipped in Sub-Saharan Africa to introduce new technologies, but also that it is lacking various vital aspects in infrastructure, technological readiness and also higher education. This will slow the adoption of new technologies.

2.4.2 Simulation study

For this study, requests for quotes, predictions, sales volumes, cost, income, discount rates, company capacity, reputation, utilisation and risks are addressed by using simulation. Regarding simulation, Jahangirian *et al.* (2010) reviewed 281 published peer-reviewed articles to show that discrete event simulation (DES) is used most, specifically in 40% of the reviewed articles. In the second place, 15% of studies used the growing system dynamics (SD) method, though DES has retaken some previous losses to SD in the last years. Hybrid methods of simulation, that combines parts of other simulation methods, is used third most, at 10%, while agent based simulation and Monte Carlo simulation are fourth and fifth respectively at approximately 5% each. Simulation methods used in less than 5% of cases included in decreasing order of use intelligent simulation, traffic simulation, distributed simulation, simulation gaming, Petrie-nets and virtual simulation.

Of the methods discussed by Jahangirian *et al.* (2010) the Monte Carlo simulation is the one used most often.

Using simulation, the expected range of outcomes are made visible, and the likelihood of the individual outcomes can be estimated. Simulation is highly dependant on the distributions that represent reality, and as such these distributions are crucial to dependable outputs. Data for the current simulation were gathered from experiments, cost models, time studies, previously published research and models based on previously published research. This is expanded in section 3.6 and Chapter 6.

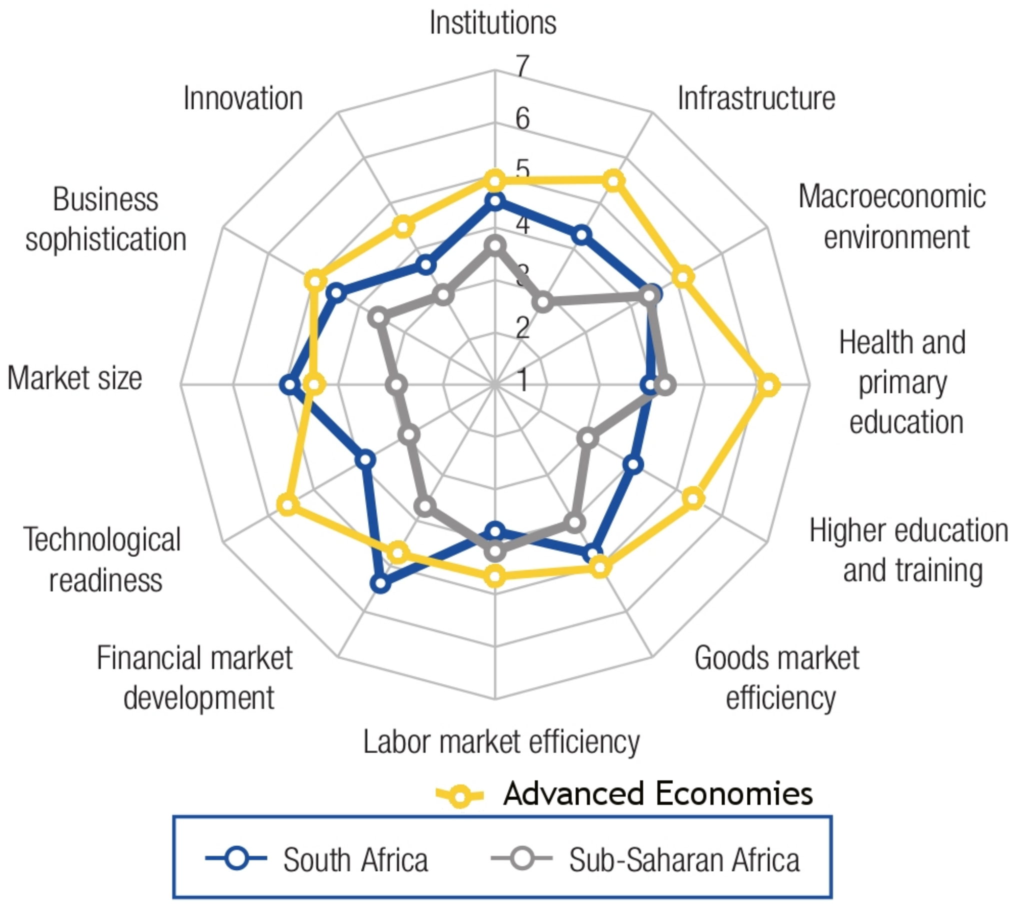


Figure 2.1: Global Competitive Index comparison of South Africa adapted from (Hellebrandt *et al.*, 2015)

The profits that can be *realised from parts* are influenced by the innovativeness (Calantone *et al.*, 2006), cost, efficiency and waste in various forms as well as the achievable precision of the processes. Case study parts and projects that are discussed in this report relate directly to part and project profitability.

One possible way to look at the environment where new technology may be implemented, would be to use Osterwalder's Business Model Canvas (Osterwalder and Pigneur., 2010) to ensure the relevant aspects are considered in a holistic way. Micro milling is used as a case to illustrate the use of this method in figure 2.2. Using the diagram we are reminded that we need key metrics to determine the success or failure of our implementation and that there are various physical aspects of the business to consider such as infrastructure, the value offer, resources, distribution, customer sectors, cost structures and revenue streams. The value of such a model is that it has proven itself in peer review, and as such is expected to include the salient aspects we need to consider.

Other aspects that are visible from figure 2.2 are that there are linkages to consider between the various entities shown. In practice these linkages may be the flows of information, orders, quotes, delivery of product, payments, planning of resources and other relevant information. Though the Business Model Canvas does not show the detail of these aspects, when we read the documentation or books of Osterwalder (2004) and Osterwalder and Pigneur. (2010) we may find more detailed reminders of these aspects. Some of these aspects are discussed next in more detail for a typical small company who do micro milling.

Assuming the company has an adequate Partner Network, and has the resources, functions and activities in place to offer some unique value proposition, then the customer segments will take note of the company. A model was developed to capture some of the complexities of a technology business which generates income from contracts. Referring to figure 2.2 the model includes the Finance, Offer and Customer/Market blocks in a simulation. The Enterprise Infrastructure aspects are only considered regarding its financial impacts.

A business that must win contracts would be dependent on somewhat random requests for quotes (RFQ's) from customers and would be awarded some of these quotes depending on the price and value perceived by the individual clients. One of the key short-term issues for any business is its cash flow. A positive cash flow during a year will result in profit for the business. However, in the day-to-day operation of the business, cash flow is sometimes positive due to income and other times negative due to expenses. At any point in time the business will have a cash balance of either money that is available, or a negative balance as an overdraft. Having cash available might have its own problems, but those pale in comparison to the problems the business will face when its overdraft goes over the limits allowed by its bank. This presents a real risk to the business, in that banks may then choose to raise the interest rate on their overdraft, refuse to pay any additional expenses the business is liable for, or in extreme cases, call for the overdraft to be settled immediately. This might in return result in a business not being able to buy materials required for their direct manufacturing contracts, pay salaries at the end of the month and spiralling into bankruptcy. For the preceding reasons it was decided to model the required processes that will enable the compilation of cash flow statements.

Modelling sales and total income is only half of the cash flow equation. The other major category is the "Cost of Sales" and general expenses of the company to manufacture the products. Although the company is only liable to pay income tax once or in some cases twice a year, provision for taxes are normally made every month. This information is compactly expressed in the cash flow statement that is generated from the monthly financial income statements that can be seen in figure 2.3. Various cash balances are included in the results section, such

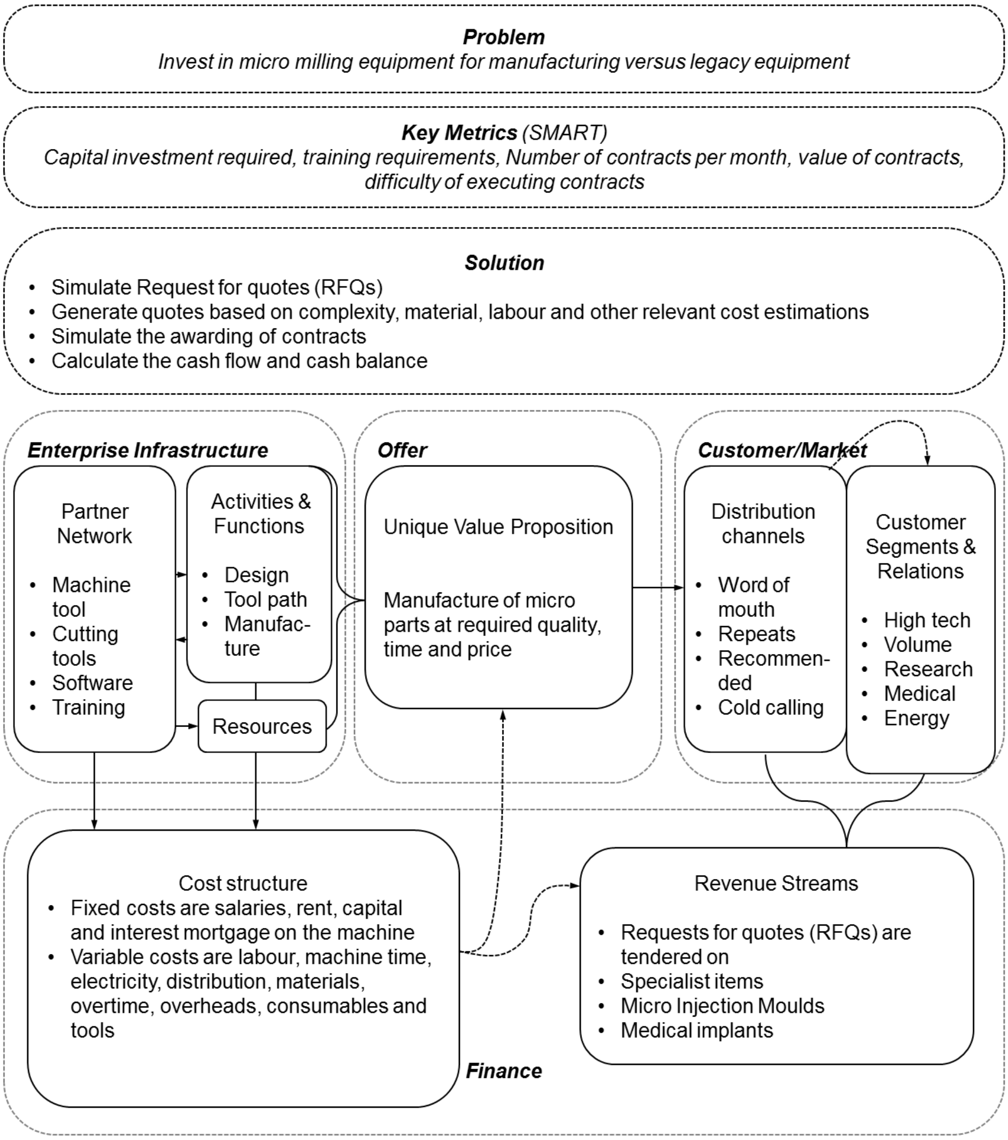
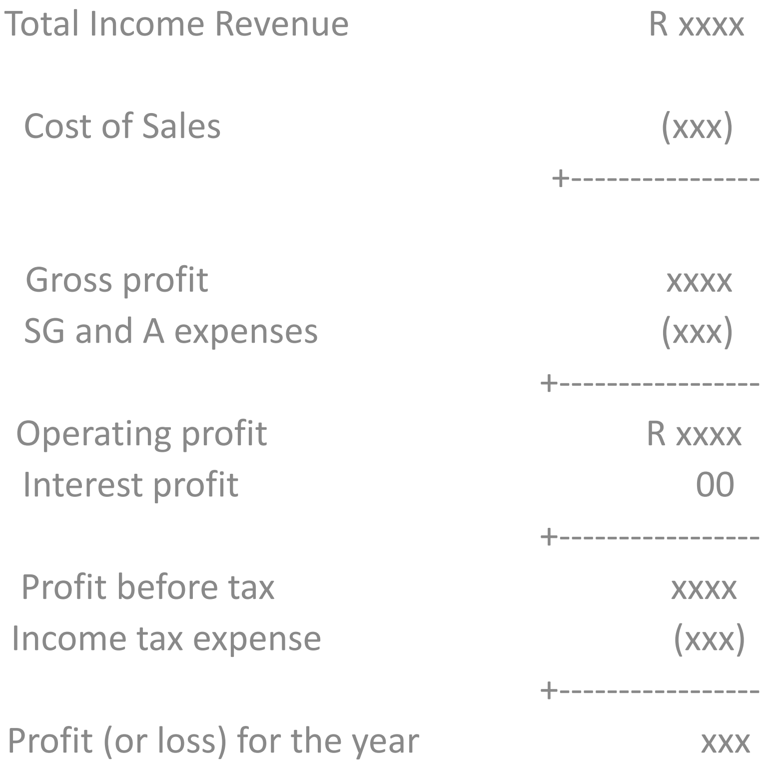


Figure 2.2: Business model canvas adapted from Osterwalder and Pigneur. (2010) for micro milling technology evaluation

as the un-discounted cash balance in figure 7.7 and discounted cash balance in figure 7.8.

The cash flow statement is of crucial importance to the business in its day-to-day operations. Once the daily cash flows are collected for a month, these flows are collated as a month statement of sales and expenses. These monthly statements are collected and compiled once a year as a standard Income statement. This Income statement is used to determine the Profit or Cash Flow for the year. Values in (brackets) are negative and for the model the interest profit may be calculated on the monthly cash balance.



Total Income Revenue	R xxxx
Cost of Sales	(xxx)
	+----------------
Gross profit	xxxx
SG and A expenses	(xxx)
	+-----------------
Operating profit	R xxxx
Interest profit	00
	+-----------------
Profit before tax	xxxx
Income tax expense	(xxx)
	+-----------------
Profit (or loss) for the year	xxx

Figure 2.3: Typical structure for an Income statement from Atrill and Mclaney (1997)

2.4.3 Strategic aspects of Advanced Manufacturing Technology

Abdel-Kader *et al.* (2001) list at least 40 authors who argue that evaluation of advanced manufacturing technology would benefit from taking into account the strategic nature and non-financial benefits, as well as traditional investment methods such as return on investment. They suggest integrated financial and non-financial factors in manufacturing technology evaluations, and demonstrate this using the mathematics of the analytic hierarchy process and fuzzy set theory. The most important factors they include are shown in figure 2.4. When the methods of fuzzy set theory are analysed, Wickramasinghe and Garusinghe (2010) in an study of 35 companies involved in technology transfer found human factors, training skills and capacity to be the critical bottleneck. From discussions with industry it is confirmed that human resources capacity is often a major limitation to increased throughput. The more autonomous the technology can operate the easier it becomes to manage the operational part of the business. However, such advanced technology is often only repairable by the original manufacturer, leading to associated risks. In thinking about Southern African small to medium sized companies, using state of the art technology might entail undue risks due to their inability to afford the required maintenance personnel and the unsuitability of outsourcing (Quinn, 2013). It follows that the level of technology should be workable and maintainable by SME's. As per section 1.1.1 the discussion regarding the seven life-cycles that enable micro milling and compound complexity comes to mind to be considered by the SME's.

Critical factors in economic modelling include market size estimation, market share and growth, technology life cycles, cost determination and learning curves for the technology. Ways of analysing success includes financial measures such as the present value of cash flows, return on investment and discounted break-even. There are also strategic measures such as dependence on foreign resources, self-reliance and global competitiveness of either the country or sector in question.

It would be desirable to model the micro milling environment so that all of these factors could be accommodated as holistically as possible. The model would then be applicable to all the related stakeholders, and also be used to trade off some conflicting goals. In practice however, any model will fall short of attaining a fully representative reality and outputs must be still be treated with caution and even suspicion. The ample use of experience, logic and common sense are advisable in this regard.

Various authors have attempted to provide some rigour to the process of evaluating a business or new technology. It remains however a difficult undertaking with most case studies opting to refer to a techno-economic evaluation that limits

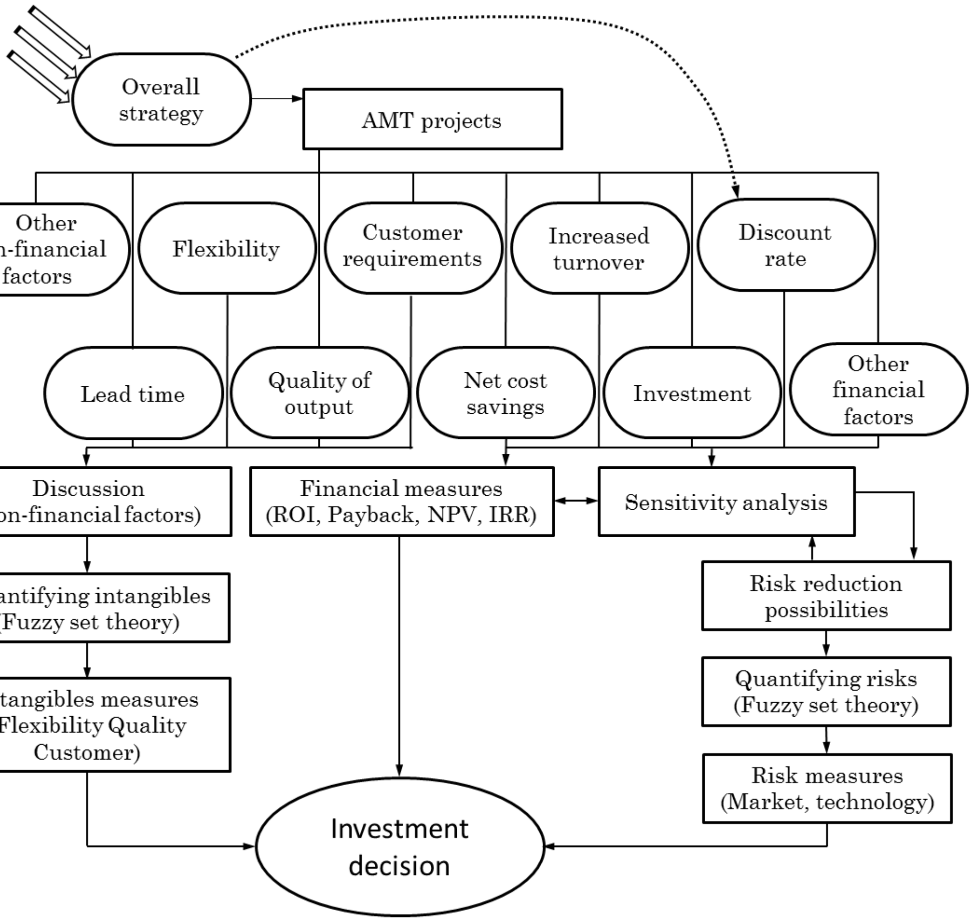


Figure 2.4: Advanced Manufacturing Technology factors to include when considering investing from Abdel-Kader *et al.* (2001)

the scope to a single technology that is evaluated. Business models are mostly regarded as the domain of the enterprise as a strategic tool.

It is clear that before attempting a techno-economic evaluation though, there needs to be an intimate understanding of how the company generates revenue, that is an understanding of its business model.

According to Shafer (2005), a recent study of 40 companies found that 62% of the 70 executives they interviewed had a difficult time describing how their own company made money in an accurate way. In general there is not an accepted definition when even academics refer to a Business Model, and even less among business people. To illustrate this, strategist Michael Porter ((2000) has referred to the phrase *business model* as part of the *Internet's destructive lexicon*.

Regardless, the following authors are regarded as the leaders of this field of research. Shafer (2005), Abe *et al.* (2009) and Osterwalder and Pigneur. (2010), use the term Business Model mostly to describe an abstract set of diagrams, concepts and connections to help visualise the flow of cost, information, services, revenue and products. Others, including Dosi *et al.* (2010), Faber *et al.* (2007), Shafer (2005) suggest that in articles they evaluated from 1998 to 2002, there were twelve somewhat conflicting definitions of what a business model should be. Going back to these articles, one can find 42 unique components that are required in such a business plan. The number of times these components were included in the Business Model are shown in the bar chart figure 2.5.

Of the twelve definitions, eight include the *suppliers* as vital to the business model, followed by the *customer or market* as the next integral component. The *value proposition* and the company *resources and assets* are included in half of the twelve definitions. *Cost* is only considered by three of the twelve definitions, *profit* in only two and *cash flow* in only one.

Using the affinity diagram method Shafer organised the 42 components into four major categories as shown in figure 2.6: strategic choices, creating value, capturing value, and the value network. Contemplating the four categories as suggested by Shafer, it seems that the business model is oversimplified to enable the grouping of all 42 components in only four categories. Some of the vital criticisms that could be levelled are:

- Strategic Choices: Having ten components in one category removes a layer of complexity that is required to be explored in more detail to gain understanding of the reality. In other words, the model is easy to grasp, explain and present visually, but it does not lead to a comprehensive understanding of reality, since reality presents a more complex structure.

- Creating value: This is potentially clear enough as it is, but the two components included in this category could easily be separated if so required, similar to what is done in the Business Model Canvas of figure 2.7.

- Capturing value: Capturing value in most companies starts with *revenue*, which in this model is listed in the *strategic choices category*. This was maybe due to a research design error, since the researchers grouped *revenue and pricing* as a single component, while in reality these are two interdependent components. Cost fit more closely to the *creation of value* since that is where the *cost* is allocated.

- Value network: To group *suppliers* and *customers* in a single category once again does not reflect the reality in most companies. Though it might make some sense due to shared infrastructure of sales revenue and suppliers' payments, the type of management of the two components and the way

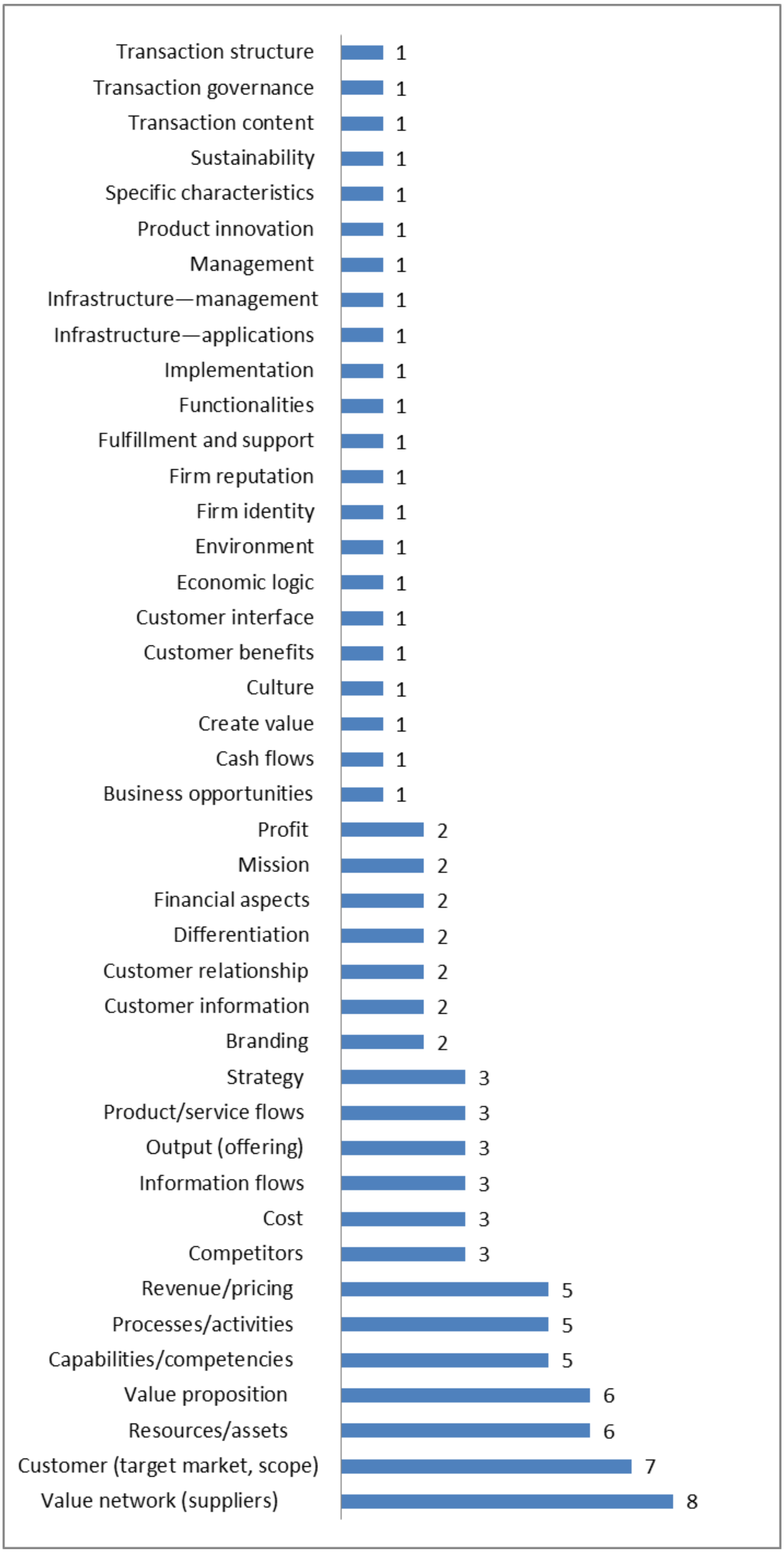


Figure 2.5: Priorities of the components of the business model by Shafer (2005)

most companies' internal structures function, makes this a dubious choice. Once again, it creates a lot more insight into reality if the *suppliers* and *customers* are shown separately in the business model as is the case in figure 2.7.

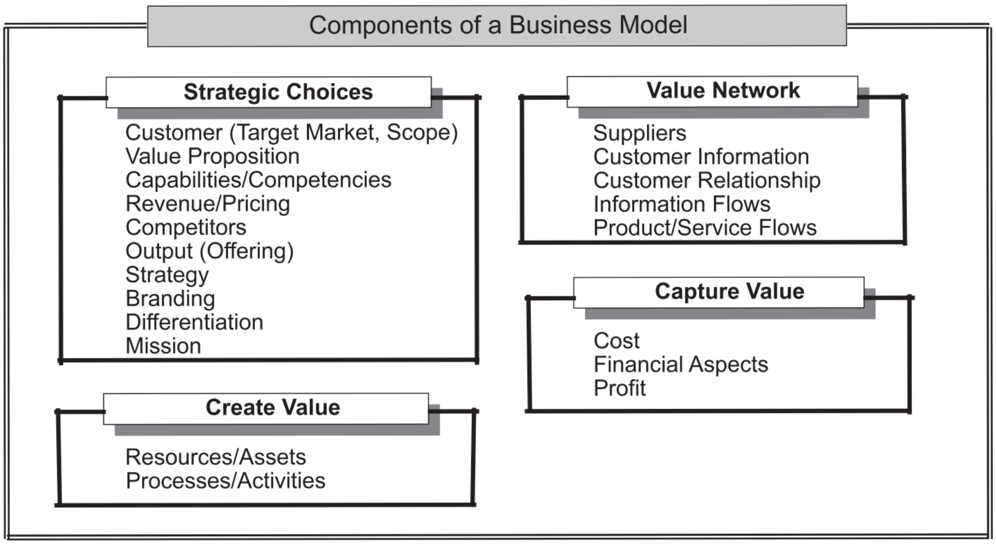


Figure 2.6: Components of the business model affinity diagram by Shafer (2005)

Referring back to Osterwalder (2004) and Figure 2.2, a more complete and logically structured Business Model is visible than was presented in Figure 2.6. To make the Business Model Canvas even more accessible, Osterwalder and Pigneur. (2010) added some graphics and integrated the linkages resulting in a more aesthetically appealing version shown in Figure 2.7. Thinking about Sinek (2009), his Golden Circle could be overlaid on the Customer experience as shown top right in Figure 2.7.

This view of the business has the added advantage of being an easy to understand visual aid when we describe our business processes. At the same time it incorporates all the aspects of Shafer (2005), albeit in a different structure and not necessarily listed as such. The golden circle places added focus on the critical importance of understanding *why* we do, *how* we do it and *what* we do to add value to our customer experience.

The combination of Osterwalder and Pigneur. (2010) and Sinek (2009) will be referred to often when discussing aspects of the business in the rest of this document.

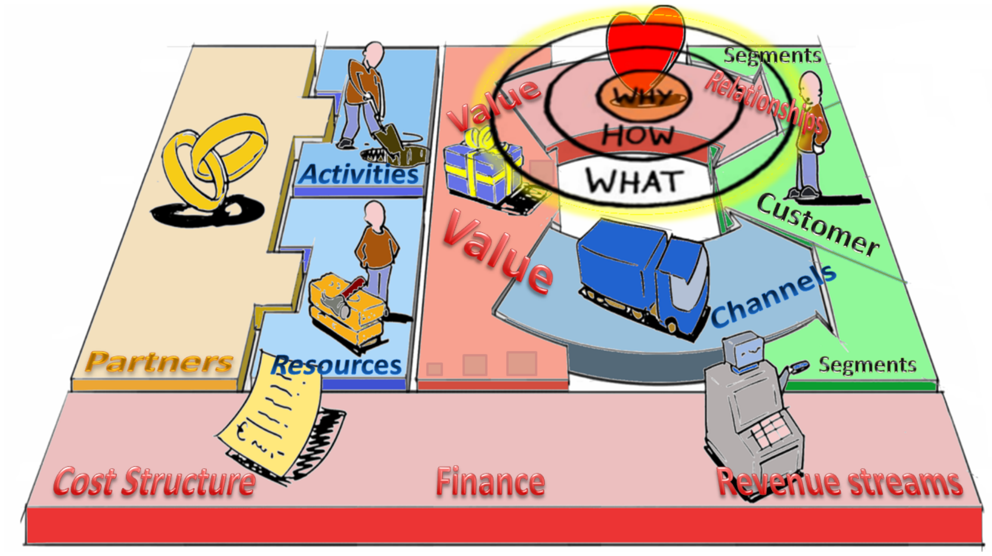


Figure 2.7: Business Model Canvas adapted from Osterwalder and Pigneur. (2010), overlaid with the Golden Circle from Sinek (2009)

2.4.4 Discussion of the Business Model Canvas (BMC) and Golden Circle (GC)

The Business Model Canvas (BMC) according to Osterwalder and Pigneur. (2010) consists of 9 building blocks, namely:

- Customer Segments; the organisation serves one or more *customer segments*.
- Value Propositions; to solve customers' problems and satisfy customers' needs.
- Channels; *value propositions* are delivered to customers through communication, distribution, and sales *channels*.
- Customer Relationships; are established and maintained within each *customer segment*.
- Revenue Streams; result from *value propositions* successfully offered to *customer segments*.
- Key Resources; Key resources are the assets required to offer and deliver the previously described elements.

- Supporting aspects: micro-machining research and applications, miniature machine factories, process optimisation and technology development.
- Design: machine tools, work-piece and design issues, simulation tools.

While the Business Model Canvas shows us clearly how the components of a business work together to get a result, the Golden Circle has a more subtle message. Most value selling propositions will tell you *what* they offer you:

- We are rolling out the new version 2017, 12 months early!
- We believe this is the best system ever.
- Version 2017 is now even cheaper to maintain.
- And that's *why* you should buy one today.

Sinek (2009) explains it all starts with *why*. The *value* we create in the Business Model Canvas must be the end result of *why* we do what we do. Using an example, imagine the following scenario of a company's vision:

- We believe in challenging the status quo and in thinking differently.
- We believe there is no compromise on quality of manufacture.
- We believe in beautifully designed and user-friendly products.
- And that's *why* we happen to make great products.

The preceding discussion will be used to guide the development of the structure of the techno-economic investigation and model.

2.5 Details of the techno-economic model

Before we can do the techno-economic evaluation or feasibility study, we need to define a model that represent the reality.

Potential benefits are usually expressed in monetary terms, but could also include qualitative issues regarding sustainability, self-reliance, health, education and competitiveness. *Costs* are self-explanatory in terms of its financial impacts, but could also refer to intangible costs such as man-hours spent on training, which results in opportunity costs or opportunities lost. Finally there are *risks* that could be expressed in either monetary or intangible terms.

Perez (2009) identifies three main areas of practice and perception for any techno-economic paradigm (TEP). It will also become clear that the TEP is inherent in the TEFS. The first of the areas for the TEP is the *dynamics of the relative cost structure of inputs to production where new low- and decreasing-cost elements appear and become the most attractive choice for profitable innovation and investment.* The second is the *detection of the profitable opportunity spaces, either in the producers of the technology or the users of the technology*. Lastly, *TEPs shape the workplace, improve processes and increase management and operational control*. This directly impacts on the quality of the products that are manufactured using the technology. It is worthwhile to also reflect on the description by Perez (2009) of a techno-economic paradigm:

> A TEP is the result of a complex collective learning process articulated in a dynamic mental model of the best economic, technological and organisational practice for the period in which a specific technological revolution is being adopted and assimilated by the economic and social system. Each TEP combines shared perceptions, practices and shared directions of change.

Considering Perez, we may infer that a TEP is an adaptive, dynamic and ever-changing beast, by no means easy to describe and likely not precise. Though it contains the shared perceptions, practices and shared directions of change, it is also likely adopted and assimilated differently in various economic and social systems. The TEP must be explored as completely as possible to enable confidence in the TEFS.

In contrast, Fokiali and Moustakas (2009) state:

> A techno-economic study should lead to clear and explicit positions of a "yes" or "no" type, hence the frequently encountered conclusion of many academic projects for the need for further investigation of the matter has no place in such a study.

Earlier in the same article Fokiali *et al.* refer to "keeping risk to a minimum". It could be argued though, that in the forcing of a "yes/no" result, that Fokiali *et al.* disregard the very real aspects of uncertainty, risk and complexity, while Perez includes space to explore these, but leaves the final decision in the hands of the investor. Each investor has a specific risk-profile depending on many factors. The more risk is made visible, the better informed choice is possible. The exasperation of Fokiali and Moustakas (2009), likely stems from TEF studies that were too limited to draw proper conclusions. Comprehensive studies should attempt to find ways to suitably represent risks, and try to enumerate these risks.

Regardless, the process described by Fokiali and Moustakas (2009) to execute a TEFS, is extensive and will be used to guide this research, along with various other authors. These types of studies mostly follows a similar approach of specifying the required technology and associated costs in a structure and scalable model unique to the technology they evaluate. The next step in a TEFS would be to estimate the potential income from the system, and in most cases they would evaluated high income, average income and low income scenarios in what is called a sensitivity analysis. As a final step, the cost model and income model is linked and calculated at the various probable volumes they expect to be most profitable.

According to Fokiali and Moustakas (2009), the structure of a techno-economic study follows from the rational steps in decision-making. Making decisions about the feasibility of ideas and following through until its fruition, the following steps may be followed: Identification of the problem, original ideas, transformation of these original ideas into proposals, setting of goals and strategy development, Analysis, i.e. detailed examination of the issue from a number of viewpoints, Synthesis, i.e. plan for implementing the proposed project, containing details on what has to be done, by whom, adopting what approach, working to what timetable and at what cost, implementation and evaluation of results. A favoured structure for techno-economic studies includes: General information on the technology and market potential, modular analysis containing a number of supporting studies and synthesis of the implementation plan, operations, the budget and the estimated results.

2.6 Conclusion

Although there is considerable agreement over the above general structure of the techno-economic study, it should be noted that there is no single approach or rigidly defined model that would fit the bill for every type, size and category of investment plan. In this sense, appropriate adjustments are necessary, so that the techno-economic study for a specific project meets the project's requirements.

Feasibility could have many aspects, but only two categories are discussed here. The macroscopic feasibility study contains the motivation why the investment should be made in a technology, given prevailing conditions and expectations. It asks why the technology is required and not necessarily if it will be financially profitable. Social, cultural and natural environment aspects, especially the effect of the technology on wages and income, employment and development at both regional and national level should be considered. If the investment is not deemed feasible at this stage, then there is no point in continuing with further details or in setting out the demands and constraints in its implementation. If, from the macro point of view there are no reasons to exclude the technology, then a micro feasibility study can help to assess the risks and probable chances of success for a company who want to implement a specific technology.

Aspects of both the macroscopic feasibility and micro feasibility will be addressed in the study, though the focus of the simulation is the single business in the marketplace with competitive bidding. Business Model Canvas adapted from Osterwalder and Pigneur. (2010), with aspects of the Golden Circle from Sinek (2009) will form the basis for the techno-economic evaluation simulation model. Researching and quantifying opportunities and potential benefits versus costs and risks of micro milling technology acquisition will be done using Monte Carlo simulation coupled with a logical structure.

Chapter 3

Analysis of micro milling (MM)

3.1 Introduction

Micro milling (MM) is gaining in popularity and applications due to its ability to produce complex 3D geometries, high material removal rate (MRR), good surface finishes and its application to many materials. Various authors including Bissacco (2004), Weinert and Petzoldt (2008) and Aramcharoen *et al.* (2008) describe the physical phenomena in micro milling as well as some of the remaining research problems regarding size effects that are introduced when machining with micro-tools. The aspects are grouped below in categories to facilitate comprehension.

1. Materials: cost, material grains, elastic-plastic deformation and micro-structure effects.

2. Technology: machine tools, miniature machine factories, tool size, feed rate and spindle speed capabilities and limits.

3. Software: optimised tool paths using strategies of constant or variable chip thickness, cutting speed, feed or spindle speeds.

4. Cutting analysis: cutting force prediction, tool dynamics, forces, vibration, chatter, size-effect, chip formation and minimum chip thickness, surface generation and finish, tool failure, wear and burrs, experiments and modelling, process optimisation, sensing and monitoring, material removal rates, accuracy, run-out, effect of the materials grains on the workpiece behaviour. Process parameters such as feed, spindle speed and step-over, have a major influence on the cutting behaviour and cost.

5. Cost relationships: process parameters, hardware and software, materials, labour, energy, consumables and tools, handling, set-up and assembly.

6. Modelling studies: molecular dynamics methods, finite element methods, mechanistic modelling techniques, tool failure prediction and multi-scale modelling.
7. Supporting aspects: micro-machining research and applications, miniature machine factories, process optimisation and technology development.
8. Design: machine tools, work-piece and design issues, simulation tools.

The aspects listed above are discussed next.

3.2 Materials

3.2.1 Part or product requirements

Materials have a large effect on the application of the parts that are manufactured. If a high strength is required from a part, we may either make the part thicker or more solid, or we may choose a material that is inherently stronger. The choice is not always obvious, since many factors such as space, weight, cost, compatibility and aesthetics must be considered. Other mechanical and physical aspects that must be considered include elasticity, rigidity, damping characteristics, electrical or thermal conductivity, transparency and useful temperature ranges. Finally the cost aspects of materials are critical to gaining acceptance in the market. Câmara *et al.* (2012) lists the following materials as the most often used in micro milling: Aluminium alloys (27 %), copper and its alloys (21%), low hardness steels (21%), hardened steels (15%), silicon and glass (6%), stainless steels (4 %) and other (6%).

3.2.2 Manufacturing process

Various material classes are suitable for specific manufacturing processes. In general, most materials can be milled, though according to Ding *et al.* (2012), Su *et al.* (2007), Endrino *et al.* (2006), Kim *et al.* (2014) and Park *et al.* (2004), some materials such as Titanium, austenitic stainless steels, glass, ceramics and others are considered to be difficult to machine. Even if it is possible to machine the material, the required accuracy and surface finish might not be attainable in a specific case due to differences in technology, knowledge and such aspects. In micro milling applications, a recurring theme is the size effect described by various previous authors such as Mijušković *et al.* (2015), de Oliveira *et al.* (2015), (Ehmann *et al.*, 2004), Dornfeld *et al.* (2006), Simoneau *et al.* (2006), Bissacco (2004) and de Oliveira *et al.* (2015). The size effect is seen mainly in two aspects, that of grain size in the materials versus the cutting edge size, and this relationship results in micro milling chips sometimes cutting through individual material grains that differ substantially in their machinability. These different material grains then cause the cutting tool to experience varying forces and this in turn could introduce unwanted vibration called chatter. The minimum required chip thickness is another important consideration, specially due to the relatively large cutting edge radius of micro tools as described by the same authors. When the feed per tooth drops below the minimum required chip thickness, the cutting of material will become intermittent and this will also introduce larger forces, vibration and chatter. Most of the published research in micro milling are focussed on optimising the cutting parameters for various materials to attempt reducing or overcoming these size effect problems.

According to Brousseau *et al.* (2010), Chua *et al.* (2014) and Piotter *et al.* (2014), micro milling also form a central part of both micro stamping and injection moulding manufacturing chains. In this regards, products are moulds used for injection moulding or die cast parts; or dies used in forging or stamping processes.

Another use of micro milling is in circuit board manufacture from copper clad laminates, in specialised cases where high accuracy is a requirement, or for cheaper and rapid prototypes as researched by Bhandari *et al.* (2014) and Sreetharan *et al.* (2014).

3.2.3 Working environment requirements

Since parts or products are designed for a specific environment, they also require environmental compatibilities due to exposure to sunlight, heat, rain, seawater, ice or other extreme natural habitats. A very relevant field that is currently a hot topic according to Budinski and Budinski (2009), Xu *et al.* (2009), Lai *et al.* (2007) and Janata and Josowicz (2003), is that of biological compatibility, and this is especially important for micro-implants in both surgical and dental fields. Corrosion is dealt with comprehensively by Roberge (2012). He lists fundamental principles governing aqueous and high temperature corrosion and covers the main environments causing corrosion such as atmospheric, natural waters, seawater, soils, concrete, as well as microbial and bio-fouling environments.

3.2.4 Material compatibility requirements

Compatibility issues may also arise regarding other materials in the same assembly, either due to chemical reactivity, expansion coefficients, magnetism or electro affinities. To prevent excessive corrosion, some materials are expressly not used together, such as described by Baboian (1976), Finšgar (2013), Misiakos *et al.* (2004), Shin *et al.* (2007) and Du *et al.* (2014). Roberge (2012) also provides insight into protective coatings, corrosion inhibitors, cathodic protection and anodic protection. In certain systems, such as batteries, reactivity is required for the system to function as described by Ng *et al.* (2015), Song *et al.* (2014) and Tellis *et al.* (2014).

3.3 Technology

Micro milling spans a wide group of technologies, with the major commonality being a higher than conventional spindle speed with the ability to accurately hold small tools. The current industry standard is to use micro tools that have a 3mm or 3,175mm clamping shaft. The actual cutting diameter might be as large as 3mm, though this would not strictly be considered micro milling by many in the field. More likely, most researchers will use tool diameters of smaller than 1mm down to about 5μm for exotic cases. Using smaller tools and higher spindle speeds results in low feed per tooth and minimal chip thickness. Therefore, though the actual technologies might differ widely on cost, quality, availability in the market and support their common aspect allow us to group them together as micro milling. As an example, many traditional leaders in milling and Computer Numeric Control machines have high-end machines that cost in excess of R1 500 000, while some new entrants to the market might acquire a basic micro milling machine for less than R300 000. For the South African market, the most common applications and products could be manufactured on a less expensive machine. Some cutting edge research will only be possible on a high-end machine. Since the author had access to a more basic machine, very similar to what Bissacco (2004) used for his research, this was the case study machine used. This machine was in fact acquired after personal discussion with Giuliano Bissacco of the Technical University of Denmark.

3.4 Software

For controlling milling processes, most modern machine shops will use Computer Numeric Control (CNC). The chain of events that lead to a tool path file that can be used by the milling machine, are described by Dankwort *et al.* (2004) and Luthardt *et al.* (2001):

1. Problem or need: a problem or need arises that has some product, physical or mechanical solutions.

2. Product specification are stated, although, in a completely new design this might evolve and iterate during the design phase.
3. Concept solutions: ideas are formed about how to address or solve the problem. One or more concepts are approved for prototyping.
4. Detailed designs are made, and drawn in CAD product specification.
5. CNC files are generated: the surfaces that require drilling or milling are analysed and tool paths are generated in CNC files.

For this process chain three main types of software is required, CAD, tool path generation software, and CNC software to control the machine tool. Together these systems make it possible to do Computer Aided Manufacturing (CAM). These types of software may be contained in a single solution or be from completely different vendors.

Luthardt *et al.* (2001) describes for instance a process to manufacture dental prosthetic restorations. He analysed the CAD/CAM processes for fixed restorations and reduced it to single steps. Similarly, De Beer (2011) describes a process chain that includes using reverse engineering via scanning of bone geometries, design and customisation, simulation and manufacture. From studying various process chains it is clear that software must be customised to the process chain.

Micro milling can utilise similar software to conventional milling down to single micron level according to Huo *et al.* (2010). For sub-micron levels i.e. nanometre accuracy, specialised software must be acquired. There is however a similar large spread of software from very high-end and expensive software to free and open source versions. For high throughput and extremely complicated design challenges the more expensive types of software would be recommended, keeping in mind that as complexity rises the skill level and remuneration of the machinist will increase as well. For most general manufacture there are software options that range in cost from about R50 000 per seat per year to buying of software for less than R10 000.

3.5 Cutting analysis

Detailed cutting analysis have been described by various authors including Bissacco (2004), Weinert and Petzoldt (2008) and Aramcharoen *et al.* (2008). This research will refer interested readers to get more detail from them. Various detail are also available from experimental studies such as those by Budak and Tekeli (2005), Malekian *et al.* (2009) and Rahman *et al.* (2001).

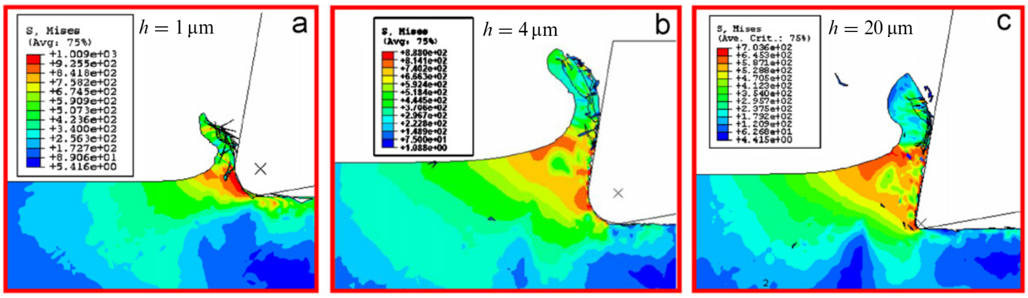


Figure 3.1: Relative size effect of cutting edge radius to uncut chip thickness (h) on the chip forming according to Lai *et al.* (2008)

Major aspects that must be considered while planning the milling process include material removal rates, tool choice, cooling, spindle speed, feed, step-over and depth of cut. The choices made will be influenced by the minimum chip thickness required, surface finish required, accuracy required, tool dynamics and work piece material. Various parameters influence the milling process such as tool rake angles, shear plane angle forces, vibration, chatter, size-effect, run-out and effect of the material's grains. Lai *et al.* (2008) clearly illustrates the effect of very small cuts in his simulation of forces and stresses when cutting in copper. In figure 3.1 the relative size of the cutting edge radius is clearly having an effect on the chip forming process. When the chip forming is interrupted, the material will be deformed instead of cut, and this process is called ploughing. This will result in intermittent cutting with about double or more the maximum force of a normal continuous cut. Specific cutting energy will also be higher in such cases. Thrust force, the component of the machining force which is perpendicular to the work-piece, increases with ploughing.

Without going into detail, the focus of much of MM research is towards finding cutting conditions and parameters that allow for smooth or uniform cutting to take place.

If the actual cut made becomes smaller than the minimum chip thickness and the chip becomes too thin, the cutting action will be replaced by sliding or ploughing across the surface. After the tool cutting edge has passed over the surface, the surface elastically bounces back. During the next tool edge pass, the chip thickness will be twice the calculated value, and the forces on the tool will approximately double as well. The alternating sliding and increased cutting forces may then introduce vibration, chatter and tool breakage in an extreme case. The minimum chip thickness is also dependant on the size effect of the cutting edge radius or edge sharpness, which becomes relatively large in micro milling.

Similar results could also arise from various other reasons such as for instance large material grain sizes. As the tool cutting edge passes through various grains in the material the differing properties of the grains influence the cutting forces. The variation in cutting force as the tool edge passes through grain boundaries could introduce vibration, chatter and tool breakage in an extreme case. Observe that although the mechanism of the variation in force is different, the end result is the same.

Another mechanism of force variation is from tool dynamics in the form of the natural frequency of the tool and machine system. In a case where the undamped natural frequency is reinforced by harmonic oscillations in force, such as the changing force due to the periodicity of rotation of the spindle, then resonance may occur and the forces normally increase until failure results. Budak and Tekeli (2005), Graham *et al.* (2014) and Singh *et al.* (2015) describes the well known method of using stability lobe diagrams to avoid these regions of instability.

A fourth mechanism that will cause changing forces, is run-out on the tool tip. Run-out is defined as an eccentric movement of the tool tip, i.e. when the centre of the tool in not aligned with its rotational centre. Depending on the exact angular position, and the linear value of maximum run-out on the tool geometry, the end result will be varying changes in the forces on the tools.

Synthesis of the previous aspects prompted the following realisation:

1. To ensure accuracy, good surface finish, long tool life and minimal rework from micro milled parts, the cutting forces should be within a tight range of variation, which should result from optimal selection of cutting parameters.

2. Cutting forces may become uncontrolled due to various reasons, such as material properties (specially small grain sizes), tool run-out, tool dynamics (specially resonance), larger cutting edge radii due to wear and intermittent cutting and ploughing at close to the minimum chip thickness.

3. If the cutting forces are not under control, the results include undue vibration, chatter, poor surface finish, limited tool life and excessive rework.

3.5.1 Tool life

ISO 8688 defines tool life at the threshold of maximum flank wear of 0.3 mm in conventional machining (ISO, 2015). However, since some tools in micro milling might be smaller in size than the ISO threshold, it is clear that this definition is not applicable. Tool life for micro milling may be defined by considering the specific application or product specifications. In some cases, the maximum material removal volume is the only objective and tools may be used during a rough cut until the tool fails by breaking. In many other cases, such as for a final cut, parameters such as surface roughness and various accuracy aspects could become the deciding factor. In specific cases, such as slot milling for the purpose of microfluidics devices the wear of the tool might become the deciding factor, since the fluid channel has a specific volume it needs to maintain for optimal operation. Groover (2014) gives nine convenient tool life descriptions that might be used in typical production machining operations:

1. Complete failure of the cutting edge due to fracture, high temperature or wear.
2. Excessive flank wear as observed by the operator; is limited by the operator experience.
3. Fingernail test across the cutting edge to detect irregularities.
4. Changes in sound level and pitch; is limited by the operator experience.
5. Chips become ribbony or stringy.
6. Rough cutting finish.
7. Increased power consumption of the machine.
8. Work-piece count; the operator is instructed to change the tool after a predetermined number of parts.
9. Cumulative cutting time; can be done in computer program or by operator.

As can be seen from the previous discussion, tool life is not a simple one-approach-fits-all calculation. The expanded tool life equation of Taylor as described by Groover (2014) includes feed, cutting speed, depth of cut and material hardness. Other aspects can be included in the specific case as part of the constant C that represents cutting parameters. Marksberry and Jawahir (2008) lists 8 tool life models, of which six are included in figure 3.2 below. Most are adaptations of the original tool-life equation of Taylor.

After comparing various tool coatings that are used in practice, Aramcharoen *et al.* (2008) concludes that TiN, TiCN, TiAlN, CrN and CrTiAlN coatings help reduce cutting edge chipping and edge radius wear as compared to uncoated ultra-fine grain carbide end mills. The study did not include a statistical method to indicate whether the differences were of statistical significance. However, by comparing the various tool life values shown in figure 3.3 the uncoated tool performs quite similar or even better than the other tools for the specific experiment. The only tool that did perform a lot better was the TiN coated tool. Part of the

The equations in figure 3.2 use various parameters that are not used in detail or central in the simulations of this research, and may be looked up in the reference supplied. In general, the parameters used are V for cutting speed, T is tool life, D is depth of cut and S refers to feed rate. For the simulation model, tool life is a stochastic variable from an appropriate distribution, given a specific material to micro mill. C, n and others are dimensionless variables that are determined experimentally.

Summary of tool-wear and tool-life models for dry machining

No.	Tool-life/tool-wear equation	Determination of constants	Comment
1	Taylor's basic equation: $VT^{n} = C$	C and n experimentally determined	Most widely used equation; however, C and n apply to a particular tool–workpiece combinations
2	Taylor's reference-speed based equation: $V / V_R = (T_R / T)^n$		
3	Taylor's extended equation: $T = C_2 =(V^{P} f^{q} d^{r})$	All constants (C 2 , p, q and r) are experimentally determined	Gives better accuracy than Taylor's basic equation, but more tool-life tests are required
4	Temperature-based tool-life equation: $\theta T^{n} = C_3$	n is found between 0.01 and 0.1 and C 3 is experimentally determined	Although the equation is set only on an empirical basis, it is not convenient for practical use in the shop floor environment
5	Taylor's extended equation including cutting conditions and workpiece hardness: $T = C_4 V^{n} f^{m} d^{P} r^{q} s^{t} i^{u} j^{x}$	Requires excessive tool-life testing to determine all constants (C 4 , n, m, p, q, t, u and x)	It is claimed that the data for setting up the equation are generated from both laboratory and industrial sources
6	Taylor's extended equation including cutting conditions and workpiece hardness: $V = C_5 /(T^{m} f^{y} d^{x} (BHN/200)^{n})$	All constants (C 5 , m, y, x and n) are experimentally determined	It is claimed to be a good approximation for tool-life ranges of 10–60 min

Figure 3.2: The expanded tool-life equation of Taylor from Marksberry and Jawahir (2008)

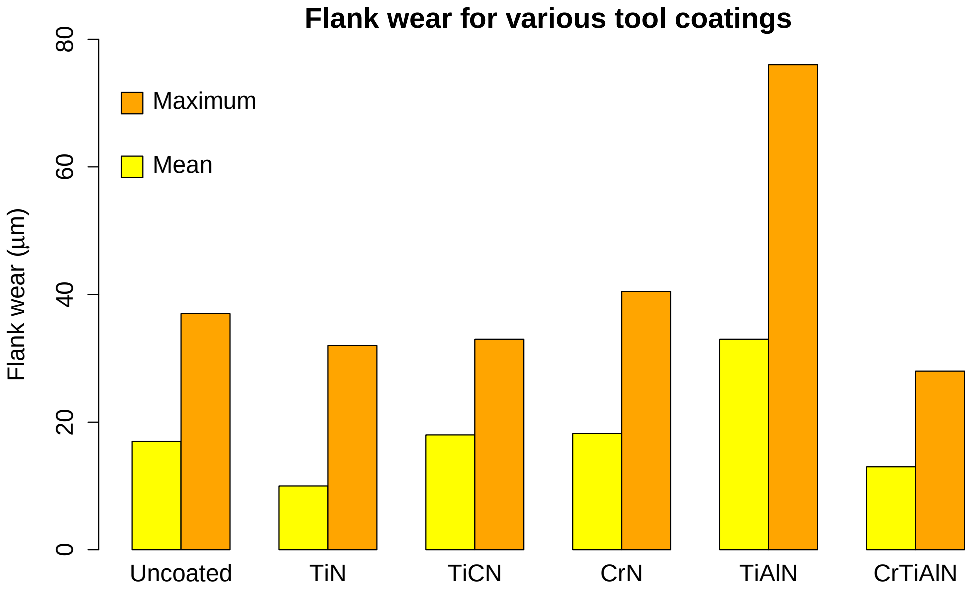


Figure 3.3: Mean and maximum flank wear comparisons for various tool coatings from Aramcharoen *et al.* (2008)

reason why most of these tools did not perform better than the uncoated ones, lie in the fact that the coatings increased the cutting edge radius. Aramcharoen *et al.* (2008) states that at the beginning of cutting (burn-in-period) none of the coatings showed any improvements in surface finish compared to the uncoated tool. However from figure 3.4, it is clear that the uncoated and the TiAlN tools are nearing the end of their useful lives after cutting an identical volume of hardened tool steel. The TiN tools cutting edges increased less than 2μ m on average while removing a similar volume of material. This would indicate that TiN tools have useful lives of approximately four times that of the uncoated tools.

Some experimental results from various authors are listed in the section 3.5 and will be used to estimate tool life for various scenarios.

3.6 Cost relationships

To determine a realistic selling price that can compete with other manufacturers in the market, costs must be accurately modelled. Costs also form an integral part of the techno-economic feasibility. In following Chapters cost details are researched and described in statistical probability terms to allow simulation of costs. Typical costs that are considered include hardware, software, materials,

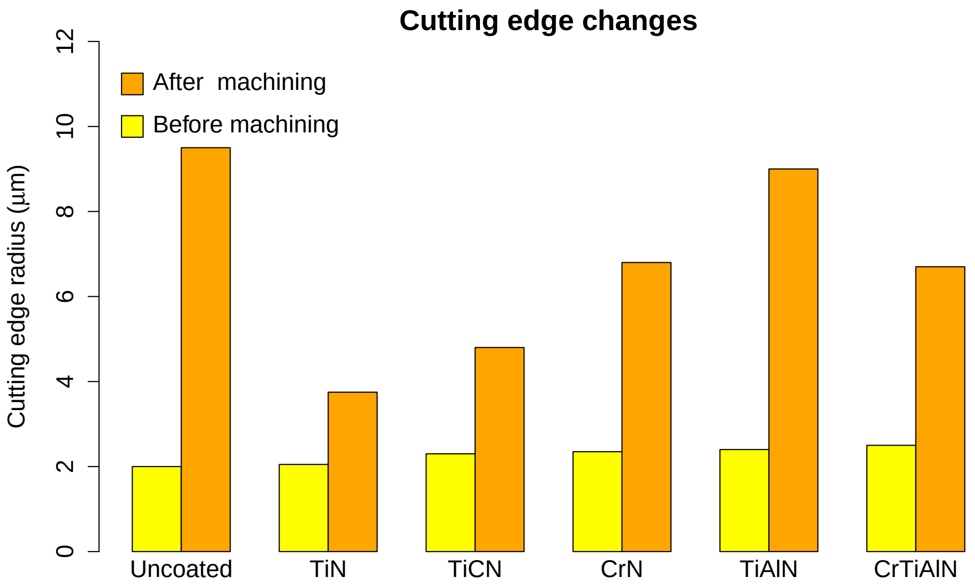


Figure 3.4: Cutting edge radius values before and after machining a 0.25mm^3 volume in hardened tool steel according to Aramcharoen *et al.* (2008)

labour, energy, consumables and tools, handling, set-up, machining time and overheads.

Various authors such as Boothroyd and Reynolds (1989); Zaman *et al.* (2006); Essmann and Dirkse van Schalkwyk (2011) and Lee, et al. (2007) have formulated overlapping cost models for the milling process. As part of the Design for Manufacture and Assembly (DFMA) methodology, Boothroyd and Reynolds (1989) developed cost models of machined components. There is a need for designers to understand how design decisions impact on manufacturing costs. Boothroyd and Reynolds (1989) compromised between traditional detailed cost estimating, and over-simplified volumetric approaches. The DFMA cost estimations consider only the direct costs. Indirect costs such as management or production overheads and salaries of administration staff, and capital cost recovery are not considered. If this methodology is used it should be supplemented with the indirect cost categories. Cost categories as defined by this methodology are included below and could be used to guide costing. Boothroyd and Reynolds (1989); Zaman *et al.* (2006); Essmann and Dirkse van Schalkwyk (2011) and Lee, et al. (2007) included different costs and groupings in their models, but in essence the following processes are included:

1. Material cost or cost of raw materials from which the component is made. Boothroyd and Reynolds (1989) state that this cost can account for more

than 50% of the total cost. It should be possible to be estimated with accuracy.

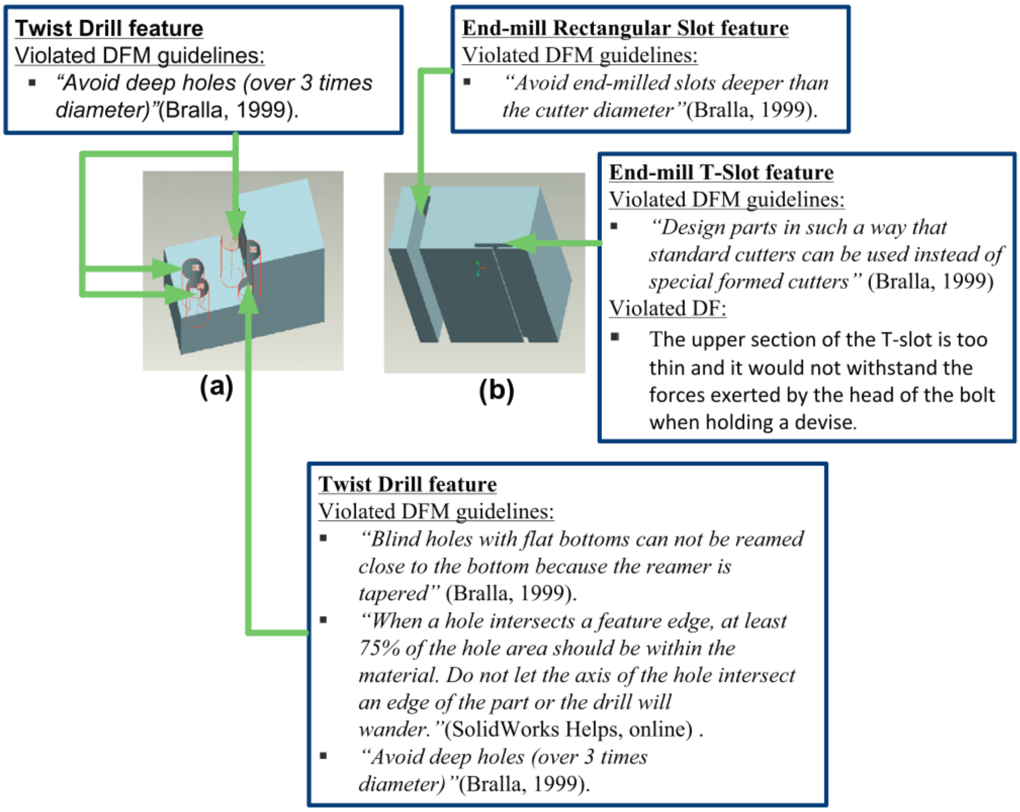
2. Preparation, set-up and other non-productive costs including labour time spent on design or redesign of parts and fixtures, converting files to various required formats, generating cutter paths, preparing and handling material, clamping or fixing the material to the machine and post-processing of parts and waste. Machine loading and unloading cost accounts for the cost incurred when parts are loaded and unloaded from the machine.

3. Other non-productive costs due to the time taken to zero the tool, set the cutting parameters, engage feed and withdraw the tool after operation. Cost also due to the time taken to move batches of partially machined work-pieces between machines.

4. Machining cost accounts for the cost incurred during the period between when the machine is engaged and disengaged. Boothroyd and Reynolds (1989), point out that the tool would not be cutting for continuously during this time. As such, allowances should be made for tool approach times.

5. Machining and cutting cost including labour cost for monitoring cutting operations, fixed cost for machine tool depreciation, cooling, lubrication, energy and cutting tools used. Cutting tool replacement costs are incurred when more than one tool is required to complete the cutting operation and accounts for machine idle time while the operator replaces the tool and the cost of providing a new cutting edge or tool.

Processes that are normally not included, but should be in the case of an economic assessment, are training, product margins expected, errors and wastage, electricity, overheads, selling, advertising and management cost. Since some of these costs are difficult to attribute directly, the simulation model will attempt to include those based on aspects such as the complexity of the part design, complexity of machining and quality requirements. These were considered key aspects by Hoque *et al.* (2013), Foster and Gupta (1990) and Martin and Ishii (1997). Specifically, Foster and Gupta (1990) lists all of the following as part of Manufacturing overheads (MOH); Procurement, with stores, purchasing, materials-engineering, -specification, -management, receiving; Production, with labour, taxes, benefits, supervision, operating overhead, depreciation, equipment, moving of work-in-progress; and Support, with engineering, sales and quality assurance. Using the Pearson and the Spearman methods allowed Bishara and Hittner (2012) to determine correlations, while Foster and Gupta (1990) found that there are strong correlations between complexity based



Twist Drill feature
Violated DFM guidelines:
- *"Avoid deep holes (over 3 times diameter)"*(Bralla, 1999).

End-mill Rectangular Slot feature
Violated DFM guidelines:
- *"Avoid end-milled slots deeper than the cutter diameter"*(Bralla, 1999).

End-mill T-Slot feature
Violated DFM guidelines:
- *"Design parts in such a way that standard cutters can be used instead of special formed cutters"* (Bralla, 1999)

Violated DF:
- The upper section of the T-slot is too thin and it would not withstand the forces exerted by the head of the bolt when holding a devise.

Twist Drill feature
Violated DFM guidelines:
- *"Blind holes with flat bottoms can not be reamed close to the bottom because the reamer is tapered"* (Bralla, 1999).
- *"When a hole intersects a feature edge, at least 75% of the hole area should be within the material. Do not let the axis of the hole intersect an edge of the part or the drill will wander."*(SolidWorks Helps, online) .
- *"Avoid deep holes (over 3 times diameter)"*(Bralla, 1999).

Figure 3.5: Violations of common DFM guidelines that will add to manufacturing complexity and cost from Hoque *et al.* (2013)

drivers and MOH. For instance, in the electronics industries they researched, direct labour cost varies from about one-tenth to six-tenths of MOH cost. This is of course not a general result, but must be determined for the specific industry and company, due to efficiency related differences. Martin and Ishii (1997) defined three indices, a Commonality Index (CI), Differentiation Index (DI) and Set-up Index (SI). It is then possible to develop regression equations that will estimate the indirect or MOH costs. Various aspects are included that influence all three indices, such as management complexity, set-ups, learning curves due to complexity, quality requirements and work in progress. Hoque *et al.* (2013) look at Design for Manufacturing (DFM) principles and base their increase of costs partly on how many guidelines of DFM are violated. These violations of DFM increase the complexity of manufacture, by requiring specialised cutters, difficult to machine deep slots, holes with sharp or right angles as examples as shown in figure 3.5.

Based on these findings above it will be imperative to include complexity

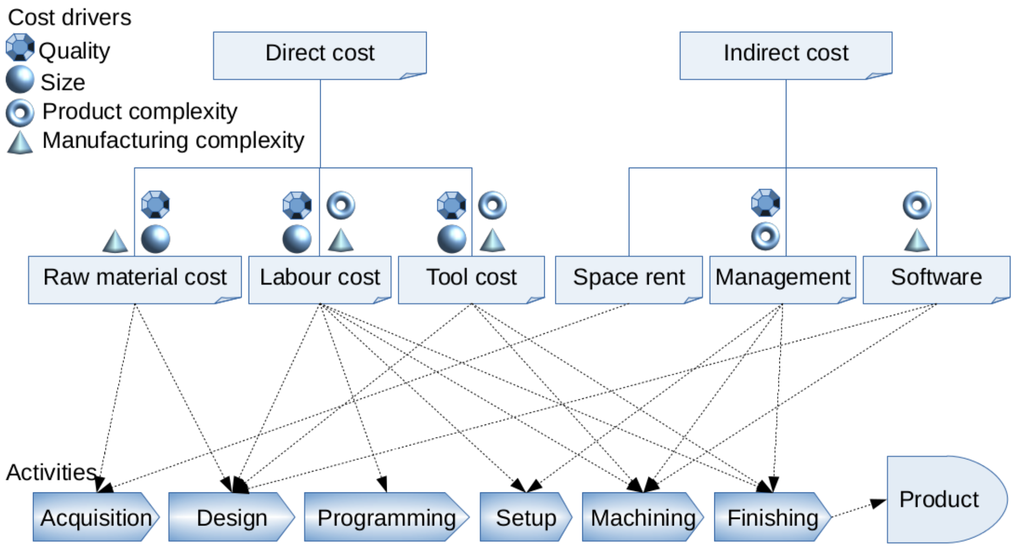


Figure 3.6: Common cost drivers that will influence product cost via various micro milling or support processes

and quality aspects in the cost simulations. The figure 3.6 was developed from ideas by Martin and Ishii (1997) and Hoque *et al.* (2013) to illustrate where the various soft issues will have the highest cost implication. As may be seen, the direct labour and tool costs are expected to be influenced by all four cost drivers of quality, size, product complexity and manufacturing complexity. High quality as well as product complexity will require management involvement and therefore higher indirect cost. Indirect software costs are influenced by product complexity and manufacturing complexity. Direct material costs are of course highly dependant on the size of the product, but also on the quality (rework might be required) and manufacturing complexity.

3.7 Modelling studies

Some authors such as Dornfeld *et al.* (2006), Van Luttervelt *et al.* (1998) and Liu *et al.* (2004) have published research or reviews on modelling of molecular dynamics methods, finite element methods and mechanistic modelling techniques. These models mostly attempts to provide simulated cutting forces, chip forming and related mechanical simulations. For this study, modelling refers to the techno-economic model including the potential sales, cost aspects and statistical probabilities of certain events occurring in a company who sell micro milling services to industry. The detail description of the techno-economic model follows in Chapter 5.

3.8 Design

The design of micro milled parts is not covered in any detail in this study. However, the specification resulting from designs are considered during the costing aspect of manufacturing. This is due to the fact that requiring for instance a very smooth surface, will require smaller step-overs during manufacturing, more machine and operator time, use more cutting tools and will result in a more expensive part. As said previously in section 3.6 some principles of DFM will impact cost through reduced or increased complexity.

3.9 Conclusion

This Chapter provides an overview of micro milling aspects to consider when developing the techno-economic model. It is clear that due to the many aspects that impact the process, the techno-economic model is simplified to able to represent reality with reasonable accuracy and precision. Main aspects that are included are material cost, preparation, set-up and other non-productive costs, converting files to various required formats, generating cutter paths, preparing and handling material, clamping or fixing the material, time taken to zero or reference the tool to the work piece, set the cutting parameters, engage feed and withdraw the tool, machining cost, monitoring cutting operations, fixed cost for machine tool depreciation, cooling, lubrication, energy and cutting tools used post-processing, training, product margins expected, errors and wastage, electricity, overheads, selling, advertising and management cost. Since some of these costs are difficult to attribute directly, the simulation model includes those based on aspects such as the complexity of the part design, complexity of machining and quality requirements. The model could be expanded in future research.

Chapter 4

Markets for micro milling

4.1 Introduction

The markets for micro manufacturing in general and micro milling in particular have been listed by various authors. Sales data for backing this up is however difficult to find. Some general indicators of growth in a sector would be an increase in patents and research published that refers to the sector. Other authors have developed methods to predict the growth of technology related to In some country specific sources it is possible to find references to processes that require micro parts. An example of this, related to medical implants, is explained in more detail in section 4.4.3.1. Just in terms of a pure logic deduction, it is common knowledge that miniaturisation of technology is an ongoing process. Examples of this abounds, but in recent years cell phones, internet of things, medical diagnostics, metal injection moulding and others have had very high growth, while packing more features into a smaller package. Micro milling is also seen by many such as (Ehmann *et al.*, 2004) as a disruptive technology and driver for the miniaturisation of various parts. Disruptive technologies are described by Spencer and Kirchhoff (2006) and Thukral *et al.* (2008) as opportunities that entrepreneurial companies may exploit with success though with some risk as well. More entrenched companies tend to change evolutionary, or using sustaining innovations rather than disruptive innovations.

4.2 Economic and development comparisons of South Africa versus other countries

To estimate the potential market for micro milling, using internationally available data, South Africa must be ranked or compared in a global marketplace.

South Africa has some unique or outlier qualities that differentiate it from the rest of the world (ROW). One such aspect is the Gini index seen in figure 4.1 as reported on by Hellebrandt *et al.* (2015). The Gini index for South Africa of about 0.66 is the highest among the stable economies listed here. To put this in perspective it would require that less than 20% of the population would earn more than 80% of the income. For most highly developed countries the Gini index would be around 0.3 or less.

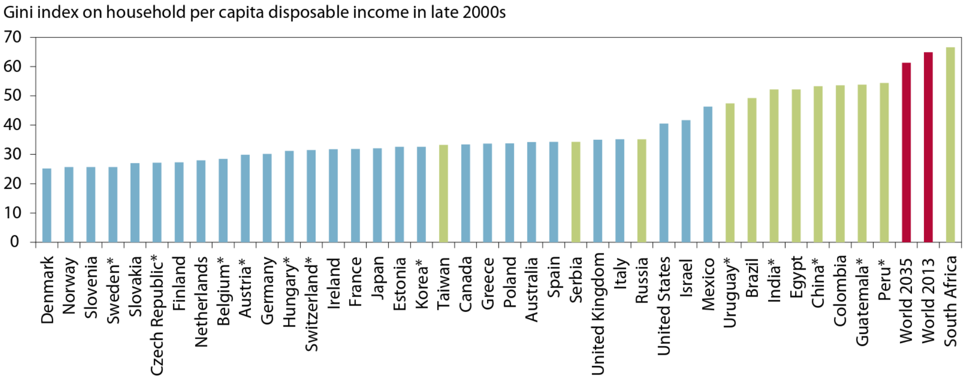


Figure 4.1: Frequency plot of global income distribution adapted from (Hellebrandt *et al.*, 2015)

Another aspect that is illustrated in figure 4.2 is that South Africa is lagging far behind the global income per household. Both the aforementioned facts will have a bearing on the size of the market in South Africa, tempering expectations.

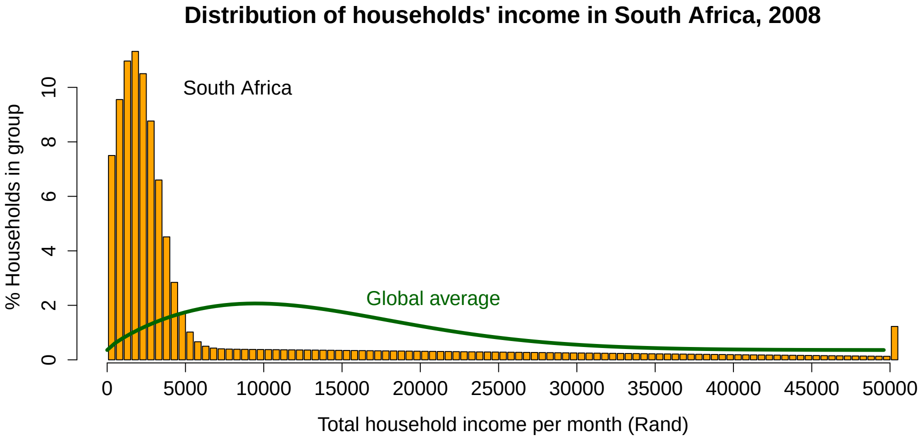


Figure 4.2: Frequency plot of South African and global income distribution adapted from (Hellebrandt *et al.*, 2015)

In section 4.4.3.1 a regression model is reported on to allow basic predictions in the absence of South African data.

4.3 Major application sectors for micro parts

When micro milling is combined in a local manufacturing process it provides the ability to deliver parts economically at the "point-of-use" (POU) with a JIT philosophy. This could provide a driving force to migrate business away from the current centralised manufacturing model to a more distributed model. This is argued by Ehmann (2007) in his study on US micro-manufacturing research and development activities and trends. Governments and local regions are in support of developing local manufacture as can be seen from research by Benkler (2006) and Gunasekaran (1998).

With increasing integration of design and communication capabilities in software and networks, centralised design availability easily co-exists with distributed manufacturing. Examples of such a centralised design repositories abound on the web and arguably the best known include *Thingiverse - Digital Designs for Physical Objects* and *Shapeways - Make, buy, and sell custom products with 3D Printing* (Chiu *et al.*, 2013), (Forrest and Cao, 2013).

Although Thingiverse is dominated by 3D printing designs, there is already a large number of milling parts in the repository, proving the working concept.

Sectors which are the major customers for micro parts include bio-medical implants, consumer electronics devices, automotive, aviation, optical, energy, the general scientific sector of research, lab-on-a-chip and micro-fluidics. The estimated sizes of these sectors are referred to in Chapter 5.

The development of innovative products and their realisation by means of advanced manufacturing methods and process combinations are becoming key issues in international competitiveness. Micro manufacturing has the advantage of faster set-up times and cheaper small production runs for prototyping purposes. "The earlier introduction of a product creates momentum that could not only increase the product's sales but also extend them much further into the future" (Moore, 2004). Faster prototyping and earlier introduction of products are of general importance, and applies fully for South Africa too. These aspects provide additional confidence that micro milling is a growth market.

4.4 Exploring other market sectors for micro milled parts

One possible way to explore potential markets for micro milling is to fully characterise the material and geometry requirements. Once we understand which materials and geometries are suitable for micro milling we may search the market for suitable parts.

To illustrate this, Takahata and Gianchandani (2003) describes an μEDM process to manufacture a stent from 50μm 304 stainless steel foil, as shown in figure 4.3. Similar stents were also previously manufactured using laser machining, and from a geometric point of view, the part could be micro-milled as well. However, from a force, vibration and work-holding point of view, the micro milling of such a part will be problematic. μEDM and laser processes generate very low forces on the work-piece, low vibration and therefore requires a low work-holding force. However, micro milling generates relatively large cutting forces, and with thin-walled designs will cause large deflections, vibrations and even total destruction of the raw material.

In contrast to this, the author has machined various copper foils, while those foils were supported by a rigid substructure such as dielectric fibreglass material. Such copper clad laminates are commonly used in the electrical industry as printed circuit board (PCB) replacements and the required circuits are then machined rather than printed. For research, the printed or etched circuit boards might be either too time-consuming, or inaccurate for a specific application to use. Specifically, etching does not give good control over the thickness of the remaining copper strips. In some applications, such as microwave-filters, the thickness of strips determine the frequency that is filtered such as the filter device shown in figure 4.3. This device was manufactured by the author on a micro milling machine.

The previous example shows that a deep understanding of the process and materials are required to explore potential markets for micro milling.

The following list of characteristics must be considered when deciding if micro milling a product will be viable.

1. Geometry of the part especially aspect ratios such as deep holes and deep channels, negative angles, radii and size of features. Thin walled structures may also be subject to vibration that could make the milling process inefficient or impossible. See figure 4.3 for a part that will be difficult to mill and clamp.

2. Work-holding regarding current technology, forces required, surfaces available to clamp onto.

3. Volumes, since milling is not suited well to mass production.
4. Material properties that could influence the final part quality, including the machinability of the required material.
5. The grain size of the part material has an influence on how small the features may be, or might make the milling more difficult.
6. Cooling might be problematic due to the volume effect (special type of size effect).
7. Spindle speed must be high enough for the tool size to prevent ploughing, and produce the minimum chip thickness.
8. Chatter must be prevented through use of feedback or stability lobe diagrams.

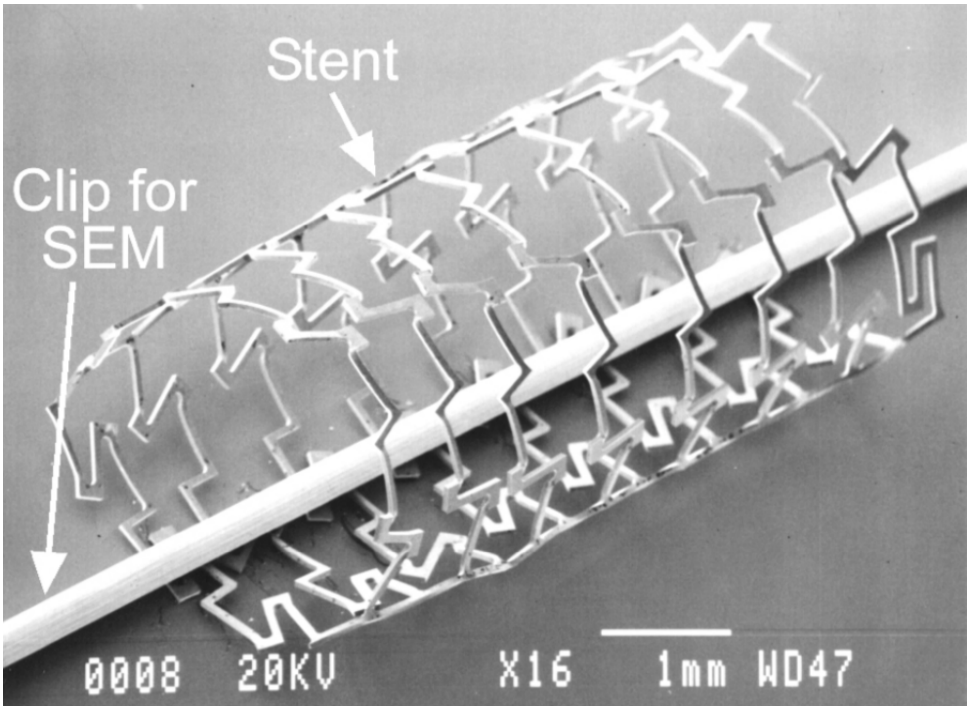


Figure 4.3: Takahata's 304 stainless steel stent design uses an μEDM process to manufacture from 50μm 304 stainless steel foil; this is an example of a geometry that will be very difficult to mill. (Takahata and Gianchandani, 2003)

Previous research also points to a number of areas where miniaturisation is prevalent. These areas are explored below.

4.4.1 Directly milled parts

Various authors Dhanorker and Ozel (2008); Aurich *et al.* (2012); Luo *et al.* (2005); Alting *et al.* (2003); Yan *et al.* (2004); Masuzawa (2000) assert that micro milling is very suitable to rapid prototyping of complex parts. Micro milling can also be substituted in place of traditional technologies due to faster turnaround, cost and versatility. One example of this is micro milling of six-axes flexural structures for Hex-flex nanopositioners. Previously, these parts were made using conventional lithographic micro-fabrication processes (Gafford, 2010). Advantages listed by Gafford includes greater design and material flexibility as well as rapid prototypes for small batches used in research and testing applications. The part is shown in figure 4.4.

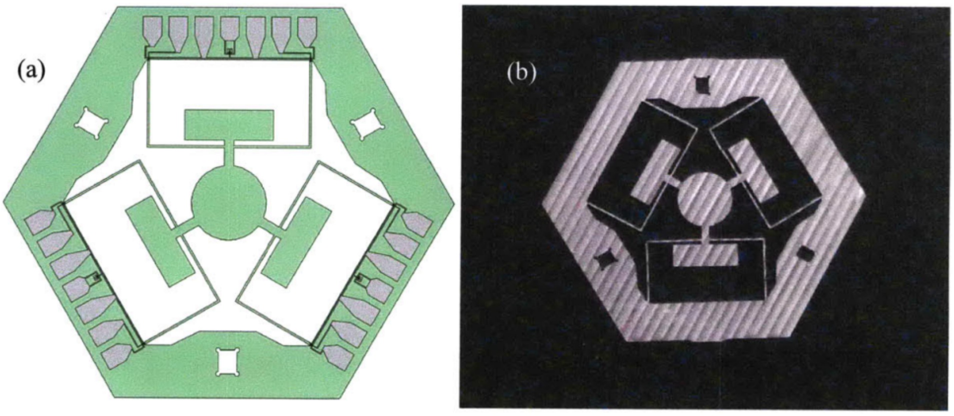


Figure 4.4: (a) Solid model of silicon-based Hex-flex nanopositioner, showing electrical traces for Lorentz actuation, and (b) a micro-milled Al 6061-T6 Hex-flex (Gafford, 2010)

Direct micro milling can also be used to create complex 3D parts that were previously manufactured by either layering technologies or direct metal sintering, using 3D printers.

4.4.2 Miniature metal and ceramic injection moulding (MIM CIM)

Shaw (2012), with supporting data from Global Industry Analysts, claims that the notable miniaturisation trend is providing opportunities galore for the metal injection moulding (MIM) and ceramic injection moulding (CIM) industry. MacNeal (2013) supports this view, quoting growth of about 14% per year for the years between 2009 and 2014. Micro milling could come into its own as it supports the drive towards the miniaturisation of surgical devices using MIM.

MacNeal (2013) also discusses firearm components as one of the major growth areas, probably due to increased tensions internally in countries as well as high conflict areas especially in the Middle East, West Asia and parts of Africa. For many of the micro moulds required for these parts, micro milling with its complex shape producing abilities are key. The growth in the MIM and powder injection moulding (PIM) are shown in figure 4.5.

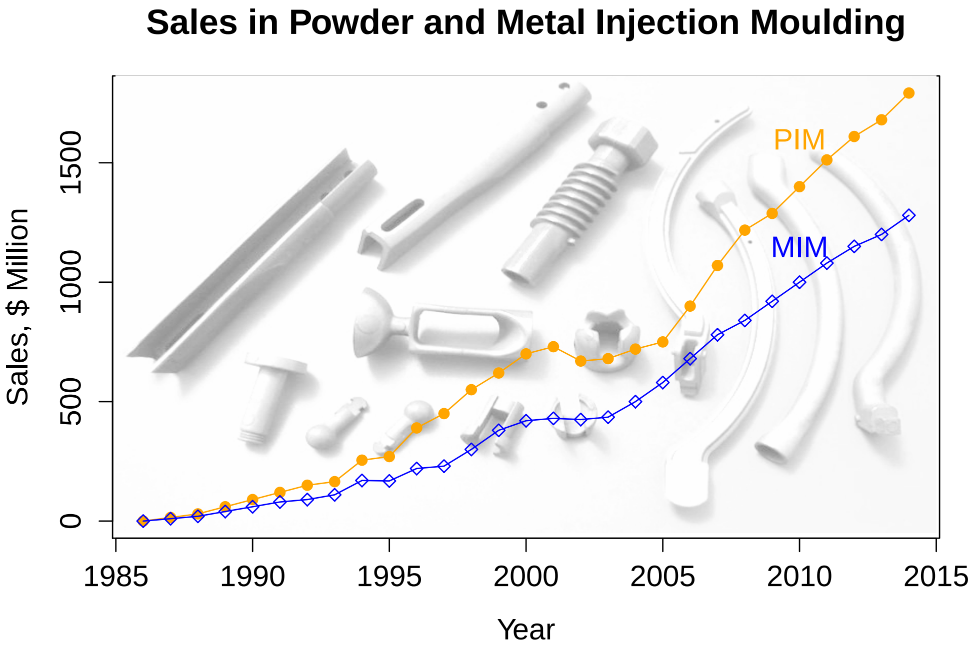


Figure 4.5: The growth of sales in the powder and metal injection moulding industry according to MacNeal (2013)

Other than direct machining of parts, micro milling can also be used as a part of the manufacturing process chain by manufacturing tooling for mass or batch production. The major sector in the recent past related to this would have to be micro injection moulded plastic parts. Depending on the smallest feature size and sometimes geometry, the moulds to make plastic injection-moulded parts could sometimes be manufactured using conventional milling centres, but would likely be more economical to manufacture on micro milling centres. Previous work on the economic evaluation of these manufacturing process chains are not sufficiently detailed, which motivated this research. Also, some newer technologies such as powder injection moulding (PIM) of metals and ceramics are increasing in use. The parts made by these processes could have advantageous properties such as higher strength, rigidity, temperature application ranges and chemical resistance. Other tool types include stamping tools or embossing tools in various configurations. These technologies all rely on milling as part of the process chain.

Another use of micro milling is the direct milling of circuit boards. One advantage of this is that better accuracy are achievable, since the typical etching process is susceptible to micro-leaks of acid into the copper traces. These inaccuracies may change the response of the circuit board, specifically in cases where induced magnetics and currents are part of the design. Typical applications are microwave and similar electromagnetic spectrum filters.

Apart from the described manufacturing process chains that add to complexity, the parts that are manufactured can be used in a plethora of fields, listed previously and some later in this report. It is important to realise that this complexity must be evaluated and either addressed in the model or excluded with proper motivation.

4.4.3 Specific markets

4.4.3.1 Medical implants

Medical implants cover a wide variety of items used to replace natural bone, teeth or organs. All of these types of items have features that make them suitable for micro milling. In some cases, such as teeth, the replacement implant has to fit into a tolerance well into the micron range. In the case of small pump systems used for heart valves or drug delivery control systems, micron range assembly requires similar or higher precision. For larger implants, such as knee or hip replacements, features to allow bone growth, better adhesion to the natural bone or allows for automated anti-infection drugs to be delivered by the implant are in the micron range.

The growth in dental implants as well as knee replacement and hip replacement operations drive the medical implants market. Figure 4.6 displays data from Riddle *et al.* (2008) that shows that the United States year on year growth is between 7% and 55%. Many components of these implants are supplied by micro milled products. In 2005, in the USA there were about 370 000 hip replacements and 380 000 knee replacements.

The dental implants market is also growing as the western population distribution moves to a higher average age. Data from Achermann and Day (2012) shows the 2010 number of implants per 10 000 people in various countries in figure 4.7. The abbreviations used are the United Nations 2-letter codes. Also BBC Research (2012) estimates that hip replacement average was 13 per year per 10 000 population just before 2000, with annual growth estimated to be 5%.

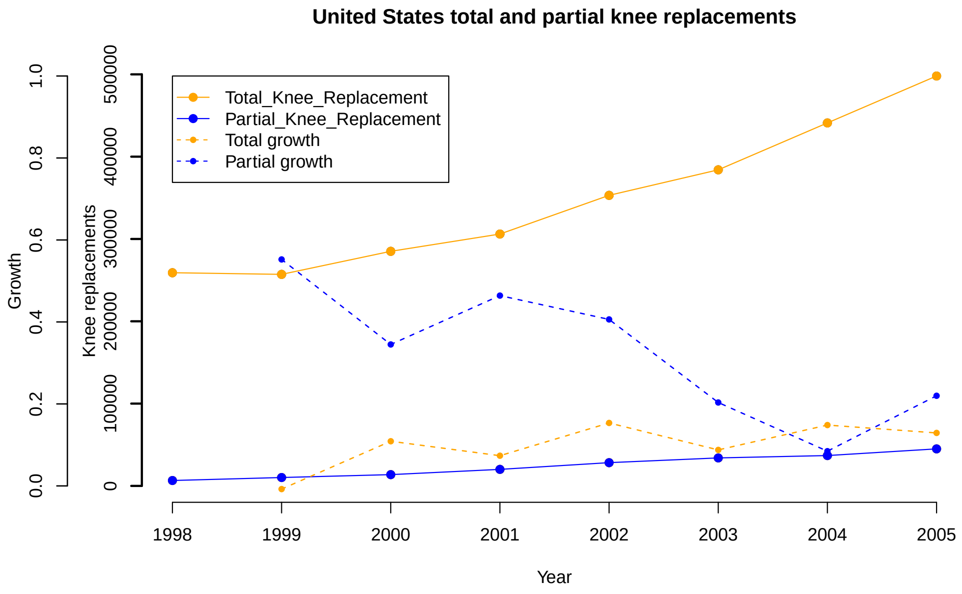


Figure 4.6: United States data on total or partial knee replacements for the years 1998 to 2005 from (Riddle *et al.*, 2008)

The global dental implant market was estimated to be 1 billion Euro in 2005 and was projected to grow to 4.4 billion Euro by the year 2015.

Previously van Schalkwyk (2013), suggested that since there is scant information on implants in South Africa, there might be some correlation that could give estimates for the local market. Using data from Kurtz *et al.* (2011) and the global competitiveness report of 2010-2011 (World Economic Forum, 2010) 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' actual data shown in figure (number 2 to 19 on the x-axis), with South Africa added to the graph as number 1 ("Actual Value" for South Africa on this graph was set to be equal to the Predicted Value, since no actual data is shared by the industry in South Africa). This yielded a regression with an adjusted R^2 value of 0.846 (and with 2 outliers removed, a R^2 value of 0.944). The regression uses the equation:

$$\% \text{ of knee replacements/100000} = (\mathrm{H}^{2.54} * I^{0.93} * \$^{0.61} * Ob^{0.46}) * 0.008 \quad (4.4.1)$$

Where H is the Health score,

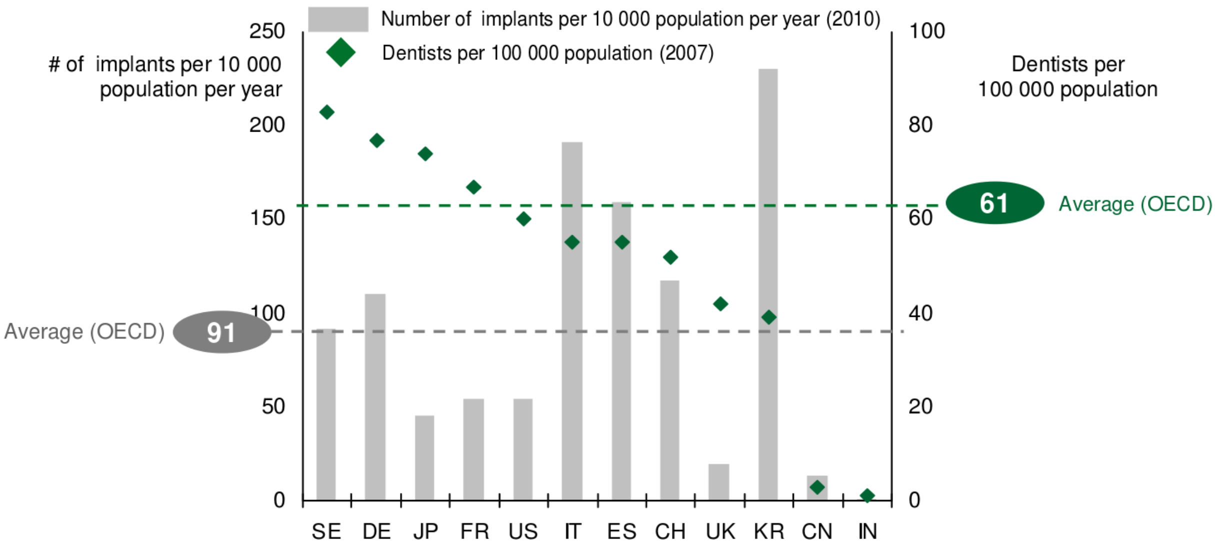


Figure 4.7: Implants and dentists per country (Achermann and Day, 2012)

I is the Innovation readiness score,
\$ is the income per capita in 1000's of dollars and
Ob is percentage of obese people in the country.

The regression is shown in figure 4.8 and as can be seen, South Africa is expected to have about 3614 knee replacements in 2011 and assuming a similar growth as the global mean, 4917 knee replacements by 2015. These numbers are a bit on the conservative side according to personal discussions with people in the field, but does give a lower limit for research purposes.

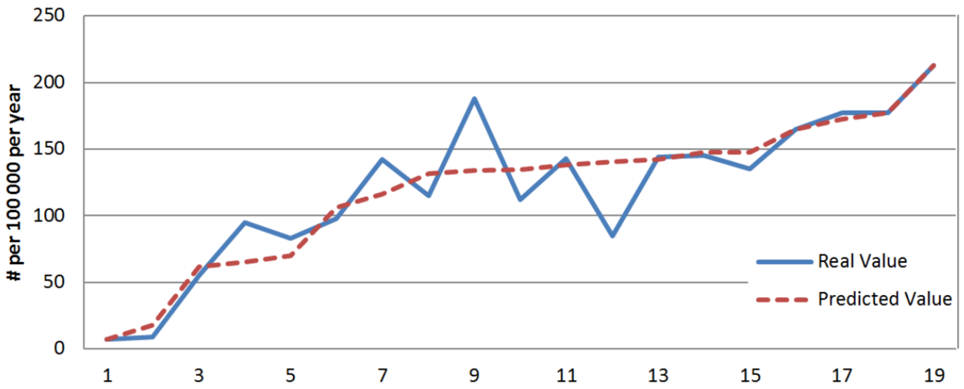


Figure 4.8: The graph shows 17 countries (from number 2 to 18) with their actual and predicted data for knee replacements. Country number 1 is South Africa, with a predicted value of 3614 (van Schalkwyk, 2013)

4.4.3.2 Consumer goods

The general trend of miniaturisation is well described in research (MacNeal, 2013; Kantak *et al.*, 2014; Kiemeneij *et al.*, 2014; Cuhls *et al.*, 2012; Boucher, 2014; Bogue, 2014). Products as diverse as cell phones, battery packs, readers, tablets, computers, drones, connectors and many more can be listed as containing multiple parts that could be micro milled or uses micro milled tools during manufacture. New companies will have to find the most lucrative markets and focus their energies on those sectors that are growing fast.

4.5 Case studies

The case studies are described in detail in Chapter 7, but are listed below for reference.

4.5.0.1 Laboratory and research cases

Various research projects were completed where micro milling played a role. The parts or products are listed as case studies for the purpose of testing the simulation values in the discussion of results. It is considered unlikely that private manufacturing companies will get enough work from the universities research sector since these institutions would normally have access to their own manufacturing facilities. There could be a small specialised marketplace in the corporate and government research sphere however.

4.5.0.2 Circuit boards

The micro milling of circuit boards are considered as viable for small batches, or for specialised circuits that have high accuracy requirements. An example was given in figure 4.4. Another example of such a circuit board is listed among the case studies, specifically for a micro-wave filter application.

4.6 Conclusion

There are various markets that could be targeted by companies who can do micro milling. Before a company may enter any specific markets it will be required to do special research of the markets requirements, adapt skills training for the manufacturing company and build a reputation in the sector. From a scan in product prices, in many research markets the profit potential or volumes are too small to make the investment into micro milling technology lucrative. In the personalised market space of medical and dental implants there are higher profit potentials that could be the main supporting sectors for micro milling. Other sectors will likely be used as additional income when the companies are not fully utilised.

The analyses in this Chapter made it possible to estimate the types and volumes of parts or products that may be expected from micro milling. This information is used to specify distributions for the number of RFQ's and the expected value of each RFQ that the marketplace requires to be manufactured. In the following Chapters the market RFQ's comprise the initial input to begin the simulations.

Chapter 5

Simulation model structure

Jacobs *et al.* (1984), in the book, *Cities and the Wealth of Nations*, explains how subsidies may deplete growth and block innovation. Wealth is not merely a matter of assets but rather the capacity to engage those assets in production and adapt to changing circumstances and needs.

5.1 Introduction

Previously, in Chapter 2, the high-level definition of a TEFS, "Researching and quantifying opportunities and potential benefits versus costs and risks of technology acquisition", was expanded to a basic level of defining each part of the definition.

In this Chapter, the simulation model will be given structure and described in detail. In less detail, the model will also be described as computer code in the statistical package R, though the complete code for running the simulations are included in Appendix 1. In order to build a model of reality, we need to understand the basic processes, simplify them to some extent and then make suitable representations of each aspect mathematically, statistically or logically.

The model that is researched and developed must mimic a market environment, complete with potential clients whom request certain work to be done. In this instance the model has the specific focus of work that can be done using micro milling machines. The model is defined from the point of view of a specific group, i.e. those companies that supply micro milling services to the market.

While the main body of coding work is implemented using R, the author used the same model logic to program a second implementation on the Insight Maker platform. This is a simplified version of the model that may be used by SME's who lack the programming skills to use the R-model. This model was available at https://insightmaker.com/insight/57050/Success-of-New-Business-in-Competitive-

EnvironmentMM and various parameters may be set by using the online sliders or text boxes. The model is not meant to replace the R-model, which is written on an open-source software. The Insight Maker simulation gives similar results to the R-model and has an easy user interface. It is however limited to the specific web-page and also therefore under the control of a third party. It is also limited in the sense that it has a fixed number of companies who compete for the market.

Kometani and Shimizu (1975) speaks about hierarchical chain structures in biological processes, but the principles of chained logic can be extended to other hierarchies of processes. According to Kometani and Shimizu (1975) the evolution of the super-system is determined by the subsystems in a statistical way, and at the same time the feedback loops put the subsystems under the control of the super-system.

5.2 General business process structure adapted to micro milling

A business reality is described as follows with activities and actors and depicted in figure 5.1, adapted and expanded from Osterwalder and Pigneur. (2010) to include the market with RFQ's:

1. The macro environment exists with clients with opportunities for products or services that may be manufactured using micro milling. Potential customers in the "Markets" environment require manufacturing of parts through micro-milling. Since there could be a number of companies that could do the work, the potential customers specify their designs in a request for quote (RFQ) that they send out to the companies that might be able to manufacture the part, product or tool. The RFQ's specify parts, products or tools using a variety of methods, sketches, drawings, CAD files and written specifications.

2. The manufacturing companies compete with each other to secure the sale for the RFQ. To do this, each manufacturing company must prepare a quote for the work and interpret the RFQ to supply a quote to the customer. Companies have unique reputations, market share, strategies regarding quality, cost models and mark-ups that influence their quotes.

3. The client reviews the quotes and awards tenders while considering factors such as described by Shen *et al.* (2004), expanded on in section 5.7.

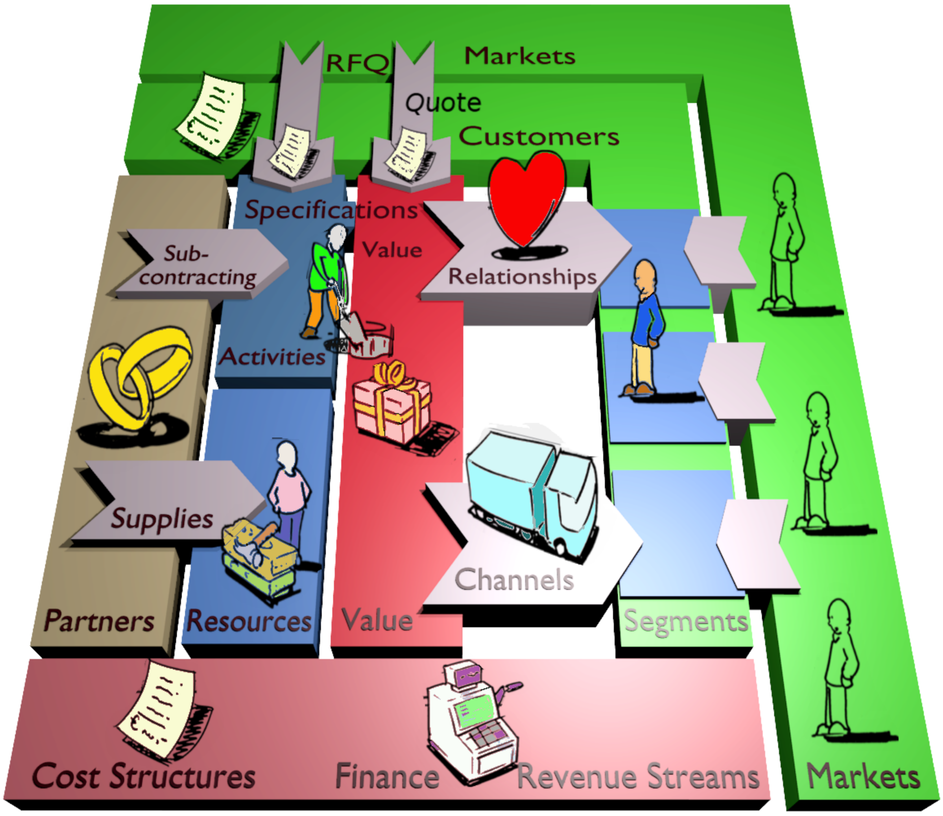


Figure 5.1: Simplified view of the business process structure showing the interaction of markets and manufacturing companies adapted and expanded from Osterwalder and Pigneur. (2010)

4. If a specific company is awarded the tender, they start incurring the actual cost of design, engineering specifications, raw materials, manufacturing costs, labour costs, overheads, cutting tools, machine and operator time to accrue the final actual cost of manufacturing. The manufacturing company has to interpret the tender specifications to realise the part or tool. Various factors influence their milling process, such as tool dynamics, forces, vibration, chatter, size-effect, chip formation and minimum chip thickness, surface finish, tool wear and burrs. Experiments and modelling, process optimisation, sensing and monitoring, material removal rates, accuracy, run-out, effect of the materials grains on the work-piece behaviour may also influence their final cost.

5. There are two ways in which the awarded tender can go wrong for the manufacturing company. Firstly, they could fail to manufacture the part, due to lack of skill, or some other unforeseen reasons. Secondly, they could

successfully complete the part or tool and then not be paid for their services due to a client related reason, such as low cash flow, going bankrupt or some other reason.

6. When a successful payment is received by the manufacturing company, the amount is added to its income for the specific month, and carried into the income statement and cash flow. In the model, the expenses for every month are deducted from the incomes for the same month, giving a profit or loss for the month before considering tax. The tax portion is provided for in a tax deduction account. At year-end in the model, the calculated tax for the company is deducted from the profit before tax, giving the profit after tax as the result.

As may be appreciated, through various variations present in real life, the outcomes for any number of manufacturing companies may vary randomly from year to year in its detail. Through the sagacious application of logic, statistics to available data and knowledge of the above processes a model may be developed that could provide insight into outcomes. The model shows the results in the form of output variables with risk expressed as dispersed or distributed outcomes i.e. distributions. These distributions may be interpreted as probabilistic outcomes and will inform investors in the technology of their financial risk.

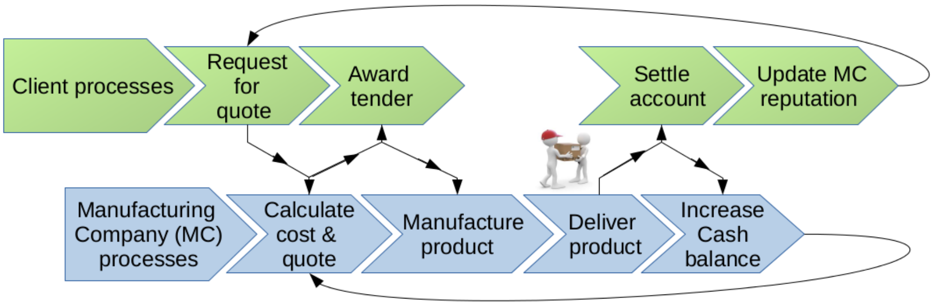


Figure 5.2: The simplified process flow of RFQ, quotes, tender awards and execution

5.3 Reality to model

Once the business process structure is understood in detail, it may be simplified to the required level of detail to develop the simulation model. Although indirect costs are estimated and simulated, the model does not show these here. The drivers for indirect costs are included in figure 3.6 that shows which cost drivers could influence various activities. Figure 5.2 shows the logic flow through the simulation model and system boundary for any general RFQ-driven system. During each loop, the client process will update the manufacturing company reputation according to whether product delivery was on time and according to specification. The parts or products are described in the RFQ according to the client sector, which includes Automotive, Medical implants, Research and Test equipment, Tooling, Energy and Bio-technology. Cost models allow the cost estimates of new, unique parts that must be micro milled according to the RFQ. In the current model, these cost aspects are also stochastic variables, that creates a stochastic quote variable for every manufacturing company. Companies then add their mark-ups to the cost to arrive at a quote amount. After receiving the various quotes, the simulated client will award the contract using a stochastic sample where the probabilities are determined by the prices and reputations of competing companies. According to Särndal *et al.* (2003) each individual sale can be seen as a Bernoulli trail for every manufacturer and the continued process of RFQ's and tenders awarded could then follow a binomial distribution. If the probability of awarding a tender is not constant then it is sometimes referred to as Poisson trails. After a sale is made, the company manufactures the products and real costs are incurred that will be different from the quote estimates. When the manufacturer delivers the products it is paid and its cash balance will increase. The client updates his view of the manufacturing company according to the quality of service experienced. The process may then repeat for a new cycle.

The simulation follows the following logic:

1. Loads the required Libraries.
2. Creates the environment with Global variables. Loads all the required variables, distributions and data.
3. *Generate the RFQ*; customers require manufacturing of products or parts through micro-milling. They design and /or specify the parts using a variety of methods, sketches, drawings, CAD files and written specifications, which they include in a Request for Quote (RFQ).Generate part specifications RFQ from markets.
4. *Prepare the quotes*; the manufacturing company has to interpret the RFQ and specifications to supply quotations to the customers. Mark-up for each company is determined by their strategy and reputation in the market. Quotations are prepared for RFQ's for each company and probabilities are calculated to influence the Bernoulli or Poisson trials.
5. *Award the contracts*; the customer receives various quotes and makes the decision to award the tender to one manufacturer. Reputation and price

feature heavily in the probability to award the contract to a specific manufacturer.

6. *Realise the product*; the manufacturing company has to interpret the quotation to realise the products or parts. Actual costs are incurred due to cutting tools, machine and operator time and overheads. The actual costs may be different to the quoted values and thus the actual costs are stochastic variables.
7. *Deliver parts and get paid, or not?* The parts or products are delivered and mostly paid for. In exceptional cases the customer does not pay, either due to non-performance of the manufacturer, or because the customer is unable to pay. The choices to either pay or not are simulated by Bernoulli trials.
8. *Create financial statements*; the costs and incomes are collated into income statements and cash flows.
9. *Reporting the results;* writing of graphs and reports to pdf files for reporting and analysis.

5.4 Request for quote (RFQ)

Since the model attempts to simulate a market, the sectors of the market that will likely have a demand for micro milled parts are researched in more detail in Chapter 4. Each product must have a RFQ specification that includes the material specification, volume, the milling volume, the quality index, a product complexity index and manufacturing complexity index. Previously in section 3.6 research were listed and displayed in figure 3.6 to support using these drivers for cost aspects. Using these parameters, the simulation will allocate costs to the product in a stochastic manner, to arrive at a basic quote cost to the manufacturing company.

5.5 Decision to bid

Bidding by tenders or quotes is a complex process due to the uncertainty of many factors that influence the outcomes (Shash, 1993). Shash used a survey to identify 55 factors that characterise the decision to bid in civil engineering contracts. The first 11 factors are very similar for the manufacturing environment and were considered for inclusion in the model. Factor 12 in the list, project location can be ignored for micro milling, since the work takes place at the manufacturing company. Of the remaining factors only factor 29, the degree of difficulty was evaluated for inclusion.

The following factors are in the order of importance (Shash, 1993) and selected to be included in the model:

1. When current utilisation is low, the motivation to bid is high.
2. When number of competitors is low, the motivation to bid is high.
3. Previous experience in similar projects will increase motivation to bid.
5. Past profit for similar projects.
6. Project size becomes important if the current utilisation is high, or the project too large to handle.
7. Risk due to various reasons will decrease the motivation to bid.
8. Degree of difficulty could influence the bid if the current skill levels are low.

5.6 Quote preparation

Once the manufacturing company decides to bid, they start preparing the tender or quote. In many cases this is done by estimating the cost and then adding some mark-up percentage to the cost. Mark-ups could be a single percentage on the total or be specific mark-ups on labour, tools, overheads and financing cost. One of the most influential factors to influence the choice of manufacturer would be the price of the tender or quote. This is in turn dependant on the cost and mark-up of the quote. The only variable we may easily control in this scenario is mark-up, and this drives demand along the price-demand elasticity curve. The fist step in the quote preparation is the cost estimation.

5.6.1 Cost estimation

Cost definitions abound in literature and are already well described by Jegers *et al.* (2002) and Kim *et al.* (2015).

Some of the ways that cost may be defined or classified include:

1. Historical values of previous costs as accounted by the finance departments.
2. Standard or average cost of resources coupled with the volumes required or used, with the simple formula: costs = usage units x price/unit.

3. Economists might define cost as a resource sacrificed or forgone to achieve a specific objective. It implies that the resource cannot be used for alternative applications. Therefore, the value of the best alternative sacrificed can be considered to be the value of the resources used. This value is defined as the opportunity cost of the resources under consideration.

4. Expenses incurred due to subcontracting or billing from third parties can form part of costs.

5. Fixed cost due to expenses that will accrue regardless of operations, production volumes or activities.

6. Variable costs that can be attributed to changing volumes, materials used, energy use or overtime labour.

7. Cost might also be considered as direct or indirect cost, where these definitions do not exclude previous listed categories. Indirect costs will also include descriptions such as overheads, percentages of management fees and other utilities.

8. Some specific allocation methods in accounting such as activity-based costing (ABC) relate indirect costs as closely as possible to to relevant activities. The method uses the concepts of cost drivers to estimate the values to assign per activity.

9. Marginal cost is the cost to produce one more unit of production at some given total volume of production. It normally is a decreasing value for higher volumes. A very common S shape results from the decreasing marginal cost, when at some large volume the trend reverses due to aspects like overtime or running at full capacity, after which the marginal cost increases, leading to a S-shape curve.

10. Cost may also be allocated on a bottom-up or top-down approach. Top-down normally uses the financial data and allocates it by using financial or management rules to various projects and departments. In contrast, bottom-up uses the activities inside projects and push the associated costs to be collated into project or department costs. This is more in line with the ABC method and this perspective will used where appropriate.

This research will use the perspective of activity-based costing (ABC) to create estimates from drivers that were identified for micro milling. Figure 3.6 shows what cost drivers could influence various activities.

Previous work by Essmann and Dirkse van Schalkwyk (2011), Rush and Roy (2000) and others have researched various costing models. These models

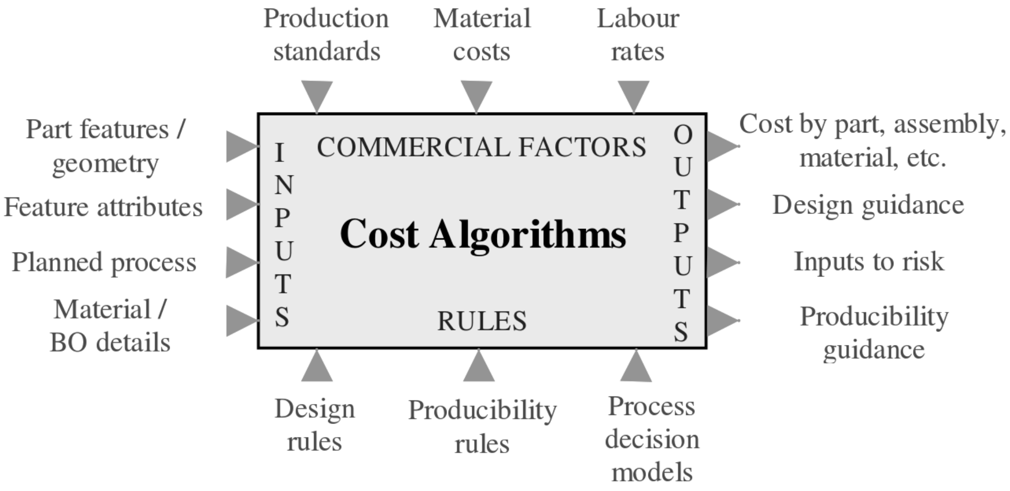


Figure 5.3: How costs are related to various factors. Adapted from Rush and Roy (2000)

are based on generic methods found in literature. The model must specify how the cost is estimated or calculated in statistical and mathematical terms and uses specific cost drivers to accomplish this. Rush and Roy (2000) shows a typical cost model in figure 5.3. In the case of micro milling, typically cost drivers are labour time, cutting tools, material, coolant, machining time, repayments of capital costs of machine tools, skill requirements, energy set-up time and fixed or overhead costs. Details of data that were used are explained in Chapter 6.

5.6.2 Design costs and the influence of design choices on manufacturing costs

A well known concept about project cost is that costs are committed to a project based on early design decisions, and long before the actual cost realises. Choices about material, accuracy required, method of manufacture and assembly are all discussed in detail during the design phase, with costs that are locked into the specification early on. The well-known graph of committed versus realised cost shown in figure 5.4.

Many costs are committed early during the concept or design phases, as can be seen by observing the quick and steep growth of committed cost during the early stages of the project. Observe though, that the realised costs are low during the start-up phase and only starts to grow rapidly once manufacturing starts. This implies that making good decisions about life-cycle cost should be a priority for the design team. Having an accurate cost model allows the design team to make

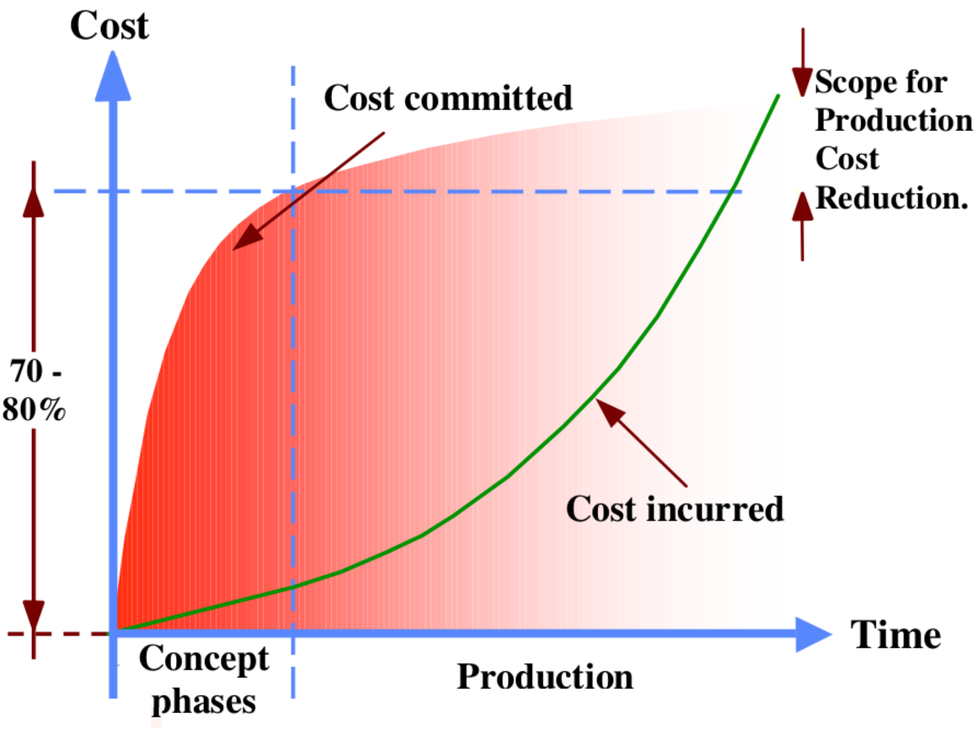


Figure 5.4: How costs are committed during design versus realised during manufacture. Adapted from Rush and Roy (2000)

better informed design decisions. For instance, tool wear has been shown to be related to cooling, lubrication, material type, tool material, tool coatings, cutting conditions and cutting parameters. All of the previous could also influence the time it takes to finish a product, and time has a direct relationship to cost. It illustrates that many costs are locked into the process due to choices made even before the design is finalised.

From a machining point of view, costs may be minimised during designing by considering the following list from Groover (2014); these aspects are included as cost drivers for the model:

1. Minimise the volume of material removed or number of cuts that will be required. This implies that designs should strive to use close to standard stock item sizes. Machine only sections that require tight tolerances or a good surface finish.
2. Ensure that specifications and tolerances are not excessive, just sufficient.
3. Machining sharp corners and edges should be avoided.

4. Expenses incurred due to subcontracting or billing from third parties can form part of costs.
5. Deep holes must be avoided.
6. Undercuts should be avoided, since they require more complex programming, tooling and set-ups.
7. Material selection should consider the machinability of the material.
8. Set-ups must be minimised to one if possible.
9. Standard cutting tools should be used, and tool changes should be minimised.

5.6.3 Machining costs

From Groover (2014) the time to manufacture a part (by machining) may be defined as composed of part handling, machining and tool change times. The total time may then be allocated to various standard costs such as labour, machine tool payback, overheads, energy and management. Machining time is dependant on the volume of material removed, as well as the required size of the tool. Smaller tool requirements will necessitate more tools used to remove the same volume, more time on the machine and higher costs.

$$T_c = T_h + \sum_{n=1}^{tools} \frac{V_n}{f_n A_n} + \frac{n T_t n_p}{} \tag{5.6.1}$$

where T_c *is the total time per part*
T_h *is the handling time per part*
V_n *is the volume removed by the* n^{th} *tool*
f_n *is the feed for the* n^{th} *tool*
A_n *is the cross-section of the tool chip in the direction of the feed*
n is the number of tools used
T_t *is the tool change time and*
n_p *is the number of products cut by a single tool.*

While this formula calculates total time per part, in practice the calculated values are seldom realised. In reality, the actual costs are influenced by human error, defective tools, random breakages and material inconsistencies. These aspects introduce variation that can be simulated and provide a more complete picture of the reality. In figure 5.5 such a simulation is shown for an arbitrary part and specific tool and material combination. Higher cutting speeds create more

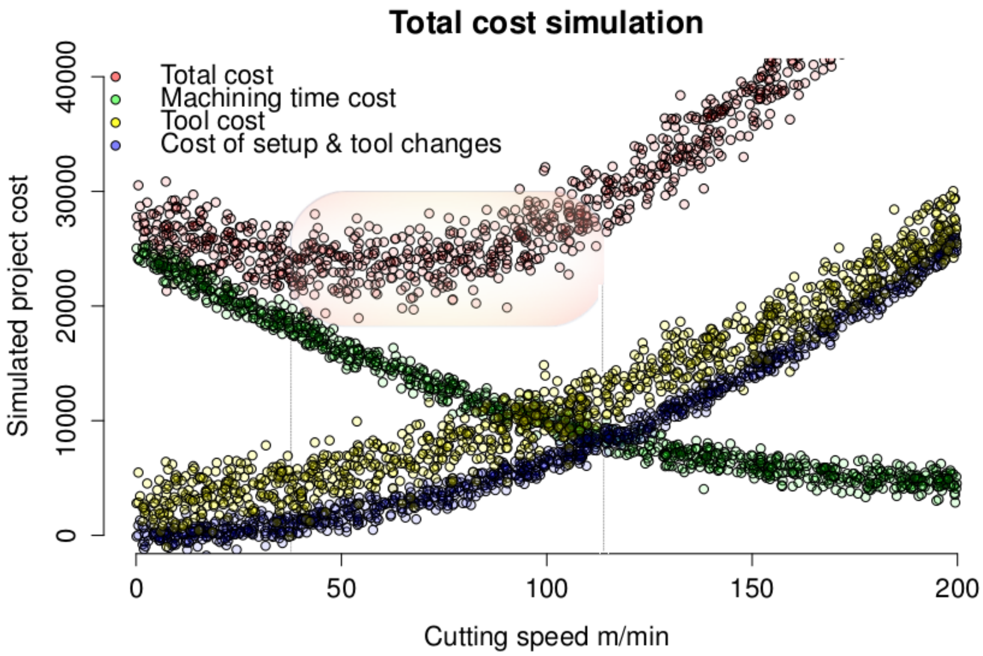


Figure 5.5: Machining cost simulation illustrating the "high efficiency range" between the two lines at speeds of 40 and 115 m/min. Adapted to include simulation; original from Groover (2014)

wear, breakage and subsequent costs on tools, while saving time on the labour, coolant and machine time costs. Somewhere there exists a cutting speed that will yield the lowest average cost. In the specific example, there is an extended area of a "high efficiency range" shown between the two lines at speeds 40 and 115 m/min. This is of course not a general solution, but only applies to a very specific application and will change if the cutter or material is changed.

5.6.4 Mark-up

Shash (1993) also lists 55 factors that determine the mark-up size. They are once again ranked by importance by various industry players. The following list includes some of the top factors according to the study.

1. When the degree of difficulty is high the mark-up will be higher than normal.
2. If there are high risks associated with the work, the mark-up will be higher. These risks could be due to skills required, expensive materials, difficult to machine materials and similar issues.

3. When the current work load is high, the mark-up will be higher than normal. This is based on the expectation that overtime, subcontracting and penalties might be incurred. Alternatively, when the work load is low, work is required to just keep busy and the mark-up will be below the norm.
4. When the company has previous experience in a similar project they can minimise risk and lower their mark-up.
5. When a simple project has a large volume of repeated parts, the mark-up will tend to be lower.
6. When the quality specifications are very strict, the mark-up will be higher than usual.

Most of the companies representatives indicated that both the factors for choosing to bid and for mark-up depends on subjective assessments that are often not expressed directly or mathematically. Shash (1993) goes on to state that this supports the previous work of other authors such as Ahmad and Minkarah (Shash, 1993) who believe that competitiveness and profitability are not the main factors in current bidding models.

Another way to express mark-up is Price-Cost Margins (PCM's). Epifani and Gancia (2011) presents data on US manufacturing industries to show that Price-Cost Margins, range from 1% in the first percentile of the distribution, to 60 % in the 99th percentile. He also remarks that these asymmetries seem to be even larger in less developed economies. Moreover, monopolies allow higher PCM's than sectors with robust exposure to international competition. The average PCM is low for goods that are typically in highly competitive markets, but about 20% higher in specialist business sectors or services. Mark-up may also be related to the companies' standing and reputation for quality in the marketplace. If the company have loyal clients due to previous contracts that were executed at a high quality then they might be able to increase their mark-up above the market average. In contrast, if a company is just starting out in the market, then they might have to drop considerably below market average to secure their first contracts. Further, since the awarding of contracts places a heavy consideration on the price of the quote, other companies compete for the same contract, and the price difference between competing quotes becomes important. Lastly, if the company is already utilising their machines and workforce at close to capacity, they might have to pay overtime and incur additional outsourcing costs if they take on new work. For this reason a responsive mark-up might be preferred to offset the additional costs. The mark-up may similarly be increased if the tender specifies a very short turn-around or very innovative, difficult or high risk work (Shash, 1993).

5.7 Awarding of contracts

If we may assume that experienced employees who decide to bid and then make their management decisions about mark-up have a logical and proven process to support their decisions, then the logic may assist us in finding the most likely reasons why contracts are awarded to specific companies. From experience, these employees perceive that certain factors will influence the awarding of contracts and reflect those factors into their bidding and mark-up structure. Doni (2006) reports on a model that points to a large effect that the manufacturing company's reputation has on the awarding of contracts. The factor however does not appear in either of the bidding or mark-up lists. From the customer view though, awarding a tender to a manufacturer with a good reputation will reduce his risk and make it more likely that the product will be on time and within specification. For that peace of mind, the customer will be willing to pay a certain premium. Shen *et al.* (2004) supports the same point of view by including the following aspects in a weighted mean to determine the winning bid:

1. Tendering price with a weight of 50% of the total.
2. Manufacturing time with a weight of 10%.
3. Quality plan or rating, with a weight of 20%.
4. Track record or reputation from previous contracts with a weight of 20%.

The percentages as shown were chosen to reflect the manufacturing industry as far as possible. Elmaghraby (2000) provides various arguments and motivations for choosing a winning bid and sourcing strategy. Much of the discussion centres around the reduction of risk, in the form of economic risk, time risk and quality of product risk. Both time risk and quality of product risk are linked to the reputation of the company according to Kotha *et al.* (2001).

In many types of supplier choice decisions there are strategies such as single or multiple sourcing. Three types of uncertainty could influence these risks according to Tullous and Lee Utrecht (1992). These include need uncertainty, market uncertainty, and transaction uncertainty. These risk could force the customer to split their risk and appoint two or more contractors. For the purpose of the micro milling model this option is not considered viable and therefore left out of the model for the moment. For the current micro milling model the most important aspects that will determine the awarding of tenders is accepted as the four listed above from Shen *et al.* (2004).

5.8 Execution of contracted work

During the execution or manufacturing, the manufacturing company has to interpret the RFQ to realise the products or parts. Real costs are incurred due to cutting tools, machine and operator time and overheads. The real costs may be different to the quoted values and thus the actual costs are stochastic variables. The actual cost will be deducted from income to give the profit before tax. It may happen that things go wrong and costs are incurred that were not planned for, so that the final profitability of each project could be different, even if mark-up was identical.

5.9 Income

In the majority of contracts, the income is received from the client if the contract is fulfilled. In some rare cases, the customer might default through no fault of the manufacturer, such as a soured relationship, insolvency or bankruptcy. In some other cases, the manufacturing company might overstretch through ambition to take on a project that is too difficult for their current skill level. In the case of failure to deliver, the company will be penalised twice, first through not receiving income after they had to spend the money and secondly by lowering their reputation in the market.

5.10 Distribution selection and real data

Kometani and Shimizu (1975) states correctly that if dubious selections of distributions are used in a Monte Carlo simulation, that the simulation will transmit the input information directly to the final result, making the simulation result as dubious as the input. If the modelling process was done thoroughly then the model will still be valid and just in need of new data. For a large and complex field, especially in a new and uncharted area there is limited real data to consider and some predictions and forecasting will be required to feed into the model.

5.11 Conclusion

In real life, a competitive bidding process has almost infinite complexities and potential outcomes full of uncertainties. This Chapter highlights only a subsection of these aspects that are vital to understanding the RFQ process, the preparation of quotes, the awarding of contracts, manufacturing cost aspects, non-delivery or non-payment instances, income and profit aspects. The most important aspects are represented in the basic simulation model. It is clear that such a simulation model is essentially incomplete, yet provides better insight into reality than contending methods.

Chapter 6

Simulation model working and outputs from the model

6.1 Introduction

The simulation and data requirements for economic modelling of developing and new technology sales are complex and it is rare to find complete data. Forecasting techniques can go some way to supplement data, as well as previous research that reports on the technology. Since a Monte Carlo simulation model was chosen to represent the reality, logic structures must be programmed to represent the real life processes. Also all data must be converted to distributions of some kind. Where data are available but sparse, bootstrapping methods are possible. In cases where primary data were not obtainable, data from other countries were analysed with regression methods to suggest expected ranges for South Africa or logic used to generate likely distributions. Costs were taken from South African industries as far as possible, excepting for technologies that must be imported.

6.2 Monte Carlo simulation

Imagine your answer to the following question: 'How long does it take you to drive from Cape Town to Stellenbosch?' Depending on your risk profile and vehicle, the answer for various people will vary between about 30 minutes and 90 minutes. There are also many factors that could influence the answer, so that rephrasing the question to account for these might be required. Regardless, let's assume the reply is most often 50 minutes, with 4 % of people who choose this. Also assume that the percentage of people who estimate they take less than 50 minutes is 34 % and that other 62 % will estimate they take longer than 50 minutes. Converting all the responses to a distribution will yield a curve such as the one shown in figure 6.1. The basic process of a Monte Carlo simulation for driving times from Cape Town to Stellenbosch can then be done by simply getting a random sample from the distribution many times. Any one of these samples values may have a value of 30 to 90, and would represent a random person driving the route. The values closer to 50 minutes will have a higher probability of being chosen, since there are more values in that region to sample from.

When we compare an average or in this case a mode driving time such as the 50 minutes, we can easily see that the reality is more complex and that the abstract Monte Carlo simulation will give us more realistic results than if we chose to use the mode or average driving time to represent reality. Using the simulated values we may determine the probability of randomly chosen drivers arriving before or after any given time.

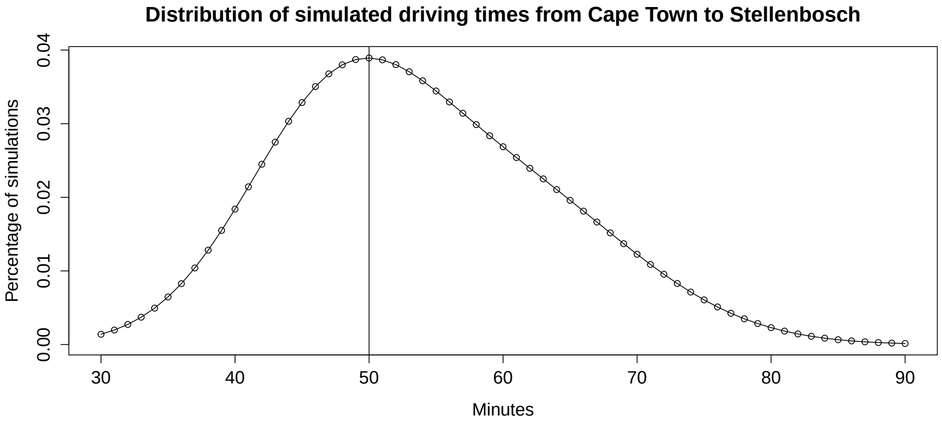


Figure 6.1: Simulation example of driving times as a distribution

The real strength of Monte Carlo simulations is however when various distributions and logic that represents processes in reality are combined to represent a complex system. In many such complex systems, an average, mode or median value is even less useful or might be completely misleading.

In most manufacturing systems that includes scheduling and material, and therefore cost aspects, it is a lot more difficult to save time, material or expenses, than to overshoot the mode prediction. For instance, in the previous example of driving times, it would be almost impossible to drive from Cape Town to Stellenbosch in less than 15 minutes, given safety issues, other traffic and current technology. It would however be quite possible that a trip becomes 120 minutes if something went wrong, such as a flat tyre, running out of petrol or encountering heavy traffic or an accident. This results in distributions that are typically skewed to the right, similar or more skew than the one shown in figure 6.1. When only averages or modes are available in the literature, we know that distributions must exist regardless, and building a model with the mode or average will be wrong. In that case, building the model to assume a distribution will give a better and more realistic result, and if the actual distribution is determined in the future, the model will be able to use the new data and give even more accurate outputs.

6.3 General background to the simulation model as developed

The model that was developed does not fit squarely into any of the singular simulation definitions and may therefore be considered a mixed model. The main architecture could be described as a system dynamics model representing cause-and-effect relationships in terms of causal-loops, flows with levels, rates and equations. The system boundary is described in section 5.3. Random variates were obtained by sampling to get particular outcomes of stochastic variables. This resulted in a self-driven simulation. Some equations in the model use linear and others non-linear forms to change variables and influence the system behaviour. Numerical models are used to solve for ROI by applying computational procedures by simple iteration. Some variables contain rudimentary artificial intelligence (AI) such as those controlling the reputation of a company. The AI aspect of the model is able to introduce some transient model behaviour and probability changes with respect to time.

The model is stable as it tends to return to a predictable, if somewhat transient, condition after being disturbed. Objects in the simulation are allocated a state by using 'flags' in the code, normally a binary '1', '0' flag for yes and no. Through these flags, the stochastic activity of objects were controlled. Time flow mechanisms were created by using loops to advance the time in the simulation, and provides synchronization of the various parts of the simulation.

The state of the system is observable in R-studio, the integrated development environment (IDE) used for writing the code. R-studio allows the exhaustive enumeration of all attribute values at a particular instant of time. This enumeration allows traceability during the code development and debugging. Pseudo-random number generation was used during testing, such that random numbers are reproducible by using a starting value called a seed. This was useful for testing purposes, but 'true' random numbers were used for the actual simulations from this point forward.

The simulation process structure initialises with some global variables that may be set to any values the user might require.

6.4 Data requirements for the complete design, management and manufacturing cost

Previously in 5.6.3 research regarding machining cost calculations was presented. Tool life equations were also described in 3.5.1 and other general cost aspects were discussed in Chapter 3. Using these aspects together, the following global variables were used to generate comparative costs for the model. Other variables and the simulation code are included in Appendix 1.

1. 'G.numMC' is a global variable to indicate the number of Manufacturing Companies to simulate.
2. 'G.CapMC' is the chosen capacity of each manufacturing company, where 2 indicates$2 * 168$ machine hours per month.
3. 'G.StdCostMC' is the standard cost of maintaining the capacity per month. It is added later if the quote is awarded.
4. 'G.productSize' represents the mean sizes of potential products in various markets; the actual sizes 'RFQsize' are randomly drawn from a distribution.
5. 'G.productQual' represents the quality requirements where high quality will lead to higher cost; the actual quality variable values 'RFQquality' are randomly drawn from a distribution.
6. 'G.managementCost, 'DesignerSalary' and 'OperatorSalary' are the Rand per hour cost of management, a CAD designer and CAD operator.
7. 'G.millVolume' represents the mean milling volumes of the job, in cm^3. The actual values are drawn from distributions as 'RFQmillVolume'.
8. 'G.productComplex' represents the complexity of the product and 'G.manu Complex' is the complexity of the manufacturing process; both influence the designer time and the machining time in the model. Actual values are again drawn from distributions to give the values of 'RFQproductComplex' and 'RFQmanuComplex'.
9. 'G.RandPerTool', the cost of a single cutting tool, and 'G.cm3PerTool', the volume of material that may be removed with a single cutting tool, are used to calculate the cutting tool cost per product.

10. 'G.RandMaterials' are material costs for various metals and engineering plastics. The actual values are drawn from distributions as 'RFQmaterial'.
11. 'G.softwareCost' are the per hour cost of software used during design and manufacture.
12. 'G.spaceRent' represents the rent of space required for the business.
13. 'quoteCost' stores the cost of the quote before the mark-up is added.

To illustrate the use of the equations, a portion of one of the equations used in the simulation is shown below. This is a portion of the equation that is used to calculate the cost of the quote in the model. It is is shown below in R-code, and it must be stressed that although the structure of the equation may be logically verified, the actual parameters that must be used should in practice be adapted to a specific company, its own works procedures and cost structures. At the moment it serves as a general concept equation and could be expanded as well. The RFQflag value has no cost meaning and is used only as a flag to indicate if the cost must be zero or as-calculated. This flag is set to one (1) if the company will quote and to zero (0) if it will not. Text behind the '- symbols are interpreted as comments. The square brackets are used as indices to do vector-like calculations, where $[, kk]$ is equivalent to $['ALL\ \ VALUES', kk]$. 'kk' is the month counter in a loop for the number of months in the simulation. Most of the variables in the equation are generated via normal distributions or bootstrapped or sampled from a general data distribution.

$$
\begin{aligned}
&\quad quoteCost[, , kk] <-\ RFQflag[, kk] * RFQsize[, kk]* \\
&G.RandMaterials[RFQmaterial[, kk] + 1] * \\
&((1 + RFQquality[, kk])^{0.3}) + RFQflag[, kk] * \\
&(1 + RFQmanuComplex[, kk])^{0.3} +' Material.cost \\
&RFQflag[, kk] * RFQmillVolume[, kk] * \\
&(1 + RFQproductComplex[, kk]) * DesignerSalary + \\
&'CNC.programming.or.design.aspects \\
&RFQflag[, kk] * RFQmillVolume[, kk] * \\
&((1 + RFQmanuComplex[, kk])^{0.5}) * \\
&(1 + RFQquality[, kk]) * OperatorSalary + \\
&'Manufacturing.aspects.work - holdingmilling.and.finishing
\end{aligned}
$$

The complete code for the simulation model is included in Appendix 1.

Manufacturing sector Automotive

Project 5 Value R: 40531

Material volume/item 65.7224 and number to manufacture 1

Material Steel stainless

Material Price R 1957

Quality 0.9

Product Complexity 0.8641

Milling volume 22.0561

Manufacturing Complexity 0.8371

Figure 6.2: Tabled RFQ cost driver values generated from simulation outputs from the model

6.5 The simulation process

The simulation model's working is illustrated by some descriptions, a product's RFQ specifications shown in figure 6.2, histograms that represent aspects of the combined RFQ's shown in figure 7.4 and 7.5, histograms of the cost of quotes for the relevant RFQ's shown in figure 6.3, the utilisation of the manufacturing companies competing for the tenders over time in figure 6.4, the reputation of the various manufacturing companies at a specific client (client 8 in the example case) shown in figure 6.5, the income statement of manufacturing company 1 shown in figure 6.6, the average simulated ROI's of six competing companies for 50 simulations in figure 6.7, the profit per month for four competing manufacturing companies for a specific simulation run shown in figure 6.8 and a histogram of 50 simulations' cash balances at month 24 for a specific manufacturing company (manufacturing company 3 in this case) shown in figure 6.9.
Additional graphs from the simulation as shown in Appendix 10.4 and Chapters 7 and 8 provide more information such as simulated cash flows, simulated dis-

counted cash flows, the potential value of work lost to the global market, cost reduction due to differing learning curves, cost of cutting tools, material costs of RFQ's, comparisons of cash flows for all competing companies and cash balances at 12, 24 and 36 months for all competing companies. These graphs are discussed later during the relevant Chapters.
It is also feasible to expand the simulation results to include additional output graphs that anyone might require.

6.5.1 Request for quote simulation

The first step in the simulation is requests for quotes (RFQ's) that clients send into the marketplace. These RFQ's in any industry can be represented by distributions that mimic the expected values for material, volumes, milling volumes, quality requirements and part complexity. The simulation generates a specification of every project in table format as shown in figure 6.2.

In Chapter 4 the markets for micro milling are analysed. The analyses makes it possible to estimate the types and volumes of parts or products that may be expected from micro milling. The author uses this information to code distributions and random sampling subroutines in R to generate the required data for the simulations. For the most part the simulations used standard R functions to represent data as either normal distributions or through the creation of general distributions.

The R-code samples volumes for the required parts, milling volumes and all the quality and complexity indices that are required to make the model function. The figure 7.4 shows the output from a simulation run for product volumes.

The specific graph in figure 7.4 is the result of one simulation run, and if the simulation is run for any non-infinite number of runs it is expected that the same values will be unlikely to repeat. This means that the specific graph has no special significance in the model and is likely not representative of an "average" outcome. It is only when the simulation is run a large number of times when the results may be analysed and interpreted.

The same may be said of all the individual graphs and tables that are shown in this research. These individual graphs are only shown as to illustrate the method used in the simulation. For this reason it would be nonsense to discuss the graphs or tables as anything significant, except to show that they drive the individual aspects represented in the simulation model.

Following the same logic as before, the volumes that must be milled are specified for every project and a single simulation run's volumes represented in

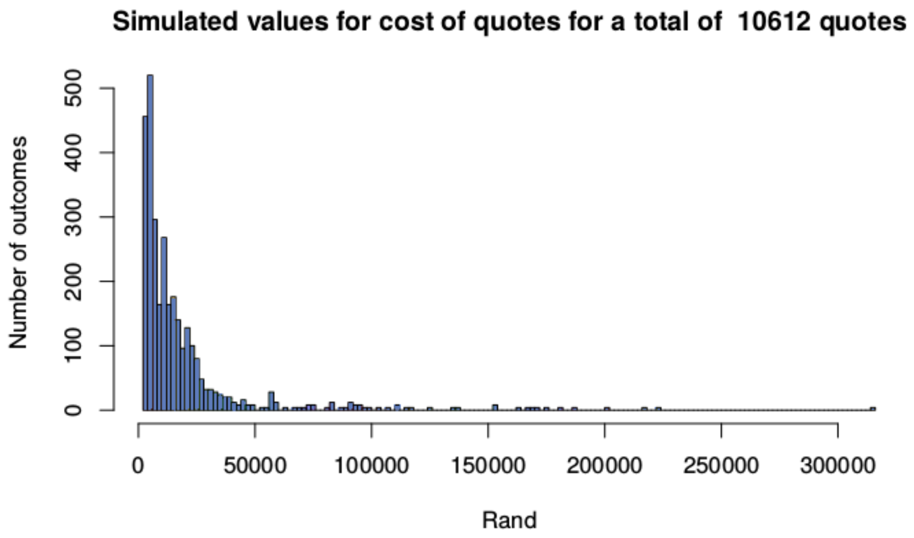


Figure 6.3: The quote values generated for tender simulation outputs from the model in the form of a histogram

the histogram in figure 7.5.

6.5.2 Cost assigning and awarding of contracts simulation

Once the complete RFQ is simulated, the costing equation may assign the costs to the quote. The figure 6.3 compactly summarises some simulated and calculated quotes in a histogram for the range of products in the model. Some aspects of validation might be clear immediately, since it is observed that the costs per quote is mostly below about R40 000, highly skewed to the right. This conforms to the expected shape as described in section 6.2.

Through the logic structure of the model it is possible to award contracts, calculate the company utilisation and the reputation changes. The relevant logic to award a contract, uses as the main parameter, a weighted mean of the inverse of quote cost shown in figure 6.3, the company utilisation shown in figure 6.4 and company reputation shown in figure 6.5. With the weighted mean calculated for every competing company, a single company is then chosen from all the competing companies, based on a sampling method that gives a company with a higher weighted mean a larger probability to be selected. This logic may be expanded to any number of aspects that the user could measure and that could make a difference to the tender process.

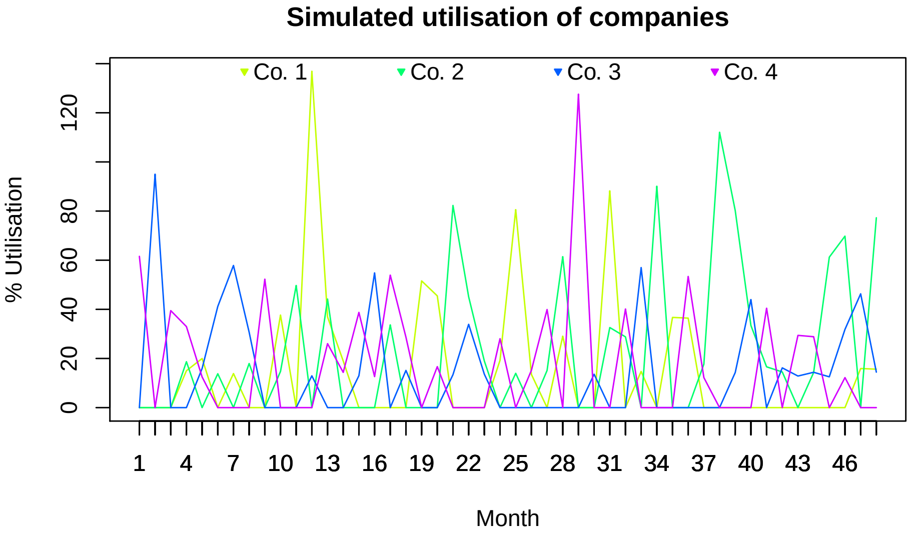


Figure 6.4: Simulated companies' utilisation outputs from the model per month

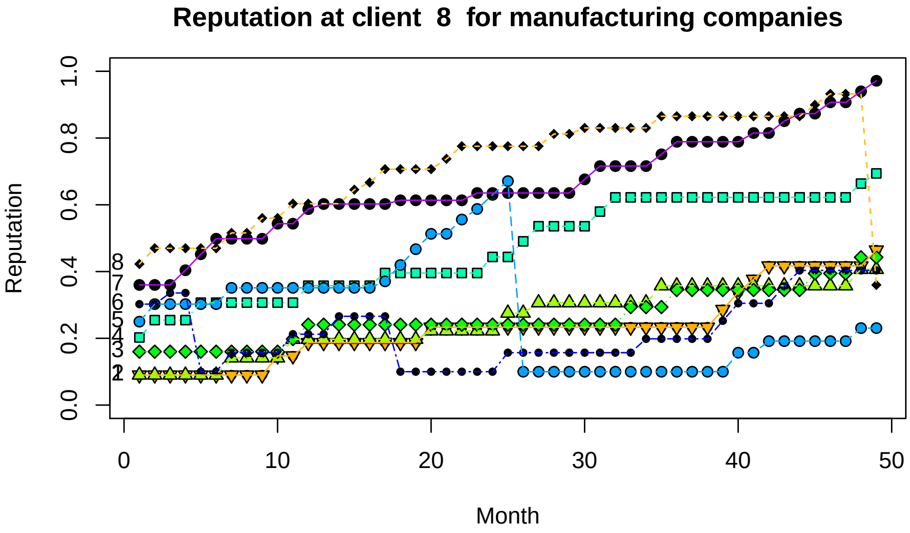


Figure 6.5: Simulated companies' reputation outputs from the model per month

6.5.3 Utilisation and reputation simulation

When a tender is awarded to a manufacturing company, the hours to complete the tender is calculated and the company utilisation goes up. Figure 6.4 shows a typical simulation output of companies' utilisations per month for four competing companies. Where the utilisation is above 100%, it means the company was awarded a large multi-month contract. The program logic then does not allow them to tender for new work until their utilisation drops below 100%. The company strategy regarding pricing, building their reputation and their current utilisation has an influence on the awarding of contracts and thus also on its future utilisation.

In figure 6.5 the logic of building up a good reputation is shown for most of the time, with the odd drop in reputation such as during month 26 for company 5 and at month 47 for company 8. These drops in reputation happen when a company does not deliver on time or not according to the specification. These non-delivery events occur randomly, but with probabilities linked to the difficulty level of the contract, the current company utilisation, skill level and reputation. In the current simulation, marketing aspects are not included, but collaboration with a marketing department could easily rectify this.

Manufacturing company 1	Rand
Total income revenue	6459752
− Cost of sales	2372955
Gross profit	4086798
− SG and A expenses	1899458
Operating profit	2187340
+ Interest	122604
Profit before tax	2309944
− Income tax	646784
Profit	1663160

Figure 6.6: The income statement values generated from simulation outputs from the model in tabular form

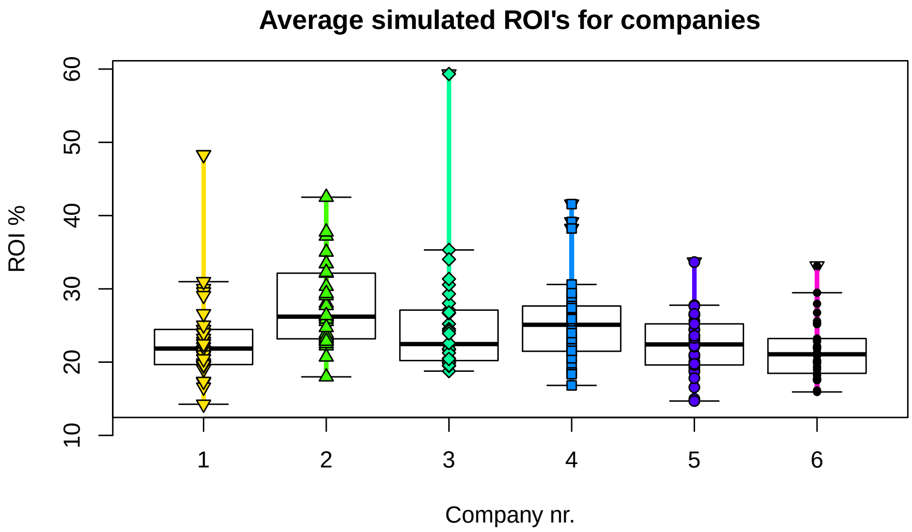


Figure 6.7: The ROI generated outputs from the model per company

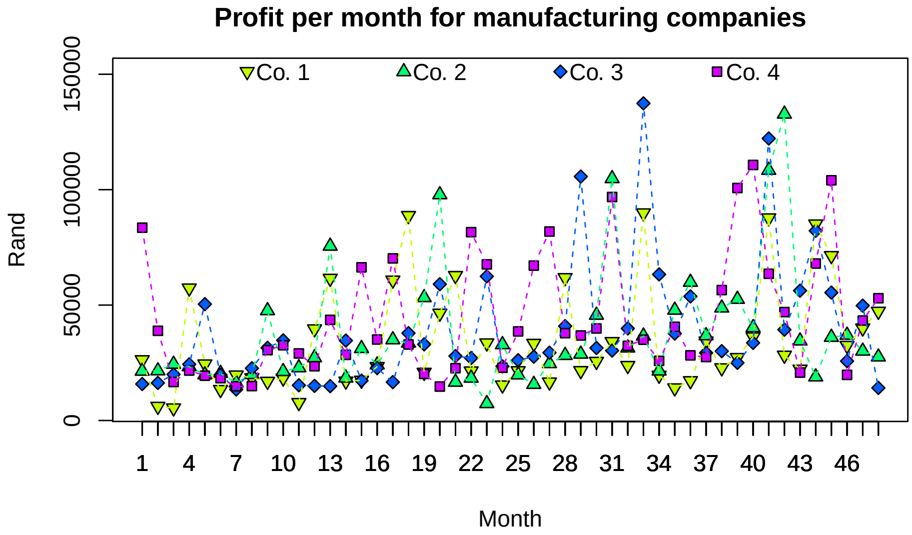


Figure 6.8: The profit per month values generated from the model

6.5.4 Income, cash flow and profit simulation

The simulation generates all the values required to draw up an income statement for every company in the simulation, per month, per year or for some user specified period. Figure 6.6 shows an example of such an income statement. Also,

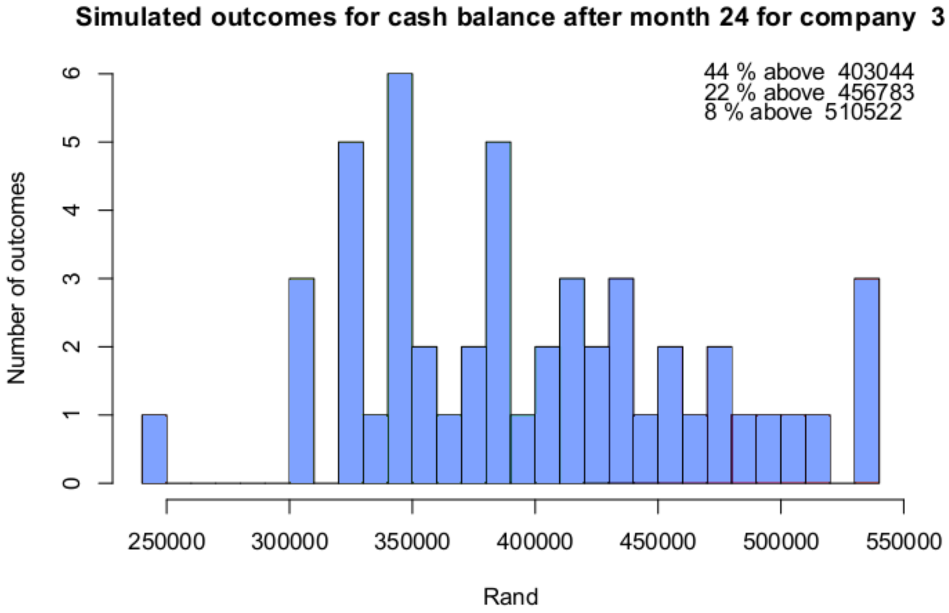


Figure 6.9: The simulated cash balance for a specific company after 24 months in the form of a histogram

companies may be compared on Return on Investment (ROI) such as shown in figure 6.7, profit per month as shown in figure 6.8, and profit over 24 months as shown in figure 6.9. Figure 6.9 shows 50 possible simulated outcomes given the exact same starting conditions. This provides probabilities, such as shown that 22% of simulations gave a cash balance of more than R456 783 after a 24 month simulated period. These graphs are generated automatically during simulation to illustrate the various aspects of a specific strategy.

6.6 Conclusion

Chapter 4 provides the market analysis to allow RFQ aspects to be modelled with appropriate distributions.
This Chapter shows how simulation may give a more complete answer than using competing methods. The model logic is explained, starting with the RFQ, assigning costs, awarding of contracts and the resulting changes in the company regarding utilisation, reputation, cash flow, ROI and profit.
The R language has all the capabilities to construct distributions for bootstrapping or to use standard distributions from statistics to represent the data required for the model. The logic structure of the model is represented by loop structures,

if and while statements and mathematics operators. The code may be inspected in Appendix 1.

Chapter 7

Preliminary results from first simulations

7.1 Introduction

It is explained how the conceptual model was developed in line with the current business models in Chapter 2, the technical requirements in Chapter 3 and the model structure in Chapter 5. Chapter 4 explores the markets that may be simulated for the request for quotes. Developing the simulation model in line with these aspects and conducting a walk-through of the model, validated the model conceptually and added critical aspects to the model to make it more realistic. Once the model is validated conceptually, the code is debugged and improved until it yields consistent results. Typical errors may be in the randomised size of how many RFQ's are sent out per month, divisions by zero values, adjustment in the reputation of the company and many other opportunities. The code is run repeatedly, and with each cycle the preliminary results are scrutinised for any illogical outputs, inconsistencies and differences from real data. These inconsistencies are then removed by either improving on the logical structure or flow in the code, or by eliminating programming errors if present. Once the code runs several simulations flawlessly, the next validation step may commence.

After program debugging, the simulation results may be used to validate the simulation code. In the research design in section 1.6 it is stated that the best method to validate the simulation is to compare the model performance measures with the comparable performance measures collected from the actual system. Since there is no actual system data available, the next best method is to use case studies to validate parts of the simulation. Regardless, the simulation analyst and other stakeholders checked the simulation results for reasonableness as well. The case studies will be described next, and was used to validate the cost aspects of the simulation. The functionality of the simulation can be improved due to finding new information from these case instances.

7.2 Typical errors in simulation models

Errors in simulation models are classified as Type I, II or III Errors. A type I Error is rejecting the credibility of a model when in fact the model is sufficiently credible. A type II Error is accepting the credibility of a model when in fact the model is not sufficiently credible and a type III Error is solving the wrong problem. It is already known that the underlying data for this simulation is not complete and that a conglomerate of resources will be required to work together in a larger project to improve this limitation. The logical structure or framework of the model, simulation logic and computer code must be verified though. Expanding this testing protocol will reduce the probability of making a Type I, II or III Error. Model instrumentation is the tools used by the programmer to find errors, to judge whether loops and if statements are executing correctly and prove the correctness of the code. It usually requires the insertion of additional code (probes, stubs or trap code) into the executable model or sub-model for the purpose of collecting information about model behaviour during execution. This aspect was done during the original writing of the code, and whenever an anomaly were discovered in the results.

7.3 Validation of cost aspects in the simulation model

The following cases were completed from design to manufacture by the author to validate the costs simulated by the model. The first case is explained in more detail, while the other cases are presented in detail in Appendix 2.

7.3.1 Case 1: Micro fluidic application for research

The basic design of the part is shown in figure 7.1, where the central circle is 1 mm in diameter. The part was milled from perspex, 2mm thick. For workholding, the perspex was fastened using double-sided tape. The planning and design aspects took about 90 minutes, most of which was spent in consultation with the client, since the original specification was not complete. To limit the torque on the double-sided tape, and limit the heat into the perspex, the centre hole was machined using a 203μm end mill. The tool path was a simple G02/G03 type arc command in x-y axis as shown in the figure. The two side

holes were drilled using the same 203μm end mill. A second tool path was required using a 25.4μm end mill as shown in figure 7.2.
The complexity index may be calculated from a simple weighted mean of Product complexity and Manufacturing complexity:

Complexity <- 0.5 + 0.4(Features/(max(Features,FM)) + Radii/(max(Radii, RM)))*
+ 0.6(Axis/6 + WorkFixture/10 + Toolchange/10)*

The last two values are user-estimated between zero and 10, to represent the difficulty level of fixing the workpiece, and the difficulty of the tool changes, given special setup requirements. With automated fixture systems or automated tool change systems the value of WorkFixture and Toolchange is assigned to be zero. FM and RM may be set by the company to represent their unique skill and design capabilities. For the study values of FM = 15 and RM = 10 was considered practical and the two weights were 0.4 and 0.6. The complexity of this part was estimated to be 0.62, where the index is from 0.5 as simple and 1 as extremely complex.

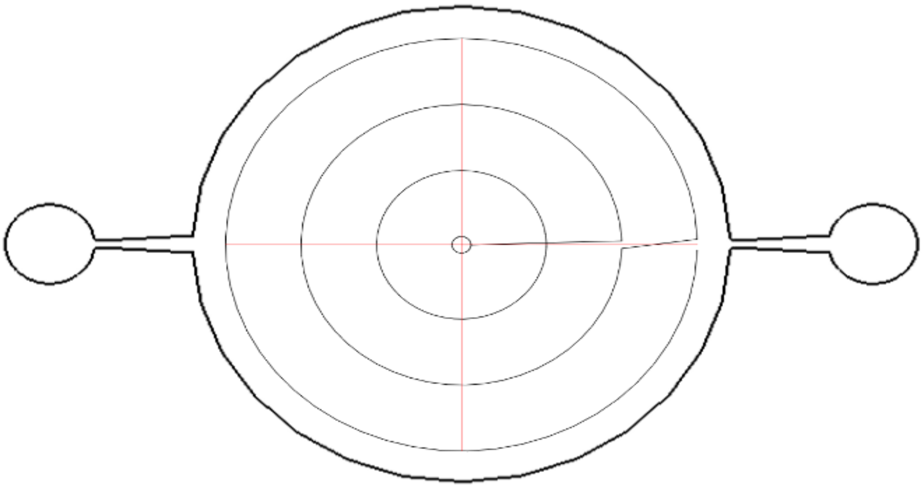


Figure 7.1: Case 1: micro fluidic product for research with partial tool path for the 203μm end mill

The simulation code was executed manually in R to get the various costs that the simulation would get if the part was required through a RFQ. The assign operator is <- with a similar meaning as equals or =. See Appendix 2 for the detail of the calculations.

Figure 7.2: Case 1: micro fluidic product for research tool path for 25.4μm end mill

The simulation calculated a material cost of R8.67, which is considered realistic for the material cost of such a small micro-part. Logistics of materials, storage and such costs are added separately to projects based on overheads.

There is a time variable in the simulation code that estimates the time aspects of the manufacturing, based on volume, complexity of the part and the complexity of manufacturing. This time variable estimates the approximate time in hours that will be spent on the project per person or machine. It is then further adapted to be specific to design, management, operating, machining etc. Since the planning and design aspects took about 90 minutes, the following R code was run to estimate a design time cost the simulation would have used. R gives the answer to the calculation as '[1] Answer'.

$(timeC/2 * (1 + RFQproductComplex)^{0.3} + 1) *$
$(1 + RFQquality)^{0.3} * DesignerSalary$

[1] 450.8198

In the original code, the '(1+RFQquality)'$^{0.3}$ code was not used. When running the code for the first time, an answer of R159 was calculated. Upon further inspection of the formula, it was decided that the quality aspect should feature in the formula, since a higher quality aspect demands more care and accuracy during design and this will impact the design and planning time. Once this aspect was added, it was possible to calibrate it to give the same answer as the case study. This approach will be repeated with other case studies to get a reasonably calibrated formula that could work for most projects. Given that the designer salary is listed as R300/h in the simulation, 90 minutes will give a cost of R450.

The machining on this part took 1 hour, of which about 20 minutes were spent in preparation, set-up, setting of the zero position and tool changes. The R code to estimate a machining time cost were the following.

$> (timeC/2 * ((1 + RFQmanuComplex)^{0.5}) *$
$(1 + RFQquality)^{0.5} + 1) * OperatorSalary$

[1] 271.3977

The answer of R271 is slightly higher than what was experienced in the case study. By calibrating the wasted time aspect of the formula from 1 to 0.65, the following estimation gave a reasonable answer of R201, where 1 hour of work is currently billed at R200 in the model.

According to the relationship $(volumemilled)/(tooldiametre)^3$ for every tool, and cost per tool aspects, the following R code was used to calculate the estimated tool cost.

$> (timeC/G.hPerTool[RFQmaterial]) * G.RandPerTool[RFQmaterial] *$
$((1 + RFQmanuComplex)^{0.5}) * (1 + RFQquality)^{0.5}$

[1] 159.9309

This answer was considered reasonable, since the small 25.4 μm tool would be used only for one such part. The larger 203 μm tool would be used for multiple parts. The current cost per tool for this application and material combination is R112, so the calculated cost is in line with the expected case study value. even though more work might be performed with the same tools, the cost for the tools are loaded against the project to provide a buffer for tool breakage etc. In that case the formula might be required to be calibrated slightly higher. This aspect will be revised again after considering the other case studies.

The next aspect to evaluate is the indirect management cost. Since this is a quite standard and simple project, the involvement of management will be expected to be minimal. In a commercial venture, this might be completely different. The following R code estimated the management cost.

$> timeC/20 * G.managementCost *$
$((1 + 3 * RFQmanuComplex)^{0.8}) * (1 + 2 * RFQquality)^{0.8}$
[1] 56.80551

The value of R56 rand represents about 6 minutes of management time, which seems quite low. For the actual case study inside a university set-up this is quite reasonable, but for a manufacturing company it is expected that it could be higher if the client has a high profile and could bring in larger projects. These aspects were not modelled and thus could be considered in future improvements.

Software is estimated to be used for about half the time of working on the project and the following R code estimated the software cost while considering complexity aspects of the product.

$> timeC/2 * G.softwareCost * ((1 + RFQmanuComplex)^2)$
$(1 + RFQproductComplex)^2$
[1] 19.65122

A cost of about R20 seems reasonable for the software cost in this case study. If this cost is expanded to a yearly figure, this would allow the company to spend about R40 000 per year on the design and manufacturing software. This is expected to be sufficient, though costs in this regard may vary considerably as well depending on the software solution chosen.

Property rent during 2015 in the Technopark area in Stellenbosch varied from about R100 to R200 per m^2. These figures are available widely in the media and must be updated when the simulations are required. Using an average cost of R150 per m^2, and a 16 m^2 space, the following estimated cost for space rent is envisioned for the case study.

$$> timeC * (G.spaceRent) * ((1 + RFQmanuComplex)^{0.3}) * (1 + RFQproductComplex)^{0.6} * ((1 + RFQquality)^{0.3})$$

[1] 23.17279

If expanded to a yearly figure this gives a yearly rental cost of about R45 000 which is considered reasonable.

When all these costs are added together, the basic cost to the company is found to be R920.

Mark-up is generally considered to be from about 5 % on high volume goods to about 2000 % in high service specialist goods. In most manufacturing however, the mark-up is normally based on a cost-plus basis at a reasonable mark-up of 10% to 60% depending on various factors. For a specialised manufacturing company, it is possible to charge slightly higher mark-ups, maybe up to 400% if they are highly skilled. For the simulations the profit margins were generally limited to between 15% and 50%.

For this project, a mark-up of 52% was added, and the final cost is R1400 for the project. This is considered a very realistic price for the case study.

7.4 Conclusion on the case studies

For brevity, the rest of the case studies are described in Appendix 2, although still in the same amount of detail as case 1. Some of the interesting aspects that were brought to light are discussed below.

There is a need to model multiple or batch products. For these products, the design cost, management cost and space rent cost may be reduced or left out. There is also a learning curve that makes large batches less expensive. These aspects are thus included in the model due to the lessons learnt from the case studies.

If the client has a high profile, management might be more involved to bring in larger projects. These aspects were not modelled and thus could be considered in future improvements. Management cost aspects regarding complexity, size and quality are included in the model though.

Additional work required for reverse engineering is not considered and future models could consider calculating reverse engineering aspects. The current model assumed a RFQ that is complete with client files and specifications.

This model may be adapted to serve various other industries by calibrating it with approriate case study data.

7.5 Validation of RFQ aspects in the simulation model

In the model, requests for quotes (RFQ's) that clients send into the marketplace drive the simulations. The RFQ's specify material, volumes, milling volumes, quality requirements and part complexity as may be seen in figure 7.3.

During the initial simulation runs the following outputs were scrutinised to decide if the results were reasonable. In figures 7.3, 7.4 and 7.5 are single examples of the simulation outputs for a single run of 50 simulations with 4 competing companies. In verifying these RFQ's hundreds of RFQ were generated and scrutinised. Some of these are shown in Appendix 3. In figure 7.3 the basic aspects that will influence the cost of quotes are listed, together with the simulated project value. Also shown are the material that the product must be made from and the sector that sent the RFQ. As previously explained, the project cost will be impacted by materials, quality aspects, complexity and volume of work. These are considered the drivers of the cost simulation.

In figure 7.4 the RFQ material volumes are shown for a set of 50 simulations of 48 months. This gives a graph that allows us to judge if such volumes are reasonable for the type of work we expect in micro milling. Typical parts are medical implants, dental implants, some automotive parts, research items, micro moulds and similar. The sizes are reasonable for the markets that was simulated, and fit into the size parameters of a micro milling machine. The volumes are used to calculate a material cost for the part.

Manufacturing sector Dental

Project 1 Value R: 13725

Material volume/item 42.4868 and number to manufacture 1

Material Aluminium

Material Price R 197

Quality 0.5

Product Complexity 0.6164

Milling volume 15.8511

Manufacturing Complexity 0.6365

Figure 7.3: Preliminary simulation results for validating RFQ qualitative and quantitative aspects

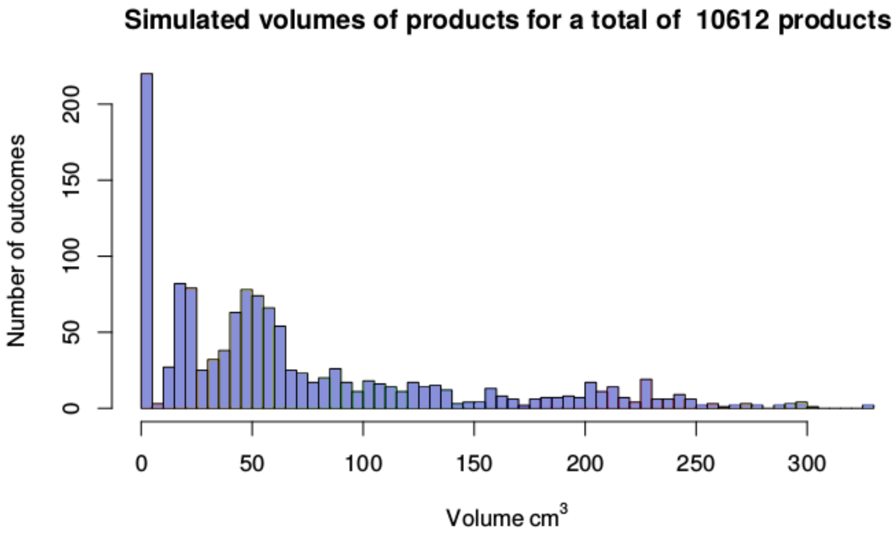


Figure 7.4: Preliminary simulation results for validating RFQ volumes

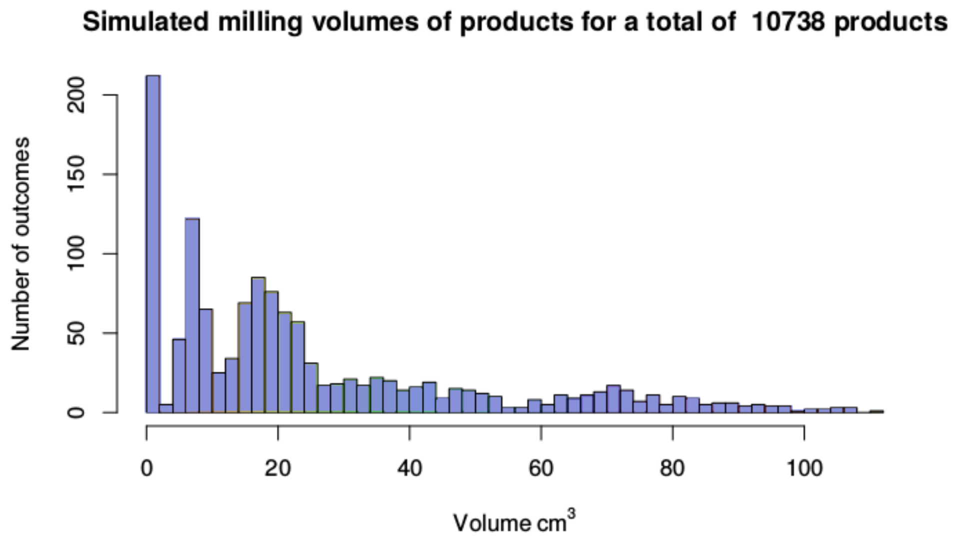


Figure 7.5: Preliminary simulation results for validating RFQ milling volumes

In figure 7.5 the volume of material removed during the milling process is shown for a set of 50 simulations of 48 months. This once again gives us the opportunity to judge if such volumes are reasonable for the type of work we expect in micro milling. As may be observed these volumes are logically smaller than the total volume of material in the products shown in 7.4. The volume of material removed is used together with the quality specification, complexity and tool size requirements to estimate a reasonable milling time and cost.

From the above discussion it is reasonable to consider that the RFQ's are consistent with the products that are expected in the micro milling market. Validation of the company reputation simulation will be adressed next.

7.6 Validation of tender awarding aspects and reputation in the simulation model

The model was designed in such a way that tenders are awarded according to probabilities that relate to the price quoted, the company reputation and how busy they are. These aspects impact highly on the tender award decision as seen in previous Chapters.

Company reputations will grow whenever they successfully deliver a project to a client, meaning it is both on time and according to specification. In figure 7.6 this growth in reputation of manufacturing companies is visible for client 2. Manufacturing company 2 has a sudden loss of reputation in month 24. The incident relates to the non-delivery of some project to client 2 during that month.

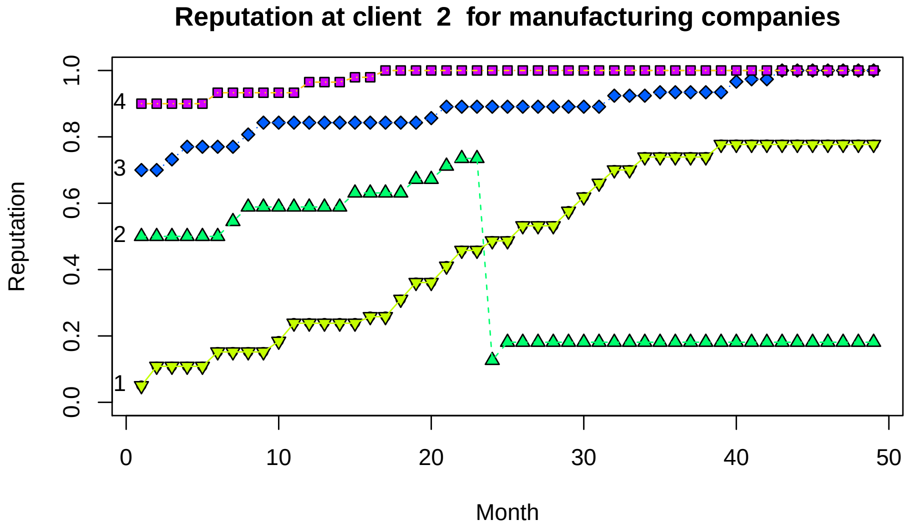


Figure 7.6: Preliminary simulation results for tender awards, completion and reputation aspects

These non-deliveries are random occurrences in the model, according to the analogies of real life failures to deliver. Also visible on the graph are which companies from 1 - 4 delivered on contracts with client 2 in what month, since their reputations will grow during those months.

From the values shown in this graph and others in Appendix 3 it is reasonable to conclude that the model is simulating these aspects correctly. Since company 1 is meant to represent a new entrant into the market, it may be reasoned that the starting reputation of 0.05 as is seen is realistic. The other competing companies are assumed to have built up their reputations previous to the start of the simulation. For future runs, it is suggested to give company 1 a low starting reputation, and at least some of the established companies a fairly high reputation as would be expected.

Starting from a zero beginning, over time the cash balance of companies are expected to grow as they complete contracts.

When running several simulations with the same starting conditions, it is expected that some results will be better than others. Each manufacturing company has a simulated cash flow and subsequent cash balance and for manufacturing company 3 that may be seen in figure 7.7.

The break even cash balance is the amount that the company invested in creating its capacity for micro milling. For this simulation and company 3, the amount is R800 000. Figure 7.7 shows the un-discounted cash balance, which does not consider the time value of money, interest rates, or minimum required

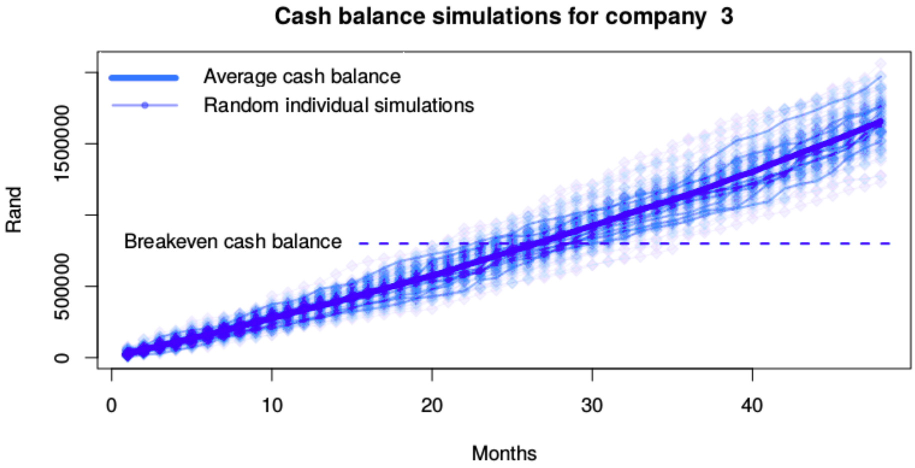


Figure 7.7: Preliminary simulation results for un-discounted cash balance for company 3

rates of return on the company's investment. A more realistic view of the cash balance is discussed below. More cash balances may be seen for other companies and simulations in Appendix 3.

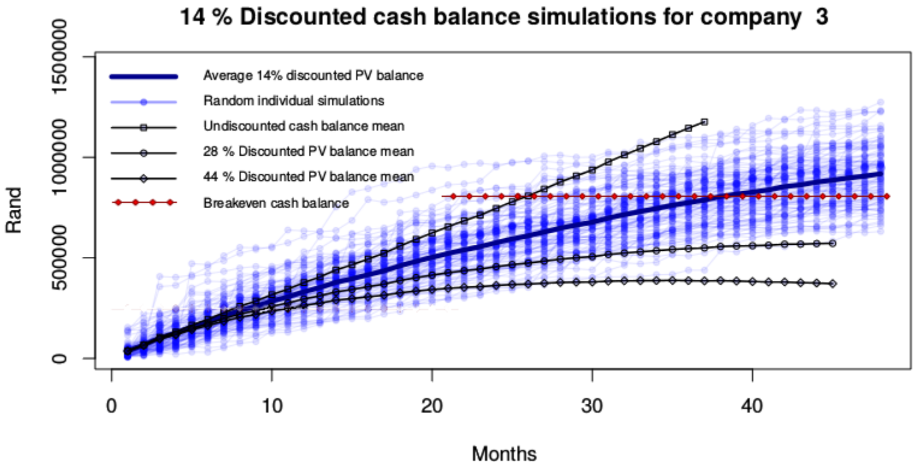


Figure 7.8: Preliminary simulation results for 14% discounted cash balance for company 3

In figure 7.8 the cash balances of company 3, that were discounted with 14% per year, takes the centre stage with various other mean values plotted for reference. The original un-discounted mean cash balance of figure 7.7 is now shown as the upper dotted line that crosses the break even line at about 27 months and labelled as such. The 50 simulated values per month are also discounted and are shown as blue diamonds with a fairly transparent colour. The transparency allows us to see where a greater density of values lie on the graph and gives a visual indication of the most expected values. Obviously these most expected values are close to the mean that is shown by the solid thick blue curve. The curve shows the mean cash balance values discounted to present values at 14% per year and crosses the break even line at month 37. Also observe that the break even month may be anywhere from month 24 to longer than month 48 for different simulations if we use 14% as the discount rate. We may also observe that at a higher minimum required rate of return on the company's investment such as 28% or 44%, the company will barely break even or not at all. This is shown by the curved dotted lines at 28.3% and 44.2% that runs below the break even cash balance. Discounted values are understood to have a decreasing slope and curve when given straight line inputs, by considering the decreasing value of money over time. From observing the way the various curves are positioned relative to each other, it is clear that the results are consistent with the time value of money theories. It is also clear that realistic choices for a company regarding what return is expected from investment in micro milling technology is critical to understanding their risk.

From the above discussion it is reasonable to accept that time value of money aspects are consistent with the theory.

7.7 Validation of utilisation of company assets in the simulation model

In the current structure of the model it is assumed that projects are awarded, completed and payment received in the same month. It is possible to model the simulation differently with queuing theory, but it was considered that the current logic gives a good enough representation of reality with a month resolution. Every company has a capacity that allows them to do a certain number of hours work per month. Once the maximum number of hours are used, their utilisation is pushed past 100% and they cannot be awarded new contracts. Depending on the size of hours of the last contract awarded to them, the utilisation sometimes goes over 100%, meaning overtime will be incurred. The profit for the month will be higher during months where the utilisation is high, so it is possible to verify this by looking at the two graphs side-by-side. In figures 7.9 and 7.10 the similarity is obvious, where for instance both the graphs for company 3 shows high values during months 19, 35 and 36.

It is also clear that there is an upper limit to the utilisation due to the fact that companies do not quote when they are already too busy.

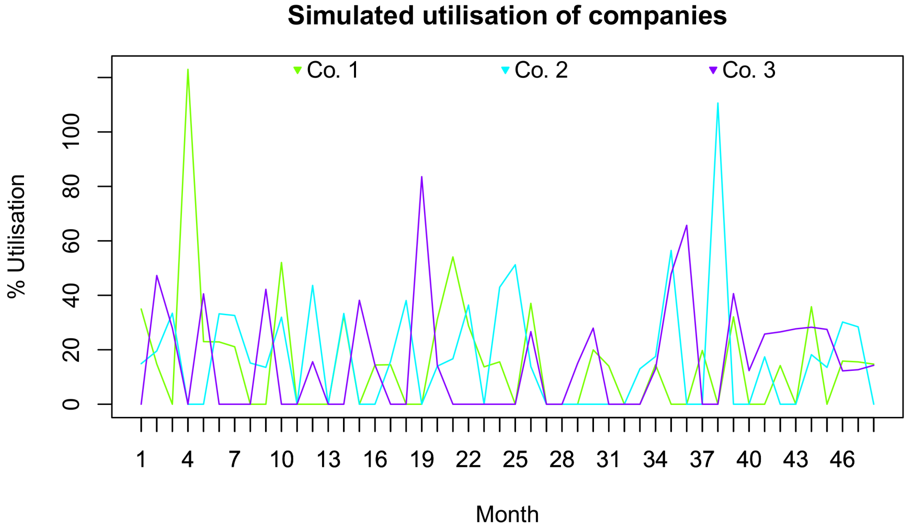


Figure 7.9: Preliminary simulation results for utilisation of 3 companies

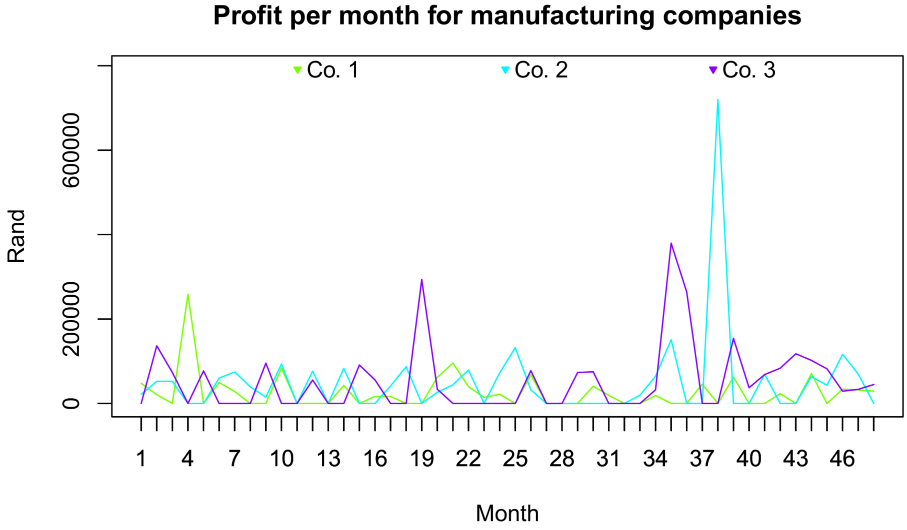


Figure 7.10: Preliminary simulation results for profit of 3 companies

Another aspect that may be verified on these graphs is that the capacity of companies are the link between the utilisation and their profit potential. For the preliminary simulation the capacity of companies 1 to 3 were set to 1, 1.2 and 2. This means that company 3 had twice the capacity of company 1. A capacity of 1 represents 186 hours per month and assumes about 18 days of holiday per year on average. As may be observed company 3 has a lot more profit than company 1 for the same utilisation, showing that link between capacity and potential for profit. The increasing trend of all three companies' income is due to a parameter that specifies the growth in the market, for this simulation it was set to 19.5% per year.

Observing the similarities as was expected is accepted that the utilisation, capacities and profits are linked correctly in the model.

7.8 Validation of income from contracts in the simulation model

The simulated outcomes for the un-discounted cash balance after month 36 in figure 7.11 may be compared to the values in 7.7. It is clear that they represent the same amounts, though the histogram presents the information in more detail. It is also possible for the company to list various probabilities such as the ones shown; that in 22% of the simulations the cash balance will be larger than R1227 559. These values may be specified as the user requires. More such graphs after 12 and 36 months are available in Appendix 3 for interest. Another point of interest is shown in figure 7.12 that compares three companies' cash balances over 48 months. The effect of higher capacity is clear, since the higher capacity allows company 3 to take on more work. Considering the above discussion, the income distribution between companies seems logical and as expected from the model.

7.9 Validation of profitability in the simulation model

Profitability measures such as ROI and NPV may be used to express a company's profitability. In the preliminary simulation NPV is shown in the discounted cash balances, minus the capital outlay or break even cash balance. Therefore, by looking at figure 7.8 we may estimate the NPV of company 3 of the project over 48 months. The simulated end cash balance at 14% discount is between R700 000 and R1200 000, while the capital outlay is about R800 000. By subtracting

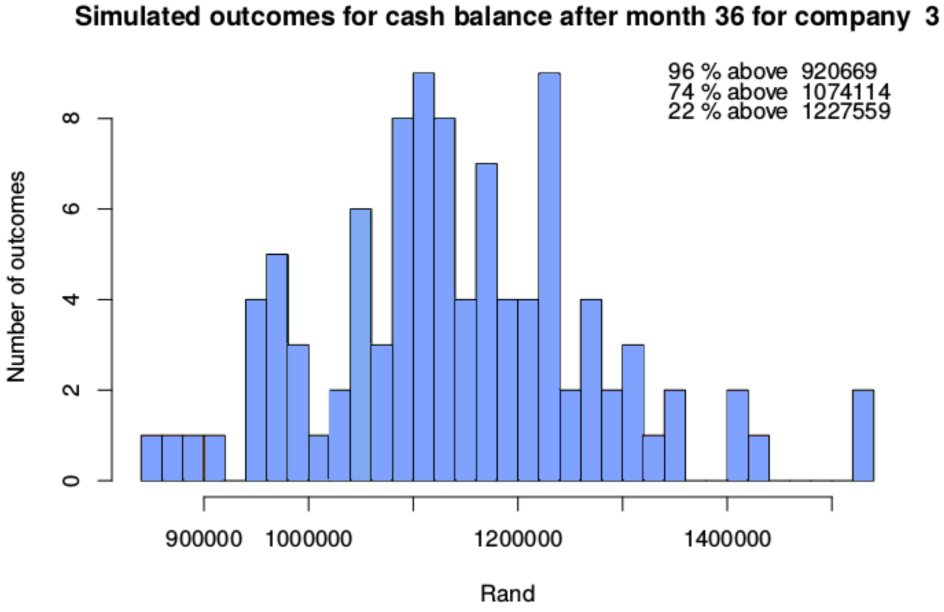


Figure 7.11: Preliminary simulation results for validating the cash balances after month 36 for company 3

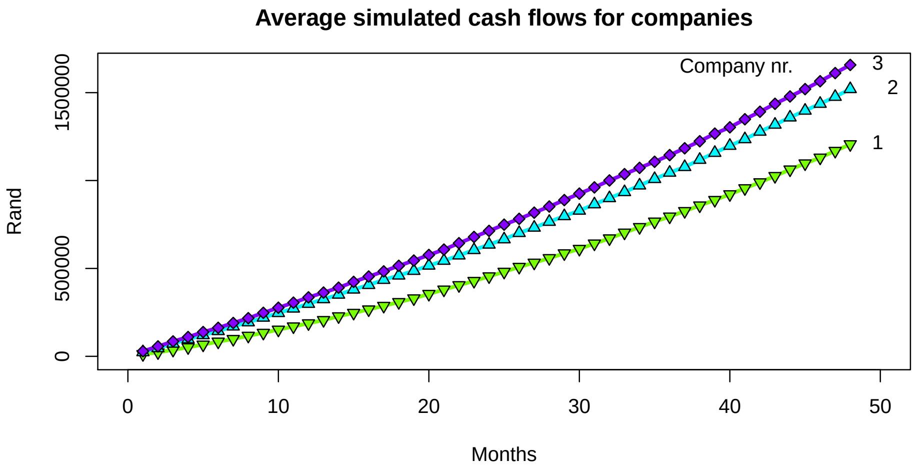


Figure 7.12: Preliminary simulation results for comparing companies' cash balances

the R800 000 from the end cash balance values we may see the NPV is between R100 000 and R400 000. Another graph showing the same information is figure 7.13 that compares 6 companies. Here the return is shown comparing the six companies using ROI. The company with the highest profit does not always have the highest ROI due to the difference in capital outlay. This graph is more effective in conveying the required information when a large number of manufacturing companies must be compared. In some of the other line graphs such as figure 7.10, comparisons become too difficult due to overcrowding the graphs with multiple values. Alternatively, such as for figure 7.12 some information must be sacrificed to simplify what can be clearly displayed.

Considering all these aspects, it is considered to be as expected and the model seems to be giving reasonable and logical outputs, and is valid for the assumptions made.

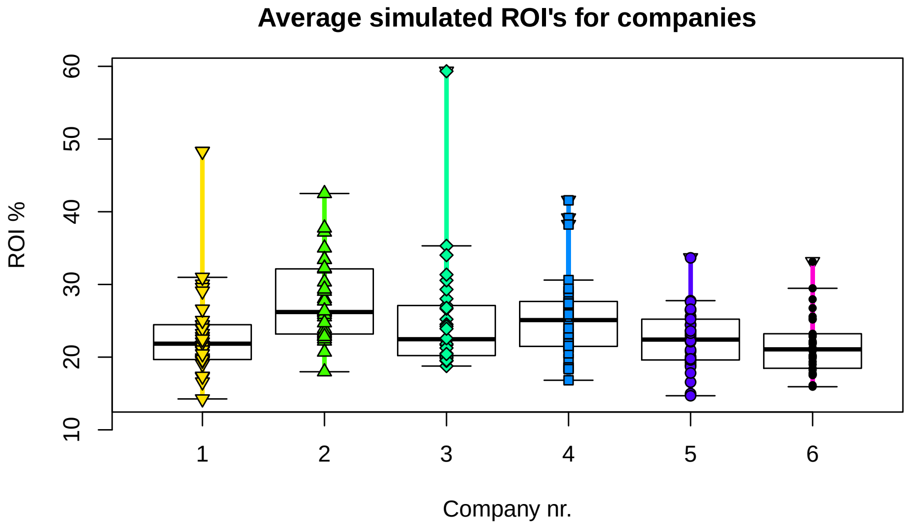


Figure 7.13: Preliminary simulation results for validating ROI for six companies

7.10 Changes made to the simulation model

The major limitation identified in the model up to this point was that it did not make provision for batch products and learning curves. A learning curve allows the company to produce products cheaper when they manufacture multiple identical products. An example of various learning curves are shown in figure 7.14.

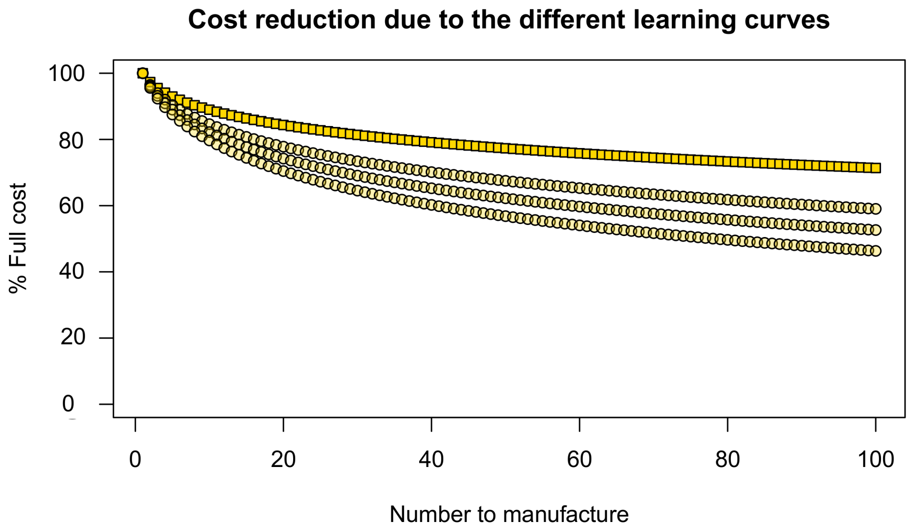


Figure 7.14: Improved simulation resulted from implementing learning curves such as shown

Also, the parameters set for reputation for a company just starting with the technology was probably set too high, while the established companies had too low reputations. These two aspects were added and the following simulation runs showed a more realistic picture.

In figure 7.15 and 7.16 the new project RFQ's now include the number of items or products to manufacture, and multiple items will be cheaper due to the learning curve effect, as well as costs that are not duplicated for multiple products. These non-duplicated costs include designer costs and 75% of management cost. As may be observed, the two projects are fairly similar due to the major drivers of cost. There is only about $R400$ difference in material cost and the milling volume is about 20% higher for the single item. The second project however has multiple items to be manufactured and a significantly lower cost per item is expected due to non-duplicated costs and the effect of the learning curve. The cost per item can be calculated by dividing the total cost of the project by the number of products i.e. $R224\ 954/12 = R18\ 746$ per product. This compares favourably with the high cost of the single item at $R38\ 893$.

The parameter changes in the initial reputation also influenced the awarding of contracts, so that it became more difficult for a new start-up to break even, as is expected. This may be observed in the lower ROI and longer time to break even.

Manufacturing sector Dental

Project 1 Value R: 38893

Material volume/item 56.9565 and number to manufacture 1

Material Steel stainless

Material Price R 1642

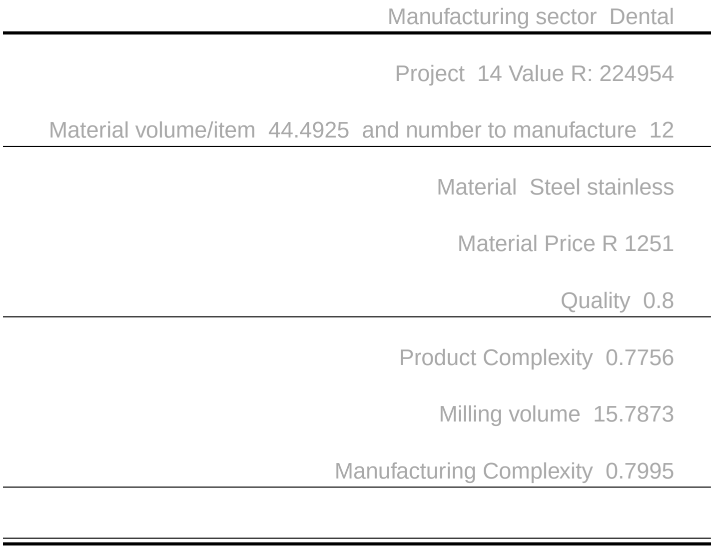
Quality 0.95

Product Complexity 0.78

Milling volume 20.2328

Manufacturing Complexity 0.8008

Figure 7.15: Improved simulation validating RFQ with batch size of 1



Manufacturing sector Dental

Project 14 Value R: 224954

Material volume/item 44.4925 and number to manufacture 12

Material Steel stainless

Material Price R 1251

Quality 0.8

Product Complexity 0.7756

Milling volume 15.7873

Manufacturing Complexity 0.7995

Figure 7.16: Improved simulation validating RFQ with batch size of 12

7.11 Conclusion

From the above discussions it is now accepted that the simulation model is valid, reasonable and consistent with the products that are expected in the micro milling market. As shown, some aspects of the model were validated from previous research, and were consistent with case studies, experimental results or data from literature. Histograms were used to check the output of probability density or mass functions versus what were expected with a good agreement. After validating all of the previous aspects, the analyst and stakeholders are reasonably in agreement that the results are consistent with how they perceive the system should operate; thus the simulation model may be said to have face validity. Since the simulation model is verified to give reasonable results, various scenarios are explored in the following Chapter.

Chapter 8

Simulation results, scenarios and discussion

8.1 Introduction

Scenarios may be set up in the simulation model to answer specific questions. There are also some additional scenarios or instantiation that are interesting to explore to determine the model's capabilities and limitations. Evaluating the outputs from various scenarios sheds light on the simulation's fitness, validity and verification for the intended use.

The following questions may be answered directly from simulations if the correct scenario is set up in the simulation:

1. How many companies may survive for a given market size?
2. How does reputation influence the sales volumes?
3. How do random or unknown aspects of cost and sales influence cash flow?
4. How do random or unknown aspects of cost and sales influence cash balance and break even?
5. How do random or unknown aspects of cost and sales influence profit?

The first question may be answered by creating a scenario where the market size is fixed. The simulation model is then run repeatedly with a different numbers of competitors and the results evaluated for ROI and discounted cash balance. NPV may be read from the discounted cash balances minus capital outlay as explained in section 7.9. This aspect is simulated during scenario 1 in section 8.2.

The question regarding reputation or brand name is tested in scenario 4 in section 8.5.

Random or unknown aspects are shown to influence the cash balance outcomes, ROI, sales and reputations as was already observed in almost all previous and also following graphs showing the simulations. The same may be said for break even, that are discussed in almost every scenario below. So these questions may be answered by creating various detailed scenarios, running the simulations and then analysing the results.

There are various scenarios that might be of interest to a researcher or to a company who is interested in starting up a new venture. The interesting parameters that might be adjusted include the number of competing companies in the market, the market size, the sectors to include in the simulation, interest rates or discount rates and more. Scenarios that are used below to explain the workings of the model are not meant to represent a particular reality in the South African market, but are meant to illustrate the flexibility of the model.

The following simulation scenarios were run to determine the effects of these parameter changes.

8.2 Change in number of competing companies: Scenario 1

When a company becomes interested in entering the market, one of the first things they will do is to determine how many competitors there are active in the market, what their capacities are and how they are rated in the market. These aspects may then be set in the simulation to account for the specific scenario. Assume we have a marketplace where there are two, three or four current manufacturing companies in the market, serving only the medical implants sector. The parameters in the simulation may then be set so that only RFQ's for that sector is generated. The new company joins the marketplace as company no 1 in the simulation.

Some of the results that allows comparisons to be made can be seen in figures 8.1, 8.2 and 8.3. The start-up company struggles more to break even, when there are larger numbers of competing companies. With three competing companies, the new entrant will break even at best after 15 and at worst about 48 months. The 14% discounted PV average crosses the break even cash at month 26. When there are four competing companies, the new entrant only breaks even six months later at the earliest, and might take more than 48 months in the worst case. With five competing companies the break even does not happen in the first 40 months for 50% of the cases as shown in figure 8.3.

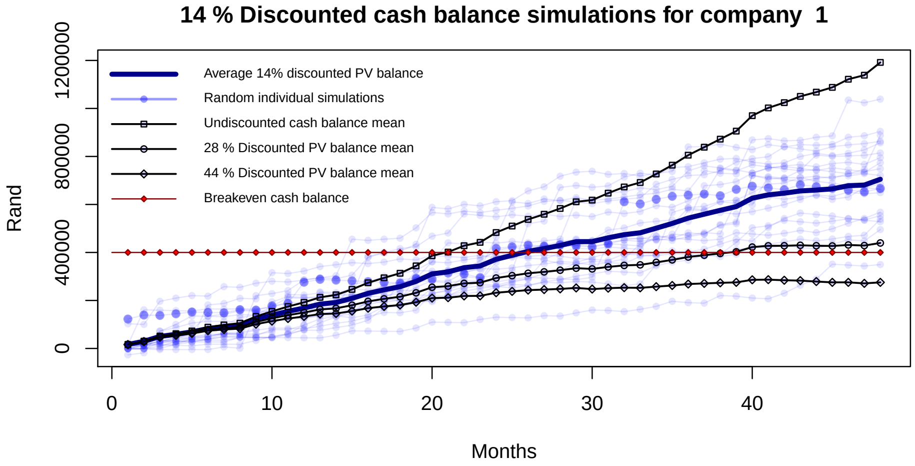


Figure 8.1: Scenario 1 simulation results with three competing companies who contest the medical implant market

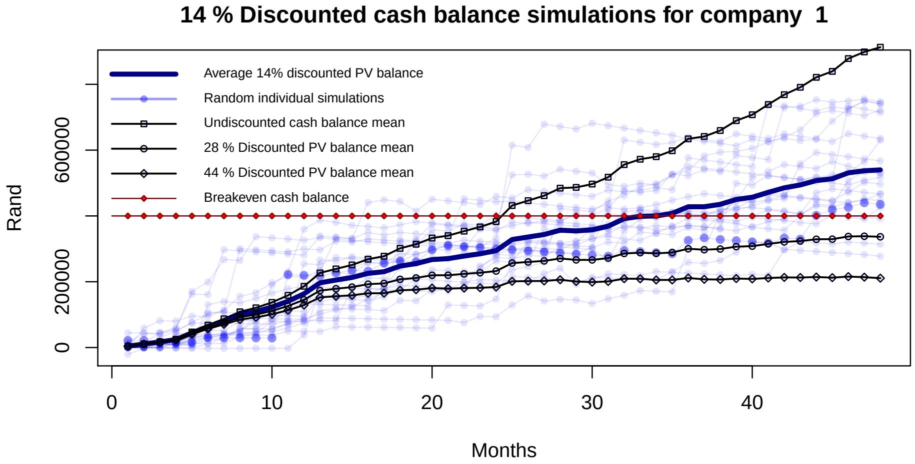


Figure 8.2: Scenario 1 simulation results with four competing companies who contest the medical implant market

The ROI also drops across the board as seen in figures 8.4 and 8.5, showing that the increased competition is affecting everyone. This suggests that the market as specified is too small for five companies and more suited to three companies. If the new entrant in the market finds that there is already four other competing companies, they will realise that the market is over saturated and not invest in such a risky sector. They might then decide to develop an alternative sector such as dental implants to leverage their entry into the market.

With this in mind, if there was this alternative scenario where there was only one competitor in the dental market, then the risk to enter the market is much

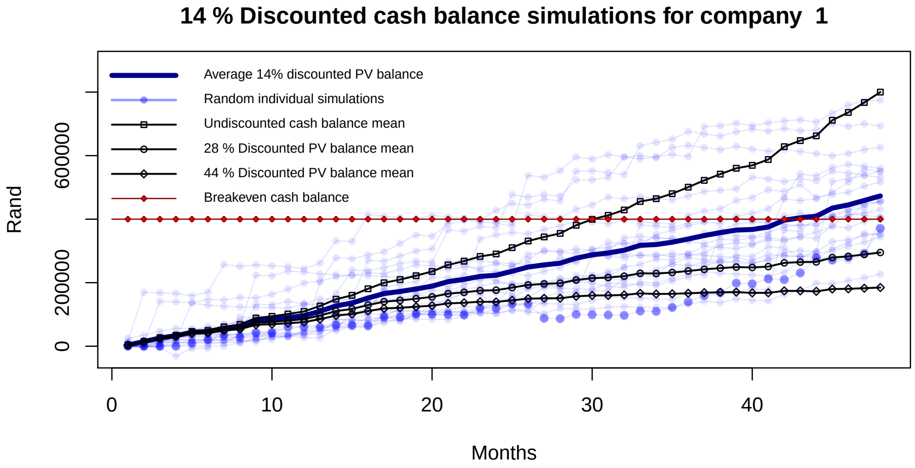


Figure 8.3: Scenario 1 simulation results with five competing companies who contest the medical implant market

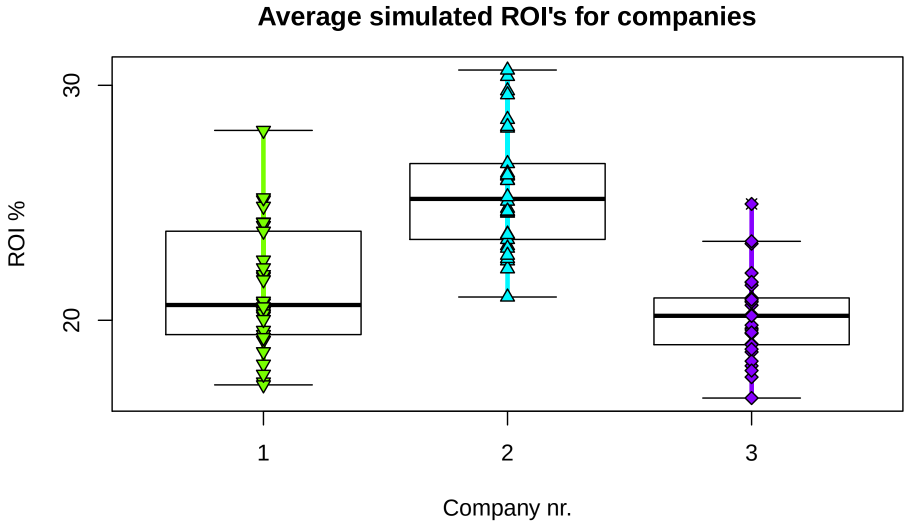


Figure 8.4: Scenario 1 simulation ROI with three competing companies who contest the medical implant market

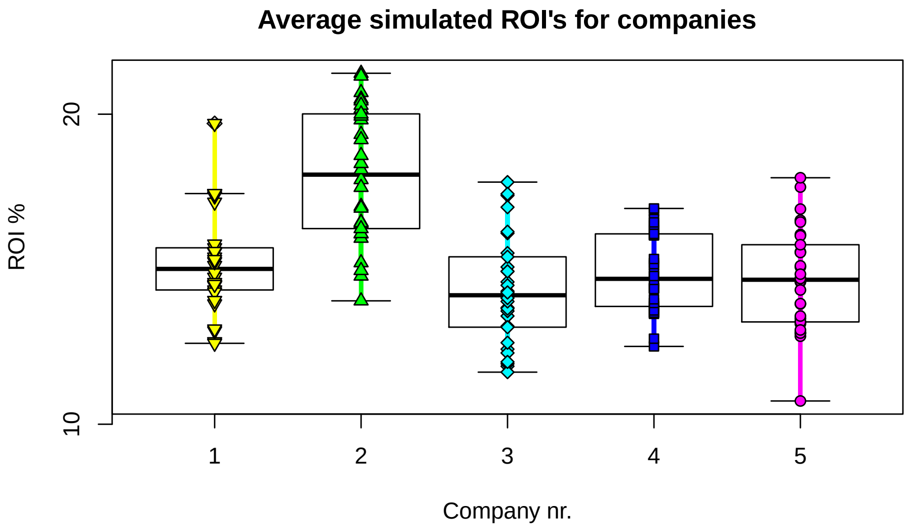


Figure 8.5: Scenario 1 simulation ROI with five competing companies who contest the medical implant market

lower in that sector. In figures 8.6 and 8.7 this is shown to be a more lucrative market to develop due to the limited competition in the market in this scenario. The break even is expected to be within five to twenty months in this scenario. However, from a utilisation view as shown in figure 8.8, the company staff is seen to be very busy and might burn out if they keep to this pace.

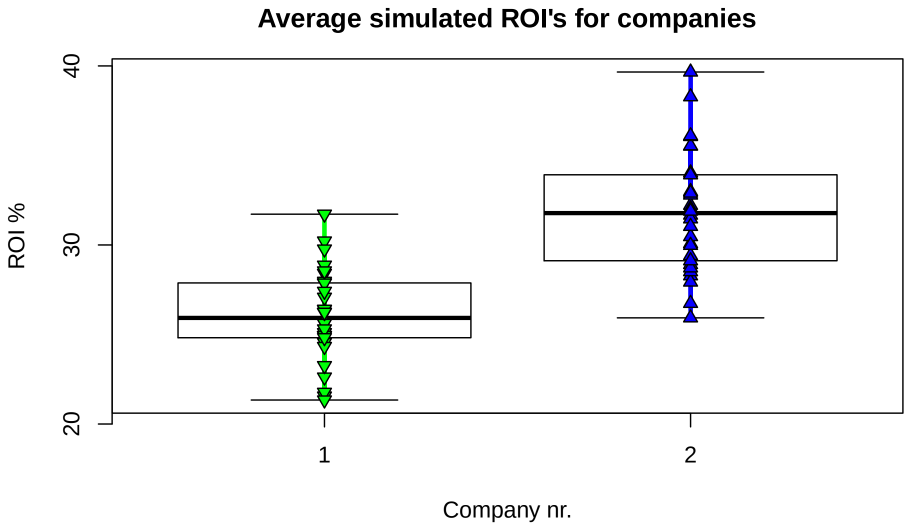


Figure 8.6: Scenario 1 simulation ROI with two competing companies who contest the dental implant market

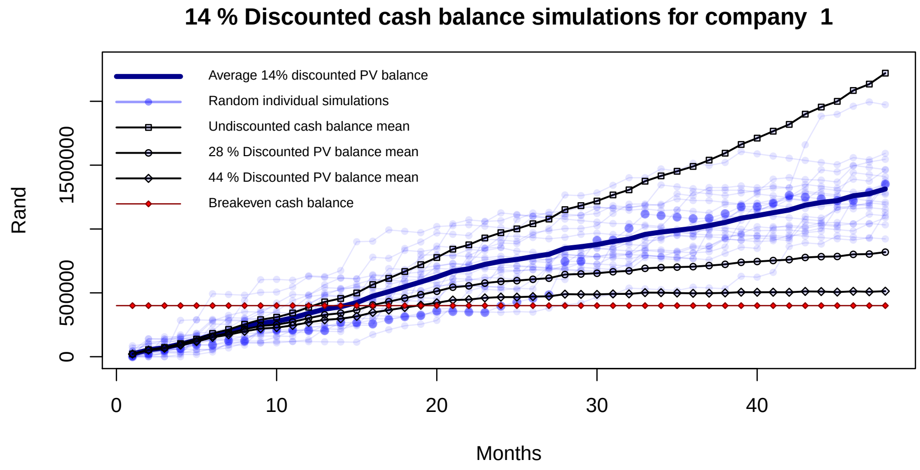

14 % Discounted cash balance simulations for company 1

Figure 8.7: Scenario 1 simulation cash balance of the new company, and one other competing company who contest the dental implant market

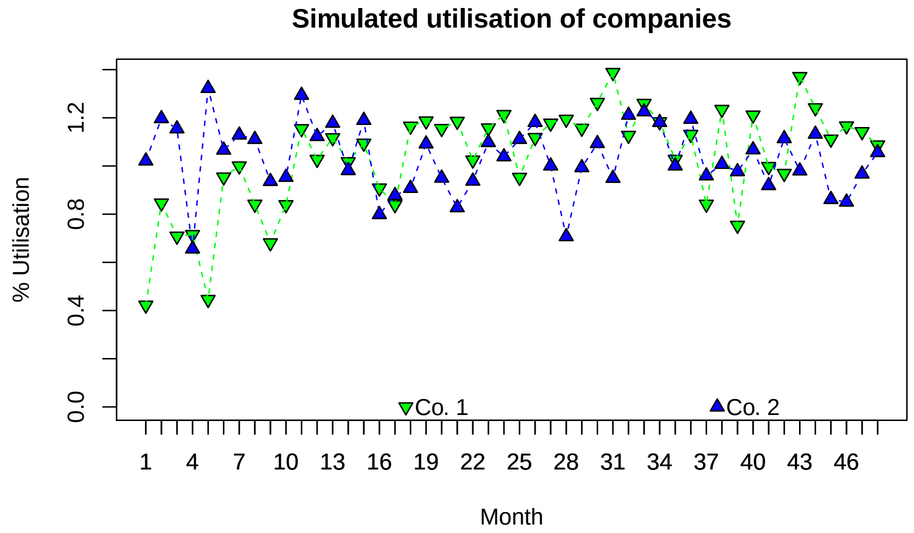

Simulated utilisation of companies

Figure 8.8: Scenario 1 simulation cash balance of the new company, and one other competing company who contest the dental implant market

8.3 Changes in the market size or sectors to include: Scenario 2

The following scenario will expand the client market from 4 clients in two sectors to 14 clients in seven sectors, namely automotive, dental, implants, research, tooling, energy and bio-technology. The size of the market will determine how many companies can be accommodated profitably. By varying the market size, the researcher or company may determine the risk to enter the market at a specific market size. This is illustrated in figures 8.9 and 8.11 where the current companies 5 and 6 struggle more to achieve higher ROI's, when the market is too small to sustain all the companies. In figure 8.11 it is observed that it may take more than 48 months to break even, or that the company may not break even at all in some simulations. Company five is shown to break even much earlier when the market requests from fourteen clients are received, shown in figure 8.12. The simulation shows that all the companies now perform better as well. This means that when a new entrant enters a small market, a random company will fail first if this is their only income. Else the larger companies might survive due to their ability to channel other profits from operations to the loss-making micro milling unit until another company quits the market. At this time the simulation does not stop when a company is making a loss, but this could be modelled in a future expansion. There is no easy way to predict which company will fail first, since the simulated companies may fail in one simulation and survive in the next. The number of sectors that a company may manufacture for, can be changed in the model as was shown. In reality, every sector might have different requirements and a company will have to increase their skills to accommodate new sectors. Regardless, the effect of penetrating an additional market on your income potential is clear when these parameters are changed to include or exclude markets. It has a similar effect to just changing the market size inside a sector. Figures 8.9, 8.10, 8.11 and 8.12 shows the effect of before and after including five additional market sectors with two clients each for the same parameters. It may be observed that break even happens earlier and ROI is higher with the addition of extra markets. Companies who start out will be well advised to penetrate as many markets as possible. For this purpose both marketing and gaining skills and acceptance in the sector are considered vital.

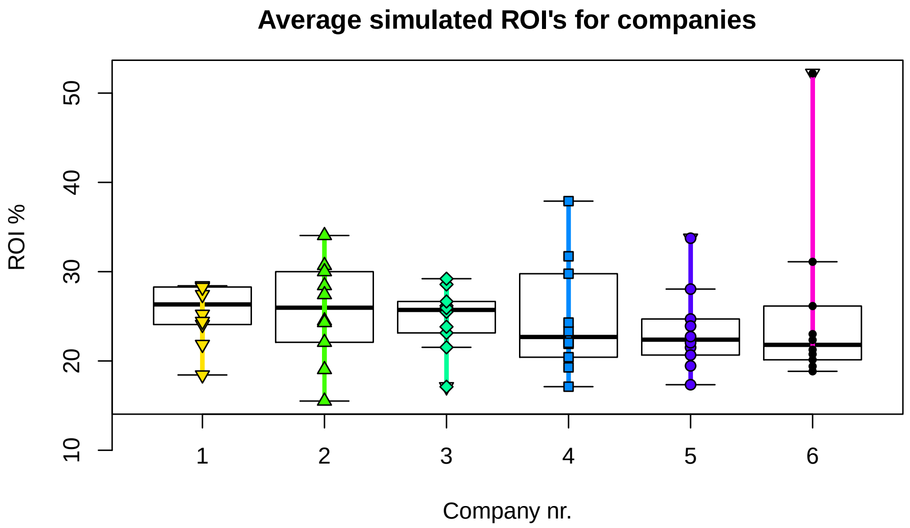


Figure 8.9: Scenario 2 contesting four clients' markets: ROI of six competing companies

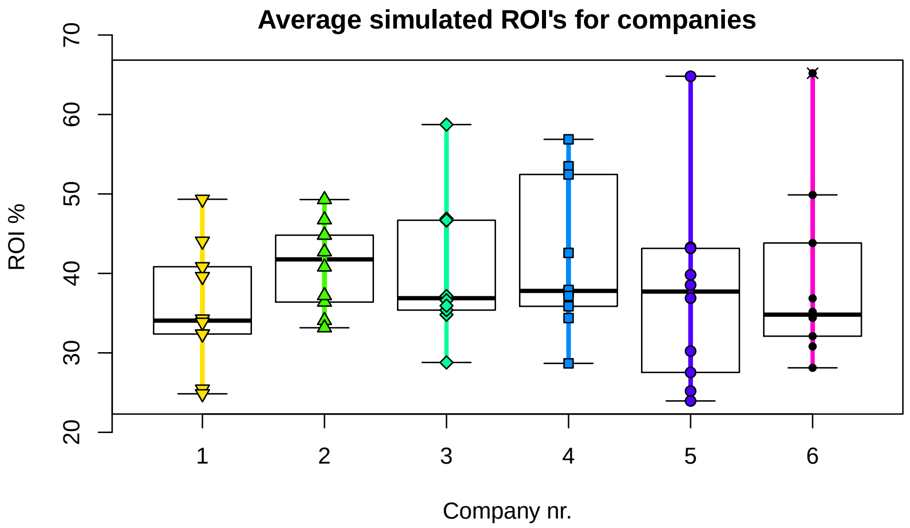


Figure 8.10: Scenario 2 contesting fourteen clients' markets: ROI of six competing companies

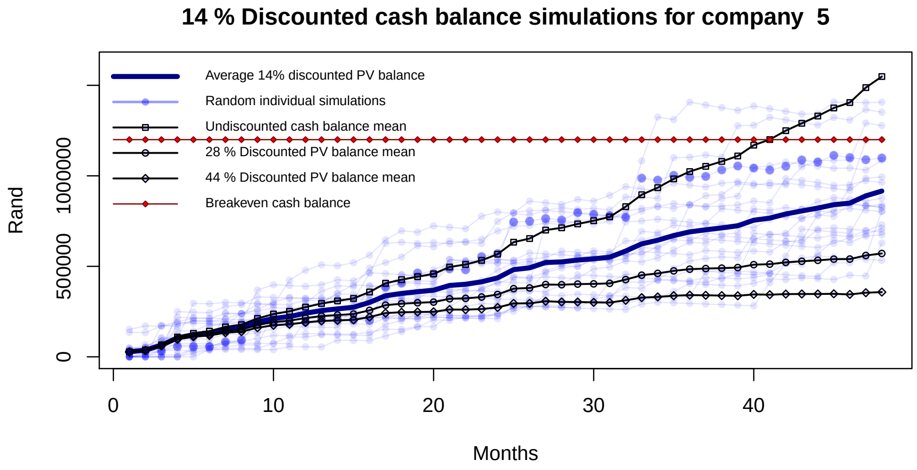


Figure 8.11: Scenario 2 simulated discounted cash balance for company 5, competing with five other companies who contest four clients' markets

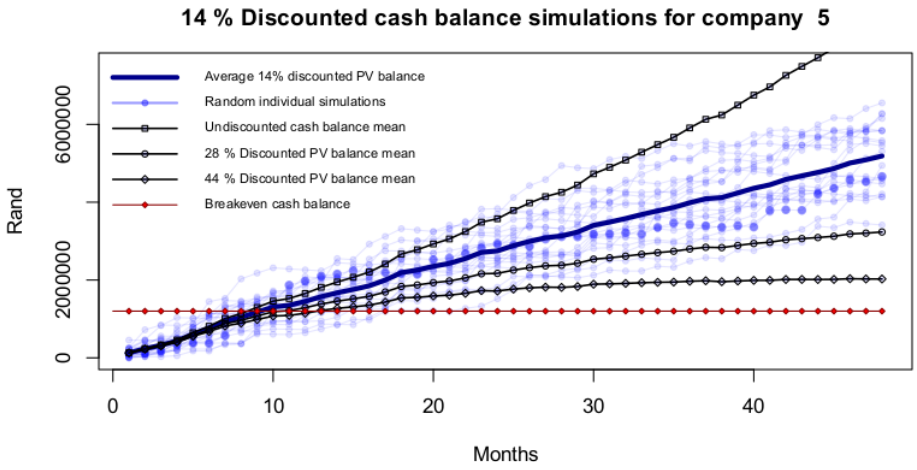


Figure 8.12: Scenario 2 simulated discounted cash balance for company 5, competing with five other companies who contest fourteen clients' markets

8.4 Changes to growth rates or discount rates: Scenario 3

When companies make decisions to invest, interest rates are central to the process. Most companies have multiple investment opportunities, each with a risk profile and different returns that are expected. While comparing these opportunities companies must have some minimum acceptable rate of return or hurdle rate to compare the opportunities to. In general, the minimum required rate of return must be at least higher than inflation, savings rates and other low-risk investments that the company may have access to. Typically, companies will use the inflation rate plus a rate of between 10% and 50% due to project risk. To show the effect of using these different required rates, the cash balance may be discounted to a present value using the different rates.

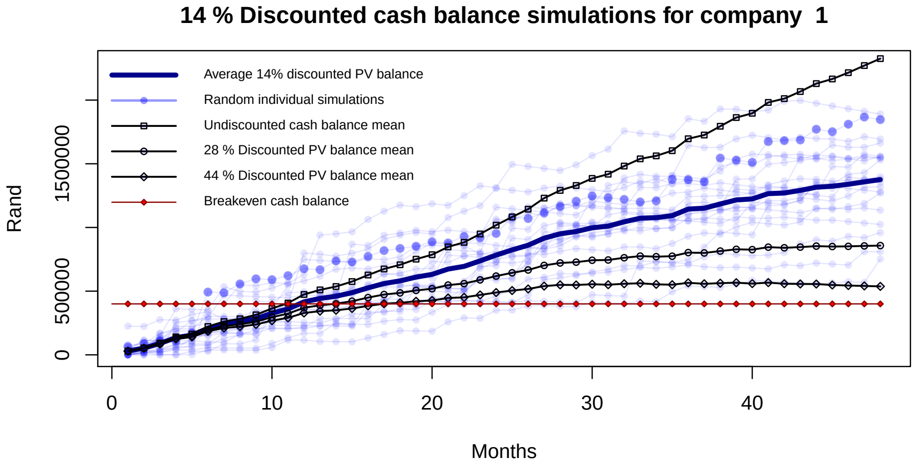


Figure 8.13: Scenario 3 simulated discounted cash balance for company 1 at 14%

This is demonstrated in the individual company's discounted cash balance graph as shown in figures 8.13. This graph deserves more discussion. It may be observed that there are various distinct data groups represented on the same graph. The major simulation data shows a thick dark blue curve due to the time value of money. The curve is labelled "Average 14% Discounted PV balance". It shows a line that connects the average values of all the simulations for the case. The actual simulated values are shown as transparent blue dots, that stack up to display darker areas that represent higher densities or probabilities. The thin blue lines are as labelled "random individual simulations". There is also a line showing the average cash, labelled un-discounted cash balance mean. This is the actual origin of the rest of the values and were calculated as the income minus the expenses for the month, and accumulated from month one to 48. At about R400 000 there is a thin line horizontal line with red dots than represents the capital or investment in micro milling, labelled "Break even cash balance". When a simulation line intersects the break even cash balance the company was able to recoup its capital or investment. However, due to companies having each their own minimum rate of return required, different discount rates may be applied to the cash flow to determine if and when they will break even. In the current example shown in figure 8.13 it is clear that break even is achieved even if the company discounts the values using a high rate of 44.2%. This is an ideal scenario and far from common. Various other scenarios shown such as in figures 8.11, 8.2 and 8.3 showed that for many combinations of discount rates there is no expected break even.

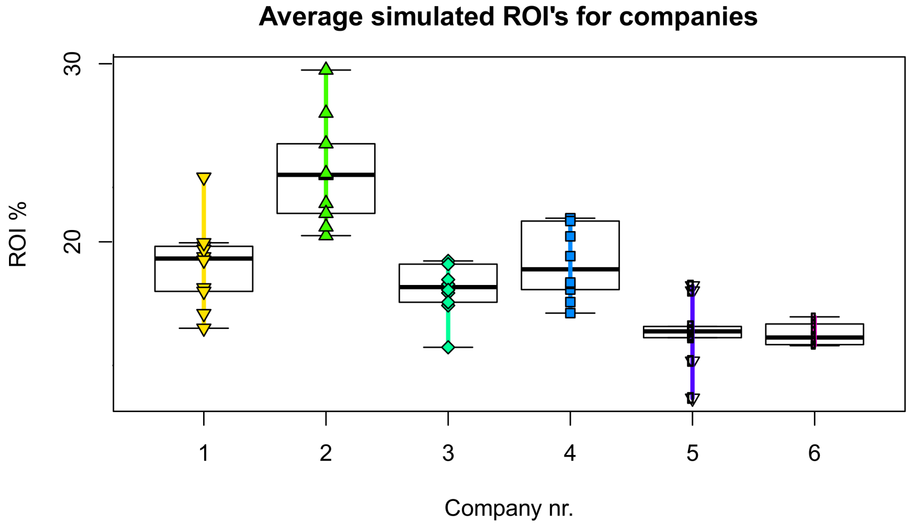


Figure 8.14: Scenario 3 no-growth market: simulated ROI for company 1 with six competing companies

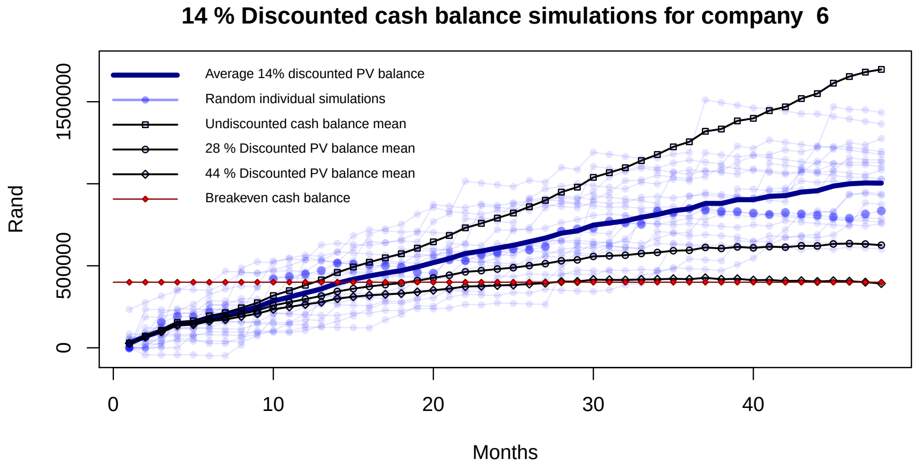


Figure 8.15: Scenario 3 no-growth market: discounted cash balance for company 6, with six competing companies

Previously in section 1.1 a typical technology life cycle is shown. Similar to this, market demands for technologies will grow during the acceptance stage and manufacturing companies may leverage this to their advantage. If a company realises that certain market sectors are in a high growth phase, then investing in the technology becomes less risky. In simulation scenarios with a low growth may be compared with a high growth scenario while keeping other parameters constant. The no growth scenario is shown in figures 8.14 and 8.15.

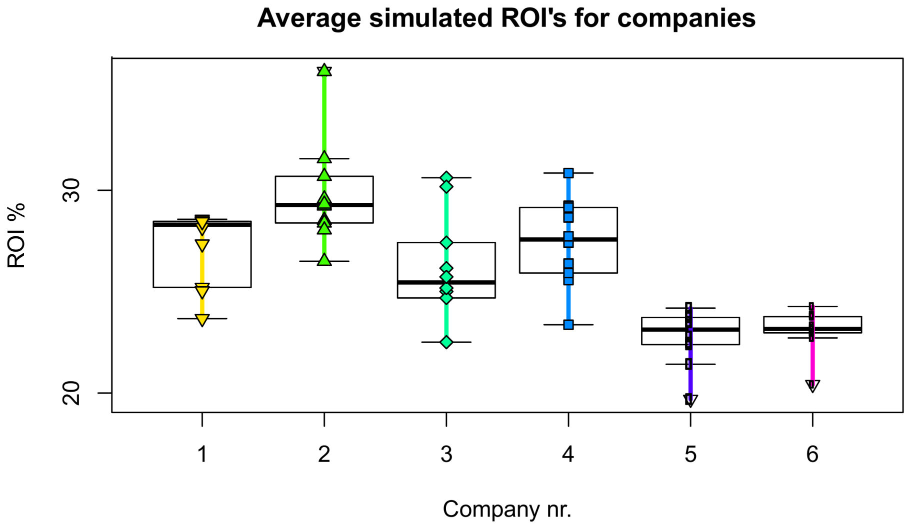


Figure 8.16: Scenario 3 high-growth market: simulated ROI for company 1 with six competing companies

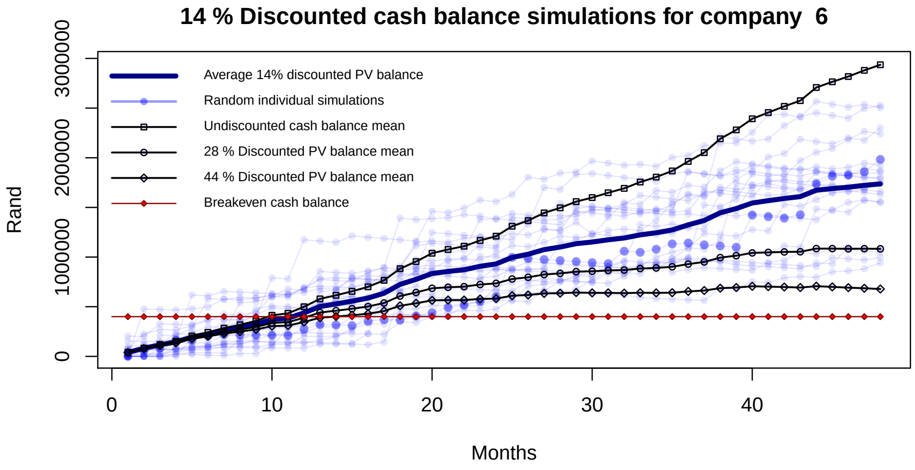


Figure 8.17: Scenario 3 high-growth market: discounted cash balance for company 6, with six competing companies

Comparing the no-growth results to the high-growth figures 8.16 and 8.17 it may be seen that the high growth scenario will reduce the risks that the company faces. Even though both payback periods seem similar from a cursory inspection, for higher discount rates the difference become clear. For instance, the high growth option easily breaks even with a 44% discount, while the no-growth scenario does not. ROI looks to be about 5% to 10% higher for the high growth option. For that reason finding markets with high growth forecasts are vital to the potential investor.

8.5 Changes in the reputation of companies: Scenario 4

Changes in a company's reputation are linked to previous successful work performed, company skill level, managerial aspects, marketing and non-delivery of work. These non-delivery events occur randomly in the model, but with probabilities linked to the difficulty level of the contract, the current company utilisation, skill level and reputation. Marketing strategy was not addressed in the model and is assumed to be similar for all competing companies. It is seen that the simulation is able to accurately model the growth of reputation as well as the loss of reputation if there is a non-delivery. Figure 8.18 shows how reputations grow when projects are successfully delivered and how a company may fall from grace due to non-deliveries. If it was assumed very difficult to change the reputation of companies in the marketplace, then companies who start late will struggle to catch up in the market. It is sometimes found that some markets are very resistant to change, such as the medical markets. The figure 8.19 shows how a consistently low reputation might make it difficult for a new entrant to such closed markets. When reputation is allowed to grow then the company will be awarded more contracts as shown in figure 8.20 and will face lower risks. The difference only becomes clearly visible during the later months, being a transient aspect. It may be observed in figure 8.20 after month 20 as a slight increase in the trend that curves the average line up as reputation improves. When the reputation stays the same, a slight downward trend may be present as per figure 8.19.

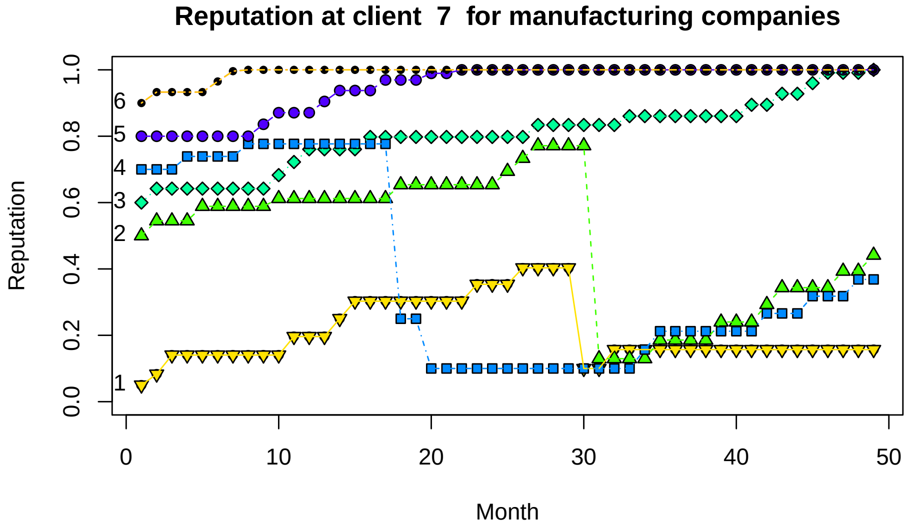


Figure 8.18: Simulation results of changing reputations of six competing companies

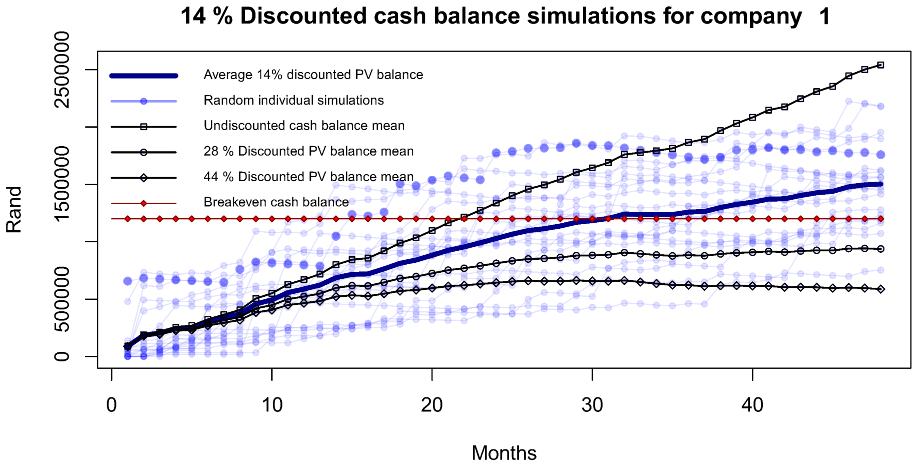


Figure 8.19: Scenario 4 with no change in reputation: simulated discounted cash flows of a new company

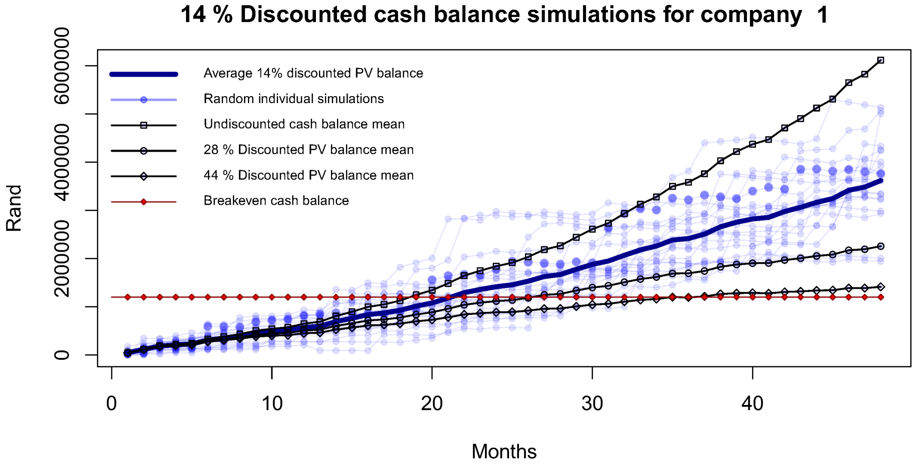


Figure 8.20: Scenario 4 with growth in reputation: simulated discounted cash flows of a new company

8.6 Conclusion

The various scenarios showed that the model may reasonably mimic reality. Calibrating such a model to work accurately for a specific region is considered possible with the assistance of interested stakeholders. The model as it stands is a working framework but could be extended for many man-years before it may be considered complete or commercial. However the model may be used with some confidence for comparative or consulting studies if the user is prepared to gather relevant market data, and gain an understanding of the capabilities and limitations of the model.

Chapter 9

Summary and discussion

9.1 Research overview

Businesses often have to decide on where to invest their money to get a good stable return at low risk. Currently, there are various methods to gather preliminary data of the current business model and new technology with as much detail as possible with the resources to their disposal. Basically, they use the high-level definition of a TEFS, "Researching and quantifying opportunities and potential benefits versus costs and risks of technology acquisition", to guide their efforts.

During this research the same guiding principles inherent in the TEFS were used to develop first a logical process description and then a simulation model of a business. The business invests in a new technology, within the larger environment of existing companies who compete for a limited market. In order to build a model of reality, it was required to understand the basic processes, simplify them to some extent and then make suitable representations of each aspect mathematically, statistically and logically. The TEFS model was given structure and described in detail. The model was programmed as computer code in the statistical package R, and the complete code for running the simulations are included in Appendix 1.

The R language has all the capabilities to construct distributions for bootstrapping or to use standard distributions from statistics to represent the data required for the model. The logic structures of the model are represented by loop structures, if and while statements and mathematics operators.

The author analysed the literature and the data to determine the flows of information, resources, money, time frames and where decisions are made. Using this information, the process logic, flows and mathematical representations of the system were sensibly combined as a simulation model. The simulation model contains logic to represent flows of money, information and resources over time.

The model may be described as a mixed model due to the large number of concepts utilised. The main architecture is a system dynamics model representing cause-and-effect relationships in terms of causal-loops, flows with levels, rates and equations. Random variates were used as stochastic variables and resulted in a self-driven simulation. Some equations in the model use linear and others non-linear forms to change variables and influence the system behaviour. Numerical models are used to solve for ROI by applying simple iteration. Rudimentary artificial intelligence (AI) controls some aspects that introduce some transient model behaviour and probability changes with respect to time.

The simulation model was run a large number of times to eliminate errors and verify its correctness. This resulted in a refined model where the users may be confident of predicting outcomes with a reasonable certainty. The outputs of the simulation runs were presented in various numerical and graphical formats and analysed. When these were interpreted it led to more insights regarding investing in the new technology. Using this techno-economic model will allow manufacturing companies to evaluate whether they should invest in a specific new technology and what the economic risks would be. The techno-economic model provides the ability to adapt to and assign localised costs, attribute market share and simulate a marketplace where contracts are awarded to the company or its competitors. Outputs of the simulation are be made available in the form of tables and graphs, and the likelihood of the individual outcomes or ranges are estimated. These likelihoods informs the user of the risks that they may encounter.

Although the model is meant to be a general model for simulating requests for quotes (RFQs), awarding of contracts and assigning of costs, it is implemented in a specific case study where micro milling is the technology of choice. Thus micro milling markets were analysed in detail to provide the data that is needed for the model.

The performance measures that are included in the simulation are ’number of months to break even’ at various capital cost rates, ROI and Net Present Value (NPV). Data and graphs of relevant simulation output are generated automatically.

Due to the fact that micro milling was the specific technology case in the simulation, the research provided an overview of possible micro milling markets. An overview of micro milling aspects to consider when developing the techno-economic model were completed as well. It is clear that due to the many aspects that impact the milling process, parameters and final parts, that the techno-economic model must be fairly complex. The current model does not claim to represent reality with complete accuracy and precision. Main cost aspects included in the final model are:

1. Material cost through volume calculations.
2. Preparation, set-up and other non-productive costs such as converting files to various required formats, generating cutter paths, preparing and handling material, clamping or fixing the material, time taken to zero the tool and setting the cutting parameters.
3. Indirect machining cost, from machine tool depreciation, operator cost for monitoring cutting operations and training.
4. Direct cutting cost from cooling, lubrication, energy and cutting tools used.
5. Post-processing, product margins expected, errors and wastage, electricity, overheads, selling, advertising and management cost.

Since some of these costs are difficult to estimate directly, the simulation model attempts to include those based on aspects such as the complexity of the part design, complexity of machining and quality requirements. The cost model could be expanded in future research.

The model that was researched and developed mimics a market environment, complete with potential clients whom request certain work to be done. The model is defined from the point of view of a specific group, that represent those companies that supply micro milling services to the market. Once the business process structure was understood in detail, it was simplified to the required level of detail to develop the simulation model. Although indirect costs are estimated and simulated, the model do not show these here. The drivers for indirect costs are discussed previously and figure 3.6 shows which cost drivers could influence various activities. In the current model, the cost aspects are stochastic variables, that creates a stochastic quote variable for every manufacturing company. Companies then add their mark-ups to the cost to arrive at a quote amount. After receiving the various quotes, the simulated client will award the contract considering the prices and reputations of competing companies. Each individual sale can be seen as a Bernoulli trail (Basu, 2014) for every manufacturer and the continued process of RFQ's and tenders awarded then follows a binomial distribution. After a tender is awarded, the company manufactures the products and costs are incurred that will be simulated in the model. When they deliver the products they are paid and their cash balance will increase. The clients the reputation of the manufacturing company according to the quality of service he experienced. The process may then repeat for a new cycle.

To estimate the potential market for micro milling, using internationally available data, South Africa was ranked and compared to the global marketplace. South Africa has some unique or outlier qualities that differentiate it from the rest of the world (ROW). One such aspect is the Gini index. The Gini index for South Africa of about 0.66 is the highest among the stable economies. To put this in perspective, it means that less than 20% of the population earn more than 80% of the income. For most highly developed countries the Gini index is around 0.3 or less.

The simulation and data requirements for economic modelling of developing and new technology sales are complex and it is rare to find complete data. Forecasting techniques went some way to supplement data, as well as previous research that reports on the technology. All data was converted to distributions of some kind. Where data were available but sparse, bootstrapping methods were used. In cases where primary data were not obtainable, data from other countries were analysed with regression methods to suggest expected ranges for South Africa or logic used to generate likely distributions. Costs were taken from South African industries as far as possible, excepting for technologies that must be imported.

Developing the simulation model in line with these aspects and then conducting a walk-through validated the model conceptually, and added critical aspects to the model to make it more realistic. Once the model was validated conceptually, the code was debugged and improved until it yielded consistent results. The simulation results after program debugging were used to validate the simulation code. Since there is no actual system data available, case studies were used to validate parts of the simulation. Also, the author checked the simulation results for reasonableness as well. The functionality of the simulation was improved due to finding new information from these case instances. Once it was accepted that the simulation model is valid, reasonable and consistent, scenarios could be defined to show the flexibility and use of the model.

Chapter 10

Conclusions

10.1 Introduction

A Techno-economic and pricing strategy simulation model of multiple manufacturing companies supplying Micro milling was researched, developed, coded, validated and used in multiple scenarios. A SME can use the model to understand their strategy options, the effect of their choices when entering the market with a new technology such as micro milling, and the economic risk can be quantified using probabilistic outcomes.
The reality is of course more complex than the model, and this aspect must be understood by SME's using the model. The model may be supplied with conservative figures and lower growth to reduce the risk of economic mishaps. This Chapter concludes with discussing of limitations and suggested improvements that may be made. Potential future research that may improve and support the simulation model are identified.

10.2 Improvements and future work

10.2.1 Limitations

The research identified various limitations. The major limitation to using such a model is the difficulty to get realistic data about sales volumes, competitors in the market and future prospects of the markets. From the literature, data and information that are available it is clear that micro milling technology is in a growth market environment and will continue to grow for a number of years. This means that even though detail data is not available, the technology may be used in so many different sectors that the risk of not having a market may be assumed as small.

Due to not having detailed data, the model was not calibrated for any specific region and sector in detail, but this can be done if a larger or commercial venture wanted to pursue micro milling. The current model does not have separate growth rates for market sectors, since it uses a single rate. If real growth rates are available then every market may be modelled separately.

The AI model that is used to increase the reputation variable is currently only dependant on the delivery of products according to specification, including being on time. Research has shown that reputation is also highly dependent on media coverage and advertising. These aspects can be added to simulate a game-playing simulation where advertising plays a role.

In the current model, the simulation does not remove a company that is economically unsuccessful from the simulation, while in real life this can happen. The model logic can be adapted to rectify this. Not all cases of loss-making will however result in the closing of the company or department, since in some companies, these loss-making units may be cross-subsidised until they become profitable. Therefore changing this behaviour will require more research and may not be realistic in all cases.

10.2.2 Improvements suggested

The current R-model is not commercially ready software. It may be used by someone who is willing to analyse the code, adapt it to their specific markets, region and cost structure. It is however within the realm of feasibility, that the simulation could be repackaged and refined until it could be used by a user with limited knowledge of the inner workings. This is not considered an academic undertaking but has some commercial merit. If this is attempted, then the suggested interface would be the "Shiny" web interface of R. In this case, animations of the simulation could be introduced to support insight into the processes that currently happen in the "black box".

There is an separate simplified implementation of the model (as per Chapter 5) available for easy access on https://insightmaker.com/insight/57050/Success-of-New-Business-in-Competitive-EnvironmentMM where various parameters may be set by using the online sliders or text boxes. It has its own set of limitations as described in Chapter 5.

10.2.3 Suggested future research

The current cost drivers could be researched in detail so that specific instances for specific companies may be modelled accurately. As was shown by the case studies, the cost calculations are reasonably accurate for the research environment where the case studies are obtained. Private companies will have different cost structures that should be researched before the model may be calibrated for them. The reputation versus media coverage and other factors will have to be researched as well. The model should be separated into modules that may then be maintained with ease and improved without changing the main framework of the research.

Another area that could be modelled is the inclusion of distinct risks. More data would be required for individual companies since each will have their own risk profile that will be researched. The risk profile will have to address skills, software, hardware and such aspects in detail. In the current model these risks were lumped together as stochastic variables, meaning that companies all experienced identical risks.

10.3 Conclusions

Simulation provides much more detailed information than other competing methods such as sensitivity analysis. The risks and rewards from investments are shown to be more complex and stochastic variates that may be assessed thoroughly with simulation. It is also possible to determine what aspects of the model will have the greatest impact on break even, profit and ROI. The simulation results show that the initial market size, required minimum interest rates or hurdle rates, growth rates of the markets, number of competing companies in the market and mark-up all have bearing on these results and will have the greatest impact in the choice of investing. Using the simulation model more completely identifies the probable outcomes and risks, but also shows that the future will not be constrained to a single outcome.

The various scenarios showed that the model may reasonably mimic reality and that the model may be used with some confidence for comparative or consulting studies if the user is prepared to gain an understanding of the capabilities and limitations of the model.

Companies that are interested in new technologies should have at least some human resources available to allow technology transfer to be successful. Software and hardware training, time to gain experience and insight into the financial aspects of the new technology will all have an impact on the success of the investment. If the company is already active in the macro milling market, the techno-economic feasibility study shows that such knowledge should be sufficient to allow the company to become more efficient and competitive if they invested in micro milling.

The market analysis of potential products that can be manufactured using micro milling showed that there is ample space in the manufacturing sector to invest in this technology and that the uptake of the technology is far from saturation. Many of the identified markets are in growth phases and will continue to grow for many years according to forecasts. Some barriers to success include skill requirements, complex process chains, compatibility issues with software and hardware and penetration of high technology markets. Universities are in a powerful position to facilitate some of the technology transfer by using their research capacities wisely.

10.4 Contributions to new knowledge

The following contributions have been made through this research. The sectors, market potential and growth of products that could be manufactured using micro milling were identified. A reasonably complete, logical and verified model was formulated to mimic the complexities of new companies which attempt to penetrate a technological market. The model was coded to do simulations in R and Insight Maker. Results from the R simulations were analysed and discussed to provide more insight into the leverage that companies may use to reduce their risks and have a higher probability of a successful entry into the market of micro milling. It is hoped that the research will develop some insight, inspiration for further research and assist potential micro milling manufacturers in making properly informed decisions.

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Appendix 1: R code for simulations

Introduction to Appendix 1

This Appendix contains the code used to simulate the logic of the business environment.

The simulation model uses Osterwalder's Business Model Canvas Osterwalder and Pigneur. (2010) to ensure the relevant aspects are considered in a holistic way.

Assuming the company has an adequate Partner Network, and has the resources, functions and activities in place to offer some unique value proposition, then the customer segments will take note of the company. The code was developed to capture some of the complexities of a technology business which generates income from contracts. The Enterprise Infrastructure aspects are only considered regarding its financial impacts.

A business that must win contracts would be dependent on somewhat random requests for quotes (RFQ's) from customers and would be awarded some of these quotes depending on the price and value perceived by the individual clients. One of the key short-term issues for any business is its cash flow. A positive cash flow during a year will result in profit for the business. However, in the day-to-day operation of the business, cash flow is sometimes positive due to income and other times negative due to expenses. At any point in time the business will have a cash balance of either money that is available, or a negative balance as an overdraft. Having cash available might have its own problems, but those pale in comparison to the problems the business will face when its overdraft goes over the limits allowed by its bank. This presents a real risk to the business, in that banks may then choose to raise the interest rate on their overdraft, refuse to pay any additional expenses the business is liable for, or in extreme cases, call for the overdraft to be settled immediately. This might in return result in a business not being able to buy materials required for their direct manufacturing contracts, pay salaries at the end of the month and spiralling into bankruptcy. For the preceding reasons it was decided to model the required processes that will enable the compilation of cash flow statements.

Modelling sales and total income is only half of the cash flow equation. The other major category is the "Cost of Sales" and general expenses of the company to manufacture the products. Although the company is only liable to pay income tax once or in some cases twice a year, provision for taxes are normally made every month. This information is compactly expressed in the cash flow statement that is generated from the monthly financial income statements.

As was discussed in previously, the cash flow statement is of crucial importance to the business in its day-to-day operations. Once the daily cash flows are collected for a month, these flows are collated as a month statement of sales and expenses. These monthly statements are collected and compiled once a year as a standard Income statement. This Income statement is used to determine the Profit or Cash Flow for the year. The code may be adapted to run for multiple years or a single year if required.

```
# Run simulation: change sims, months, sectors, G.numMC,
# change capacity, discountRate, strategy, standard costs,
#Simulation starts here, anything before must be moved below this line...............................meant to give error if run otherwise.
# Settings
options(scipen=999)

# Used variables, functions and actual program are below. Variables above must be integrated and moved below.

# General Variables
assign("G.lb2kg", 0.453592 , envir = .GlobalEnv)  #convert lb to kg
assign("G.D2R", 12.2 , envir = .GlobalEnv)  #convert $ to Rand; may change

#simulation variables
'differing reputations, market share, stratagies regarding quality, cost models and markup
Some global variables required to store the information that must stay active for all simulations[G.numMC,months,sims]
some variables are declared/removed per month only, these are not required for the final answers (inbetween steps)[RFQnum,G.numMC]
 To connect these MCP[,i,months]< profitMC[,i] and lossMCT[,i,months]+lossMC[,i] '
assign("sims", 30, envir = .GlobalEnv)  #number of simulations
assign("months", 48, envir = .GlobalEnv)   #number of months to simulate
assign("discountRate", 0.011, envir = .GlobalEnv)   #discount rate
assign("marketGrowthRate", 0.025, envir = .GlobalEnv)   #overall growth rate
assign("sectors", 7, envir = .GlobalEnv)   #number of sectors to simulate

assign("G.numMC", 6 , envir = .GlobalEnv)  #!!!!number of local manufacturing companies (also change G.CapMC)
assign("G.CapMC", c(1,1.2,2,2,3,3), envir = .GlobalEnv) #!!!!capacity *186 (hours/month) of local manufacturing
companies#assign("G.MCstrategy", rep(0.150,G.numMC) , envir = .GlobalEnv)
#assign("G.MCstrategy", (20+(1:G.numMC))/(20+G.numMC) , envir = .GlobalEnv) #increase number to increase competitive bidding
assign("G.MCstrategy", c(0.3, 0.5, 0.6, 0.7, 0.8, 0.9) , envir = .GlobalEnv)
#assign("G.MCstrategy", runif(G.numMC)*0.05+0.50 , envir = .GlobalEnv) assign("growthRate", rep(0.011, G.numMC, envir = .GlobalEnv)  ) #MC
growth rate
assign("G.marketsRFQ", c(1,0,1,1,1,2,2), envir = .GlobalEnv) #how many client requests per sector

assign("G.capital", 400000, envir = .GlobalEnv)  #capital required of local manufacturing companies per MM
assign("G.StdCostMC",G.CapMC*2.5 , envir = .GlobalEnv)  #capacity cost of local manufacturing companies per hour
assign("G.numCsector", 2 , envir = .GlobalEnv)  #number of local manufacturing companies per sector
assign("G.numC", G.numCsector*sectors , envir = .GlobalEnv)   #number of clients (G.numCsector per industry), each have reputation of MC
#Markets
assign("G.markets", c("Automotive","Dental","Implants","Research","Moulding",
                "Energy","Bio-technology"), envir = .GlobalEnv) #sector market
assign("G.marketsNr", 1:sectors, envir = .GlobalEnv) #how many client


assign("G.productSize", c(100,2,50,20,200,50,20), envir = .GlobalEnv)#sizes from sector
assign("G.marketsSD", c(25,0.4,10,5,50,13,5), envir = .GlobalEnv)
assign("G.productQual", c(rep(0.8,5),rep(0.9,10),rep(0.95,5),  #"Automotive :total 20 per sector
                    rep(0.9,5),rep(0.95,10),rep(0.98,5),                    #"Dental"
                    rep(0.8,5),rep(0.9,10),rep(0.95,5),                     #"Implants"
                    rep(0.7,5),rep(0.8,10),rep(0.85,5), #"Research"
                    rep(0.8,5),rep(0.9,10),rep(0.95,5), #"Moulding"
                    rep(0.5,5),rep(0.6,10),rep(0.65,5), #"Energy"
                    rep(0.5,5),rep(0.6,10),rep(0.65,5)),envir = .GlobalEnv) #"Bio-technology"
dim(G.productQual)<-c(20,sectors)
```

```
#assign("G.productQual", c(0.9,0.7,0.7,0.8,0.9,0.6), envir = .GlobalEnv)
assign("DesignerSalary", 300, envir = .GlobalEnv)
assign("OperatorSalary", 200, envir = .GlobalEnv)

assign("G.millVolume", G.productSize/3, envir = .GlobalEnv)
assign("G.productComplex", c(0.7,0.8,0.8,0.9,0.9,0.6,0.5), envir = .GlobalEnv)
assign("G.manuComplex", c(0.8,0.9,0.9,0.9,0.8,0.7,0.6), envir = .GlobalEnv)
assign("G.RandPerTool", c(112,112,112,112,112,112,215,220), envir = .GlobalEnv)#0 added for empty projects
assign("G.cm3PerTool", c(10,10,10,10,10,10,2,1), envir = .GlobalEnv) #3mm tool varies with linear size
assign("G.managementCost", 500, envir = .GlobalEnv) #R500/h
assign("G.softwareCost", 12, envir = .GlobalEnv) #R12/h
assign("G.spaceRent", 9, envir = .GlobalEnv) #R9/h
assign("RFQave", sum(G.marketsRFQ[1:sectors]), envir = .GlobalEnv)  #number of quotes per month on average,normal distribution
assign("RFQsd", 1, envir = .GlobalEnv)  #number of quotes per month standard deviation,normal distribution
assign("RFQbatch", c(rep(1,120),rep(2,60),(3:22)), envir = .GlobalEnv)  #number of items in batch
RFQnumA<-round(RFQave+8*RFQsd)+1  # calculate a maximum number of quotes from the distribution for Array
par(mfrow = c(1,1),mar=c(3, 3, 3, 1))#, xpd=TRUE)


assign("G.materials", c("Aluminium offcuts","Aluminium","Brass","Copper","Steel hot rolled",
                    "Steel cold rolled","Steel stainless","Titanium"), envir = .GlobalEnv)
assign("G.DollarMaterials", c(0.04, 0.08382253, 0.1513165, 0.2072364,  0.02735184, 0.01002004, 0.3976332, 0.3449738) , envir = .GlobalEnv)#
price per cm3
assign("G.RandMaterials", G.DollarMaterials*G.D2R, envir = .GlobalEnv)
assign("G.matDistr", c(rep(2,5),rep(4,3),rep(5,3),rep(6,4),rep(7,5),  #"Automotive :total 20 per sector
                   rep(7,14),rep(8,6),                        #"Dental"
                   rep(7,14),rep(8,6),                        #"Implants"
                   rep(1,5),rep(2,5),rep(3,1),rep(4,1),rep(5,1),rep(6,1),rep(7,3),rep(8,3), #"Research"
                   rep(2,8),rep(5,5),rep(6,5),rep(7,2), #"Molding"
                   rep(2,8),rep(3,2),rep(4,5),rep(5,1),rep(6,1),rep(7,2),rep(8,1),#"Energy"
                   rep(7,14),rep(8,6)),envir = .GlobalEnv) #"Bio-medical"
dim(G.matDistr)<-c(20,7)
cashF<-rep(0,G.numMC*months*sims)
dim(cashF)<-c(G.numMC,months,sims)
discountedCashF<-rep(0,G.numMC*months*sims)
dim(discountedCashF)<-c(G.numMC,months,sims)
assign("iROI", rep(0,G.numMC*sims) , envir = .GlobalEnv)
dim(iROI)<-c(G.numMC,sims)
lostToGlobal<-rep(0,months)

# Start of main Simulation
#Request For Quotes

for (ss in 1:sims){
  #variables for simulation
  RFQnum<-rep(0,months)#market asking RFQ
  dim(RFQnum)<-c(months)
  RFQcust<-rep(0,RFQnumA*months)#market asking RFQ
  dim(RFQcust)<-c(RFQnumA,months)
  RFQflag<-rep(0,RFQnumA*G.numMC*months)#market asking RFQ
  dim(RFQflag)<-c(RFQnumA,G.numMC,months)
  MCRep<-rep(0.05,G.numC*G.numMC*(months+1))  #Reputation for upstart =0.05
```

```
dim(MCRep)<-c(G.numC,G.numMC,(months+1))
for (mm in 1:G.numC){MCRep[mm,(2:G.numMC),]<- G.MCstrategy[(2:G.numMC)]} #starting strategy gives a reputation strategy^0.7

MCP<-rep(0,RFQnumA*G.numMC*months)  #Profit <- (quoteValMC[,i]-cost[,i])*quoteAward[,i]
dim(MCP)<-c(RFQnumA,G.numMC,months)
lossMCT<-rep(0,RFQnumA*G.numMC*months)
dim(lossMCT)<-c(RFQnumA,G.numMC,months) #only if not getting paid!
costT<-rep(0,RFQnumA*G.numMC*months)
dim(costT)<-c(RFQnumA,G.numMC,months)
RFQmarket<-rep(0,RFQnumA*months)#market asking RFQ
dim(RFQmarket)<-c(RFQnumA,months)
RFQmaterial<-rep(0,RFQnumA*months)#market asking RFQ
dim(RFQmaterial)<-c(RFQnumA,months)
RFQquality<-rep(0,RFQnumA*months)#market asking RFQ
dim(RFQquality)<-c(RFQnumA,months)
batch<-rep(0,RFQnumA*months)#market asking batch
dim(batch)<-c(RFQnumA,months)
MCquality<-rep(0,G.numMC*months)#manufaComp quality
dim(MCquality)<-c(G.numMC,months)
for (mm in 1:G.numMC){MCquality[mm,]<-G.MCstrategy[mm]}
RFQsize<-rep(0,RFQnumA*months)#market asking RFQ
dim(RFQsize)<-c(RFQnumA,months)
RFQmillVolume<-rep(0,RFQnumA*months)#market asking RFQ
dim(RFQmillVolume)<-c(RFQnumA,months)
RFQproductComplex<-rep(0,RFQnumA*months)#market asking RFQ
dim(RFQproductComplex)<-c(RFQnumA,months)
RFQmanuComplex<-rep(0,RFQnumA*months)#manufacturing complexity due to quality and geometry
dim(RFQmanuComplex)<-c(RFQnumA,months)
RFQtoolComplex<-rep(0,RFQnumA*months)#setup and tool changing complexity
dim(RFQtoolComplex)<-c(RFQnumA,months)
quoteCost<-rep(0,RFQnumA*G.numMC*months)#setup and tool changing complexity
dim(quoteCost)<-c(RFQnumA,G.numMC,months)
sc1<-rep(1,RFQnumA*G.numMC*months)# fixed cost aspect
dim(sc1)<-c(RFQnumA,G.numMC,months)
sc2<-rep(1,RFQnumA*G.numMC*months)# variable cost aspect
dim(sc2)<-c(RFQnumA,G.numMC,months)
timeC<-rep(0,RFQnumA*G.numMC*months)#setup and work time
dim(timeC)<-c(RFQnumA,G.numMC,months)
quoteValMC<-rep(0,RFQnumA*G.numMC*months)#setup and tool changing complexity
dim(quoteValMC)<-c(RFQnumA,G.numMC,months)
utilMC<-rep(0,RFQnumA*G.numMC*months)#setup and tool changing complexity
dim(utilMC)<-c(RFQnumA,G.numMC,months)
probMC<-rep(0.2,RFQnumA*G.numMC)#defined per month
dim(probMC)<-c(RFQnumA,G.numMC)
quoteAward<-rep(0,RFQnumA*G.numMC)#0 means quote is not awarded, 1 gets the quote
dim(quoteAward)<-c(RFQnumA,G.numMC)
qualityMC<-rep(0,RFQnumA*G.numMC*months)#difference in quality asked, given
dim(qualityMC)<-c(RFQnumA,G.numMC,months)



for (kk in 1:months){
```

```
 #SubRoutine "s1" : Generate part specifications RFQ from markets
  RFQnum[kk]<-round(rnorm(1,mean=RFQave,sd=RFQsd),0)
  RFQmarket<-sample(G.marketsNr,RFQnumA,replace = TRUE,prob=G.marketsRFQ) # this generates a list of markets to get RFQ from
  RFQcust1<-sample(1:G.numCsector,RFQnumA,replace = TRUE) # this generates a list of customers (1 or 2) to get RFQ from (1:G.numCsector
in sector)
  RFQcust1<-(RFQcust1-1)*6+RFQmarket #1 or 2 MC per sector 1 to 6 (1,2)(3,4)...(11,12)
  #RFQmarket2<-ceiling(RFQcust1/2) # this generates a list of customers' sectors every month
  RFQcust[,kk]<-RFQcust1 # customer 1 to 12
  #RFQcust is influenced to increase reputation or not.
  #RFQ<-round(rweibull(RFQnum[kk],1.5,scale=20000)) + 1   #on average RFQave quotes
  for (i in 1:RFQnum[kk]){RFQflag[i,,kk]<- 1} #Yes = 1 for quote 0 = No


  for (i in 1:RFQnumA){RFQmaterial[i,kk]<- sample(G.matDistr[,RFQmarket[i]], 1,replace=TRUE)} #material
  for (i in 1:RFQnumA){RFQquality[i,kk]<- sample(G.productQual[,RFQmarket[i]], 1,replace=TRUE)} #quality asked
  for (i in 1:RFQnumA){batch[i,kk]<- sample(RFQbatch, 1,replace=TRUE)} #quantity asked
  for (i in 1:G.numMC){MCquality[i,kk]<- rnorm(1,mean=(RFQquality[i,kk]+RFQquality[i,kk]/10),sd=(RFQquality[i,kk]/25))} #quality given by MC
  for (i in 1:RFQnumA){RFQsize[i,kk]<- (G.productSize[RFQmarket[i]])+
             G.marketsSD[RFQmarket[i]]*rnorm(1,mean=3) } #size cm3
  for (i in 1:RFQnumA){RFQmillVolume[i,kk]<- RFQsize[i,kk]/3+G.millVolume[RFQmarket[i]]/25*(2+rnorm(1)) } #millvolume cm3
  for (i in 1:RFQnumA){RFQproductComplex[i,kk]<-
min(sample(G.productComplex[RFQmarket[i]],1,replace=TRUE)+G.productComplex[RFQmarket[i]]/20*rnorm(1),1) } #productComplexity
  for (i in 1:RFQnumA){RFQmanuComplex[i,kk]<-
min(sample(G.productComplex[RFQmarket[i]],1,replace=TRUE)+G.productComplex[RFQmarket[i]]/20*rnorm(1),1) } #manufComplexity
  for (i in 1:RFQnumA){RFQtoolComplex[i,kk]<-
round(sample(G.productComplex[RFQmarket[i]],1,replace=TRUE)+2+G.productComplex[RFQmarket[i]]/2*(1+rnorm(1)),0) } #manufComplexity
  timeC[,,kk]<-((1+RFQmillVolume[,kk]/10)*((1+1*RFQmanuComplex[,kk])^0.5)*(1+3*RFQquality[,kk])*1)

  #time spent may be adjusted to get other costs
  #SubRoutine "s2" : Quote for RFQ
 }
 for (kk in 1:months){

  sc1[,,kk]<- RFQflag[,,kk]*RFQsize[,kk]*G.RandMaterials[RFQmaterial[,kk]]*((1+RFQquality[,kk])^0.3)*1.5* #wasteage allowance
   RFQflag[,,kk]*(1+RFQmanuComplex[,kk])^2 +  #Material cost aspect including coolent
   RFQflag[,,kk]*(timeC[,,kk]/2*((1+RFQmanuComplex[,kk])^0.5)*(1+RFQquality[,kk])^0.5+1)*OperatorSalary+    #Manufacturing    aspects,
workholding, milling and finishing
   RFQflag[,,kk]*(RFQmillVolume[,kk]/G.cm3PerTool[RFQmaterial[,kk]])*G.RandPerTool[RFQmaterial[,kk]]*
   ((1+RFQmanuComplex[,kk])^0.5)*(1+RFQquality[,kk])^0.5+  #Tool cost
   RFQflag[,,kk]*timeC[,,kk]/20*G.softwareCost*((1+RFQmanuComplex[,kk])^0.3)*(1+RFQproductComplex[,kk])^0.8+   #Indirect software cost
   RFQflag[,,kk]*timeC[,,kk]/2*(G.spaceRent)*((1+RFQmanuComplex[,kk])^0.3)*
   (1+RFQproductComplex[,kk])^0.6*((1+RFQquality[,kk])^0.3) +  #Indirect space rent cost
   (RFQflag[,,kk]*timeC[,,kk]/50*G.managementCost*((1+3*RFQmanuComplex[,kk])^0.8)*(1+2*RFQquality[,kk])^0.8)*0.25          #direct
Management cost
  sc2[,,kk]<- RFQflag[,,kk]*(timeC[,,kk]/2*(1+RFQproductComplex[,kk])^0.3+1)*DesignerSalary+   #CNC programming or design aspects
    (RFQflag[,,kk]*timeC[,,kk]/50*G.managementCost*((1+3*RFQmanuComplex[,kk])^0.8)*(1+2*RFQquality[,kk])^0.8)*0.75          #Indirect
Management cost

  quoteCost[,,kk]<-((sc1[,,kk]*batch[,kk])/(batch[,kk]^0.5+9)*10+sc2[,,kk])*(1+marketGrowthRate)^kk   #cost with batch logic and learning
curve
  if(kk>1){
   for (ff in 1:G.numMC) {utilMC[,ff,kk]<-max(utilMC[RFQnumA-1,ff,(kk-1)] - G.CapMC[ff],0)}}
```

```
   markup<-((1+G.MCstrategy)^0.25)*(1+colMeans(MCRep[,,kk]))*(1.5-utilMC[1,,kk])^2
   markup<- markup/(6+G.numMC)+1
  quoteAward<-rep(0,RFQnumA*G.numMC)#0 means quote is not awarded, 1 gets the quote
  dim(quoteAward)<-c(RFQnumA,G.numMC)
  difMC<-rep(0,RFQnumA*G.numMC)#defined per month
  dim(difMC)<-c(RFQnumA,G.numMC)

  #utilMC[,,kk]<-pmax((utilMC[,,kk] - 1),0)
  for (i in 1:RFQnum[kk]){
   markup<-((1+G.MCstrategy)^0.25)*(1+colMeans(MCRep[,,kk]))*(1.5-utilMC[1,,kk])^2
   markup<- markup/(6+G.numMC)+1
   for (j in 1:G.numMC){
    quoteValMC[i,j,kk] <- (quoteCost[i,j,kk])*(markup[j])*(1.1+rnorm(1,mean=1,sd=0.1))#+timeC[i,j,kk]*G.StdCostMC[j]
    }
   #SubRoutine "s3" : Award the contracts( method 1.Sample from quotes with probabilities method 2.Lowest Quote,)
   #Begin Method 1: calculate probabilities related to price etc.RFQcust[,kk]
   for (j in 1:G.numMC){
  difMC[i,j]<-(max(quoteValMC[i,,kk])*3/quoteValMC[i,j,kk])/3 #values between 0.1 and 0.005 depends on price sensitivity
  probMC[i,j]<-max(difMC[i,j]*0.4*MCRep[RFQcust[i,kk],j,kk]*0.6/((max(utilMC[i,j,kk],0.02))^2),0)
  if (utilMC[i,j,kk]>1.1){probMC[i,j] <-0 } #No quote/award if too busy already
  if ((MCquality[j,kk]*3)<(RFQproductComplex[i,kk]+RFQmanuComplex[i,kk]+RFQquality[i,kk])) {probMC[i,j] <-0 } #No quote/award if skills do
not match the complexity
   }
  best<-sample(x=(1:(G.numMC+1)),size=1,prob=c(probMC[i,],0.3)) # last prob value is for international work
  if (best<(G.numMC+1)){quoteAward[i,best]<- 1  # 1 means the MC gets the bid Else the bid goes to international
   utilMC[(i+1),best,kk]<-utilMC[i,best,kk]+(timeC[i,best,kk]*batch[i,kk])/(batch[i,kk]^0.5+9)*10/(186*G.CapMC[best])  +0.1
   for (ff in (i+1):(RFQnumA-2)){
     utilMC[(ff+1),best,kk]<-utilMC[ff,best,kk]}}
  if (best==(G.numMC+1)){lostToGlobal[kk]<-mean(quoteValMC[i,,kk])+lostToGlobal[kk] }

  }

  #SubRoutine "s4" : Realise the part and assign the costs
  cost<-rep(0,RFQnumA*G.numMC)
  dim(cost)<-c(RFQnumA,G.numMC)
  profitMC<-rep(0,RFQnumA*G.numMC)
  dim(profitMC)<-c(RFQnumA,G.numMC)
  for (i in 1:G.numMC){
   for (j in 1:RFQnum[kk]){
    cost[j,i]<-quoteCost[j,i,kk]  + rnorm(1,sd=quoteCost[j,i,kk]/30)# basic quotes 20 replaced by accuracy of quote[i]
    profitMC[j,i] <- (quoteValMC[j,i,kk]-cost[j,i])*quoteAward[j,i] #20 quotes for MCi
   }
  }


  #SubRoutine "s5" : Deliver parts, get paid, or not?     dim(MCRep)<-c(G.numC,G.numMC,months)

  deliverMC<- pmax(rnorm((RFQnumA*G.numMC))-1,0)#sample(c(0,1),size=(RFQnumA*G.numMC),prob=c(0.90,0.1),replace=TRUE)   #can MC
deliver on promise

  for (j in 1:G.numMC){
  for (i in 1:RFQnumA) {qualityMC[i,j,kk]<- max((RFQquality[i,kk]-MCquality[j,kk]),0)}} #difference in quality
  getPaidMC<-sample(c(0,1),size=(RFQnumA*G.numMC),prob=c(0.98,0.02),replace=TRUE)
```

```
    dim(deliverMC)<-c(RFQnumA,G.numMC)
    dim(getPaidMC)<-c(RFQnumA,G.numMC)
    lossMC<-rep(0,RFQnumA*G.numMC)
    dim(lossMC)<-c(RFQnumA,G.numMC)

    for (i in 1:RFQnum[kk]){
     for (j in 1:G.numMC){
      if (getPaidMC[i,j]*profitMC[i,j]+deliverMC[i,j]*profitMC[i,j]>0){
       lossMC[i,j]<- (cost[i,j]*(1+(deliverMC[i,j]>0))+profitMC[i,j]*qualityMC[i,j,kk])
      }
      if (deliverMC[i,j]*profitMC[i,j]>0){
       MCRep[RFQcust[i,kk],j,((kk+1):(months+1))]<- max((MCRep[RFQcust[i,kk],j,kk] - 0.25*(1+deliverMC[i,j])*(1+qualityMC[i,j,kk])),0.1) #rep
low at 0.11, high at 200

      }
      if ((deliverMC[i,j]-1)*profitMC[i,j]<0){
       MCRep[RFQcust[i,kk],j,((kk+1):(months+1))]<- min((MCRep[RFQcust[i,kk],j,kk] + (2-MCRep[RFQcust[i,kk],j,kk])*0.03 -
0.3*qualityMC[i,j,kk]),1) # rep high at 1
      }

     }

    }

    if ((kk + ss) == 2){
    par(mfrow = c(1,1),mar=c(0, 0, 0, 0), xpd=TRUE)
    MIMx <- 1:100
    MIMy <- 1:100
    for (i in 1:RFQnum[kk]){
     if(sum(quoteValMC[i,,kk]*quoteAward[i,])>0) {
      pdf(file = paste("plots/ProjectRFQ",i,".pdf"),height=6)
      par(mar=c(0, 0, 0, 0), xpd=TRUE)
      plot(MIMx,MIMy,col="white",axes = FALSE)
      rowsP<-10;rD<-100/rowsP
      columnsP<-2;cW<-100/columnsP
      abline(h=c(c(1.1,2,5,8,10)*rD-6));abline(h=c(-6+rD,(rowsP)*rD-6),lwd=3) #or c(1,3,5,9)*rD-6  or 1:(rowsP+1)*rD-6))
      values<-c(paste("Manufacturing sector ",G.markets[RFQmarket[i]]),paste("Project ", i, "Value
R:",round(sum((quoteValMC[i,,kk]*quoteAward[i,])))),
           paste("Material volume/item ",round(RFQsize[i],4), " and number to manufacture ", batch[i,kk]),
           paste("Material ",G.materials[RFQmaterial[i]]),
           paste("Material Price
R",round(RFQsize[i,kk]*G.RandMaterials[RFQmaterial[i,kk]]*((1+RFQquality[i,kk])^0.3)*1.5*(1+RFQmanuComplex[i,kk])^2)),
           paste("Quality ",round(RFQquality[i],4)),
           paste("Product Complexity ",round(RFQproductComplex[i],4)),
           paste("Milling volume ",round(RFQmillVolume[i],4)),
           paste("Manufacturing Complexity ",round(RFQmanuComplex[i],4)),"","","","","")
      #    amounts<-c("Rand",round(sum(TIR[,i,]),0),round(sum(costT[,i,]),0),"",round(sum(MCP[,i,]),0),
      #           round(sum(lossMCT[,i,]),0),"",round(sum(OP[,i,]),0),round(sum(Interest[,i,]),0),
      #           "",round(sum(PBT[,i,]),0),round(sum(Tax[,i,]),0),"",round(sum(Profit[,i,]),0))
      text(x=100,y=c(100-(1:(rowsP)*rD-6.5)),values, col ="darkgrey",pos=2,cex=1.3);dev.off()
      #text(x=90,y=c(100-(1:(rowsP)*rD-4.5)),amounts, col ="black",pos=2,cex=1.2)
     }
    }
```

```
  }

  #SubRoutine "s6" : The costs and incomes are collated into income statements and cash flows.

  #for (kk in 1:months){
  for (i in 1:G.numMC){
   MCP[,i,kk]<-MCP[,i,kk]+profitMC[,i]  #Gross Profit total for all months kk all projects
  }#}
  for (i in 1:G.numMC){
   lossMCT[,i,kk]<-lossMCT[,i,kk]+lossMC[,i] + G.StdCostMC[i]/RFQnumA #Loss total due to non-payment and standard cost etc all simulations
SG A
  }
  for (i in 1:G.numMC){
   costT[,i,kk]<-costT[,i,kk]+cost[,i]*(MCP[,i,kk]>0)  #cost all months kk
  }
  #MCP[,,kk]<-MCP[,,kk]
  TIR<- MCP+costT*(MCP>0)
  Interest<-0.03*MCP
  OP<-MCP-lossMCT
  PBT<-OP+Interest
  Tax<-0.28*PBT
  Profit<-PBT-Tax

  #ProfitS[,,kk]<-Profit[,,kk]
  if (kk==1){
   for (i in 1:(G.numMC)){
    cashF[i,1,ss]<-sum(Profit[,i,1])# cashBalance = previous cashBalance + CASHFLOW
   }
  }
  if (kk>1){
   for (i in 1:(G.numMC)){
    cashF[i,kk,ss]<-cashF[i,kk-1,ss]+sum(Profit[,i,kk])# cashBalance = previous cashBalance + CASHFLOW
   }
  }
 }#end of months loop
 for (i in 1:G.numMC){
  npv<-100
  discountedCashFt<-rep(0,months)
  while (npv>0){
   iROI[i,ss]<- iROI[i,ss]+0.0001
   for (kk in 1:months){   discountedCashFt[kk]<- cashF[i,kk,ss]/(1+iROI[i,ss])^kk }
   npv<- (-G.capital*G.CapMC[i])+sum(discountedCashFt)
  }
 }
}
# end of sims loop!
for (kk in 1:months){   discountedCashF[,kk,]<-cashF[,kk,]/(1+discountRate)^kk }


#ROI report companies
par(mfrow = c(1,1),mar=c(4, 4.2, 3, 2), xpd=TRUE)
pdf(file = "plots/ROI.pdf",height=4)
```

```
par(mar=c(4.1, 4.2, 3, 2), xpd=TRUE)
plot(x=(1:G.numMC),y=rep(0,G.numMC),xaxt="n", xlim=c(1,G.numMC),ylim=c(0,max(iROI)),col="white",
    main="Average simulated ROI's for companies",xlab="Company nr.",ylab="ROI %",pch=i)
for (i in 1:G.numMC){
  #points(x=1:months,y=cashF[i,,j],pch=i,bg=rainbow(n=1,start=i/(G.numMC+1)+0.005))
  lines(x=rep(i,sims),y=(iROI[i,]),lwd=3,col=rainbow(n=1,start=i/(G.numMC+1)+0.005))
  points(x=rep(i,sims),y=(iROI[i,]),pch=26-i,bg=rainbow(n=1,start=i/(G.numMC+1)+0.005))
  axis(1, at=c(1:G.numMC),labels=(1:G.numMC), col.axis="black", las=0)
  };dev.off()
par(mfrow = c(1,1),mar=c(6, 4.2, 3, 2), xpd=TRUE)
for (i in 1:G.numMC){
  pdf(file = paste("plots/",i,"ROIhist.pdf"),height=5)
  par(mar=c(6, 4.2, 3, 2), xpd=TRUE)
  hist(iROI[i,],freq=TRUE, main=paste("Simulated ROI outcomes for company ",i),
     xlab="ROI %",ylab="Number of outcomes",col=rainbow(n=30, s = 1, v = 1, start = 0, end = 1, alpha = 0.5),
     breaks=30);dev.off()
}
#text(x=c(months+3,months+4),y=rowSums(cashF[1:G.numMC,months,])/sims,1:G.numMC, col ="black",pos=2,cex=1)
#text(x=months-3,y=max(rowSums(cashF[1:G.numMC,months,])/(sims+1)),"Company nr.", col ="black",pos=2,cex=1);dev.off()
#single company simulation output
par(mfrow = c(1,1),mar=c(4, 4, 3, 1))
par(mfrow = c(1,1),mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
for (i in 1:G.numMC){
  pdf(file = paste("plots/Single",i,".pdf"),height=4,,width=8)
  par(mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
  plot(x=1:months,y=cashF[i,,1],ylim=c(min(cashF[i,,]),max(cashF[i,,])),col=rainbow(n=1,start=i/(G.numMC+1)+0.005,alpha=0.05),
     main=paste("Cash balance simulations for company ",i),xlab="Months",ylab="Rand",pch=16)

  for (j in 1:sims){
    points(x=1:months,y=cashF[i,,j],pch=26-i,col=rainbow(n=1,start=i/(G.numMC+1)+0.005,alpha=0.05),
bg=rainbow(n=1,start=i/(G.numMC+1)+0.005,alpha=0.05))
    lines(x=1:months,y=cashF[i,,j],col=rainbow(n=1,start=i/(G.numMC+1)+0.005,alpha=0.05))
  }
  lines(x=1:months,y=rowSums(cashF[i,,])/sims,lwd=5,col=rainbow(n=1,start=i/(G.numMC+1)+0.005))
  for (j in 1:10){
  lines(x=1:months,y=cashF[i,,round(runif(1)*(sims-1))+1],lwd=2,col=rainbow(n=1,start=i/(G.numMC+1)+0.005,alpha=0.4))
  }
  text(x=c(5,5),y=c(max(cashF[i,,]),max(cashF[i,,])*0.85),c("Average cash balance","Random individual simulations"),pos=4)
  lines(x=c(0,4),y=c(max(cashF[i,,]),max(cashF[i,,])),lwd=5,col=rainbow(n=1,start=i/(G.numMC+1)+0.005,alpha=0.8))
  lines(x=c(0,4),y=c(max(cashF[i,,])*0.9,max(cashF[i,,])*0.9),lwd=2,col=rainbow(n=1,start=i/(G.numMC+1)+0.005,alpha=0.8))
  lines(x=c(15.5,49),y=rep(400000,2)*G.CapMC[i],lty=2,lwd=2,col = rainbow(n=1,start=i/(G.numMC+1)+0.005,alpha=1))
  text(x=0,y=G.capital*G.CapMC[i],c("Breakeven cash balance"),pos=4);dev.off()
 }
#discounted

for (kk in 1:months){   discountedCashF[,kk,]<-cashF[,kk,]/(1+discountRate)^kk }
for (i in 1:G.numMC){
  pdf(file = paste("plots/Discounted",i,".pdf"),height=4,width=8)
  par(mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
  d1<-round(((1+discountRate)^12-1)*100,1)

plot(x=1:months,y=discountedCashF[i,,1],ylim=c(min(discountedCashF[i,,]),max(discountedCashF[i,,])),col=rainbow(n=1,start=i/(G.numMC+1)+
0.005,alpha=0.05),
```

```
      main=paste(d1,"% Discounted cash balance simulations for company ",i),xlab="Months",ylab="Rand",pch=16)

  for (j in 1:sims){
    points(x=1:months,y=discountedCashF[i,,j],pch=26-i,col=rainbow(n=1,start=i/(G.numMC+1)+0.005,alpha=0.05),
bg=rainbow(n=1,start=i/(G.numMC+1)+0.005,alpha=0.05))
    lines(x=1:months,y=discountedCashF[i,,j],col=rainbow(n=1,start=i/(G.numMC+1)+0.005,alpha=0.05))
  }
  text(x=c(5,5),y=c(max(discountedCashF[i,,]),max(discountedCashF[i,,])*0.9),c("Average 14% discounted PV balance","Random individual
simulations"),pos=4)
  lines(x=c(0,4),y=c(max(discountedCashF[i,,]),max(discountedCashF[i,,])),lwd=5,col=rainbow(n=1,start=i/(G.numMC+1)+0.005,alpha=0.8))

lines(x=c(0,4),y=c(max(discountedCashF[i,,])*0.9,max(discountedCashF[i,,])*0.9),lwd=2,col=rainbow(n=1,start=i/(G.numMC+1)+0.005,alpha=0.
8))
  for (j in 1:10){
    lines(x=1:months,y=discountedCashF[i,,round(runif(1)*(sims-1))+1],lwd=2,col=rainbow(n=1,start=i/(G.numMC+1)+0.005,alpha=0.4))
  }
  lines(x=1:months,y=rowSums(discountedCashF[i,,])/sims,lwd=5,col=rainbow(n=1,start=i/(G.numMC+1)+0.005))
  lines(x=1:30,y=rowSums(cashF[i,1:30,])/sims,lwd=1,lty=2,col="darkgray")
  text(x=37,y=max(rowSums(cashF[i,1:30,])/(sims)),"Undiscounted cash balance mean",pos=3,col="darkgrey")
  for (kk in 1:months){   discountedCashF[i,kk,]<-cashF[i,kk,]/(1+discountRate+0.01)^kk }
  lines(x=1:48,y=rowSums(discountedCashF[i,1:48,])/sims,lwd=1,lty=2,col="grey")
  d2<-round(((1+discountRate+0.01)^12-1)*100,1)
  text(x=37,y=max(rowSums(discountedCashF[i,1:30,])/(sims*1.1)),paste(d2,"% Discounted PV balance mean"),pos=3,col="darkgrey")
  for (kk in 1:months){   discountedCashF[i,kk,]<-cashF[i,kk,]/(1+discountRate+0.02)^kk }
  lines(x=1:months,y=rowSums(discountedCashF[i,,])/sims,lwd=1,lty=2,col="grey")
  d3<-round(((1+discountRate+0.02)^12-1)*100,1)
  text(x=37,y=max(rowSums(discountedCashF[i,,])/(sims*1.5)),paste(d3,"% Discounted PV balance mean"),pos=3,col="darkgrey")



  lines(x=c(17.5,49),y=rep(G.capital,2)*G.CapMC[i],lty=2,lwd=1,col = "red")
  text(x=0,y=G.capital*G.CapMC[i],c("Breakeven cash balance"),col = "red",pos=4);dev.off()
}
#hist of cashF to see percentage probabilities
par(mfrow = c(1,1),mar=c(6, 4.2, 3, 2), xpd=TRUE)
for (i in 1:G.numMC){
  lhist<-hist(cashF[i,12,],freq=TRUE, breaks=30)# to be able to count outcomes
  pdf(file = paste("plots/",i,"month12.pdf"),height=5)
  par(mar=c(6, 4.2, 3, 2), xpd=TRUE)
hist(cashF[i,12,],freq=TRUE, main=paste("Simulated outcomes for cash balance after month 12 for company ",i),
     xlab="Rand",ylab="Number of outcomes",col=rainbow(n=30, s = 1, v = 1, start = 0, end = 1, alpha = 0.5),
     breaks=30)#round(sims/16))
text(x=max(cashF[i,12,])*0.86,y=max(lhist$counts),paste(sum(cashF[i,12,]>max(cashF[i,12,])*0.6)/sims*100, "% above
",round(max(cashF[i,12,])*0.6,0)),pos=4)
text(x=max(cashF[i,12,])*0.86,y=max(lhist$counts)*0.95,paste(sum(cashF[i,12,]>max(cashF[i,12,])*0.7)/sims*100, "% above
",round(max(cashF[i,12,])*0.7,0)),pos=4)
text(x=max(cashF[i,12,])*0.86,y=max(lhist$counts)*0.9,
     paste(sum(cashF[i,12,]>max(cashF[i,12,])*0.8)/sims*100,
          "% above ",round(max(cashF[i,12,])*0.8,0)),pos=4);dev.off()
}
par(mfrow = c(1,1),mar=c(6, 4.2, 3, 2), xpd=TRUE)
for (i in 1:G.numMC){
  lhist<-hist(cashF[i,24,],freq=TRUE, breaks=30)
  pdf(file = paste("plots/",i,"month24.pdf"),height=5)
```

```
  par(mar=c(6, 4.2, 3, 2), xpd=TRUE)
  hist(cashF[i,24,],freq=TRUE, main=paste("Simulated outcomes for cash balance after month 24 for company ",i),
      xlab="Rand",ylab="Number of outcomes",col=rainbow(n=30, s = 1, v = 1, start = 0, end = 1, alpha = 0.5),
      breaks=30)#round(sims/16))
  text(x=max(cashF[i,24,])-0.25*(max(cashF[i,24,])-
min(cashF[i,24,])),y=max(lhist$counts),paste(sum(cashF[i,24,]>max(cashF[i,24,])*0.75)/sims*100,        "%        above
",round(max(cashF[i,24,])*0.75,0)),pos=4)
  text(x=max(cashF[i,24,])-0.25*(max(cashF[i,24,])-
min(cashF[i,24,])),y=max(lhist$counts)*0.95,paste(sum(cashF[i,24,]>max(cashF[i,24,])*0.85)/sims*100,        "%        above
",round(max(cashF[i,24,])*0.85,0)),pos=4)
  text(x=max(cashF[i,24,])-0.25*(max(cashF[i,24,])-min(cashF[i,24,])),
      y=max(lhist$counts)*0.9,paste(sum(cashF[i,24,]>max(cashF[i,24,])*0.95)/sims*100,
                         "% above ",round(max(cashF[i,24,])*0.95,0)),pos=4);dev.off()
}
par(mfrow = c(1,1),mar=c(6, 4.2, 3, 2), xpd=TRUE)
for (i in 1:G.numMC){
  lhist<-hist(cashF[i,36,],freq=TRUE, breaks=30)
  pdf(file = paste("plots/",i,"month36.pdf"),height=5)
  par(mar=c(6, 4.2, 3, 2), xpd=TRUE)
  hist(cashF[i,36,],freq=TRUE, main=paste("Simulated outcomes for cash balance after month 36 for company ",i),
      xlab="Rand",ylab="Number of outcomes",col=rainbow(n=30, s = 1, v = 1, start = 0, end = 1, alpha = 0.5),
      breaks=30)#round(sims/16))
  text(x=max(cashF[i,36,])-0.3*(max(cashF[i,36,])-
min(cashF[i,36,])),y=max(lhist$counts),paste(sum(cashF[i,36,]>max(cashF[i,36,])*0.6)/sims*100,        "%        above
",round(max(cashF[i,36,])*0.6,0)),pos=4)
  text(x=max(cashF[i,36,])-0.3*(max(cashF[i,36,])-
min(cashF[i,36,])),y=max(lhist$counts)*0.95,paste(sum(cashF[i,36,]>max(cashF[i,36,])*0.7)/sims*100,        "%        above
",round(max(cashF[i,36,])*0.7,0)),pos=4)
  text(x=max(cashF[i,36,])-0.3*(max(cashF[i,36,])-min(cashF[i,36,])),
      y=max(lhist$counts)*0.9,paste(sum(cashF[i,36,]>max(cashF[i,36,])*0.8)/sims*100,
                "% above ",round(max(cashF[i,36,])*0.8,0)),pos=4);dev.off()
}
#multiple company comparison
par(mfrow = c(1,1),mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
pdf(file = "plots/cashflows.pdf",height=4,width=8)
par(mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
plot(x=1:months,y=cashF[1,,1],xlim=c(0,2+months),ylim=c(min(cashF),max(rowSums(cashF[1:G.numMC,months,])/sims)),col="white",
    main="Average simulated cash flows for companies",xlab="Months",ylab="Rand",pch=26-i)
for (i in 1:G.numMC){
  #points(x=1:months,y=cashF[i,,j],pch=i,bg=rainbow(n=1,start=i/(G.numMC+1)+0.005))
  lines(x=1:months,y=rowSums(cashF[i,,])/sims,lwd=3,col=rainbow(n=1,start=i/(G.numMC+1)+0.005))
  points(x=1:months,y=rowSums(cashF[i,,])/sims,pch=26-i,bg=rainbow(n=1,start=i/(G.numMC+1)+0.005))
}
text(x=c(months+3,months+4),y=rowSums(cashF[1:G.numMC,months,])/sims,1:G.numMC, col ="black",pos=2,cex=1)
text(x=months-3,y=max(rowSums(cashF[1:G.numMC,months,])/(sims+1)),"Company nr.", col ="black",pos=2,cex=1);dev.off()


#lines(x=1:months,y=cashF[3,,sims])
#lines(x=1:months,y=cashF[4,,sims])
par(mfrow = c(1,1),mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
#max(colSums(MCP[,1,]);min(colSums(MCP[,1,])
pdf(file = "plots/Profitpermonth.pdf",height=4)
par(mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
plot(1:months,colSums(MCP[,1,]), xaxt="n",ylim=(c(min(colSums(MCP[,,])),
```

```
  max(colSums(MCP[,,]))*1.1)),col= "white",main="Profit per month for manufacturing companies",
   xlab = "Month",ylab="Rand")
for (i in 1:G.numMC){
 points(1:months,colSums(MCP[,i,]),bg=rainbow(n=1,start=i/(G.numMC+1)+0.005),pch=26-i)
}
for (i in 1:G.numMC){
 lines(1:months,colSums(MCP[,i,]),col=rainbow(n=1,start=i/(G.numMC+1)+0.005),lty=2)
 text(x=i*months/G.numMC/1.2,y=max(colSums(MCP[,,]))*1.1,paste("Co.",i),bg=rainbow(n=5,start=i/(G.numMC+1)+0.005))
 points(x=i*months/G.numMC/1.2-2.3,y=max(colSums(MCP[,,]))*1.1,bg=rainbow(n=1,start=i/(G.numMC+1)+0.005),pch=26-i)
 axis(1, at=c(1:months),labels=(1:months), col.axis="black", las=0)
}
dev.off()



MIMx <- 1:100
MIMy <- 1:100
rowsP<-14;rD<-100/rowsP
columnsP<-2;cW<-100/columnsP
par(mfrow = c(1,1),mar=c(0, 0, 0, 0), xpd=TRUE)

for (i in 1:G.numMC){
 values<-c(paste("Manufacturing company ",i),"Total income revenue","- Cost of sales","","Gross profit","- SG and A expenses",
      "","Operating profit","+ Interest","","Profit before tax","- Income tax","","Profit")
 pdf(file = paste("plots/IncomeS",i,".pdf"),height=5)
 par(mar=c(0, 0, 0, 0), xpd=TRUE)
 plot(MIMx,MIMy,col="white",axes = FALSE)
 abline(h=c(c(1,3,6,9,12,14)*rD-6));abline(h=c(-6+rD,(rowsP)*rD-6),lwd=3) #or c(1,3,5,9)*rD-6  or 1:(rowsP+1)*rD-6))
 amounts<-c("Rand",round(sum(TIR[,i,]),0),round(sum(costT[,i,]),0),"",round(sum(MCP[,i,]),0),
      round(sum(lossMCT[,i,]),0),"",round(sum(OP[,i,]),0),round(sum(Interest[,i,]),0),
      "",round(sum(PBT[,i,]),0),round(sum(Tax[,i,]),0),"",round(sum(Profit[,i,]),0))
 text(x=50,y=c(100-(1:(rowsP)*rD-4.5)),values, col ="darkgrey",pos=2,cex=1.3)
 text(x=90,y=c(100-(1:(rowsP)*rD-4.5)),amounts, col ="black",pos=2,cex=1.2);dev.off()
}
par(mfrow = c(1,1),mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
pdf(file = "plots/costofquotes.pdf",height=4)
par(mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
hist(quoteCost[(1:min(RFQnum)),,],freq=TRUE, main=paste("Simulated values for cost of quotes for a total of
",round(sims*months*mean(RFQnum)/G.numMC),"quotes"),
   xlab="Rand",ylab="Number of outcomes",col=rainbow(n=50, s = 1, v = 1, start = 0, end = 1, alpha = 0.5),
   breaks=150);dev.off()
par(mfrow = c(1,1),mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
pdf(file = "plots/volumesofproducts.pdf",height=4)
par(mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
hist(RFQsize,freq=TRUE, main=paste("Simulated volumes of products for a total of
",round(sims*months*mean(RFQnum)/G.numMC),"products"),
   xlab=expression(Volume ~ cm^{3}),ylab="Number of outcomes",col=rainbow(n=50, s = 1, v = 1, start = 0, end = 1, alpha = 0.5),
   breaks=50);dev.off()
par(mfrow = c(1,1),mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
pdf(file = "plots/Simulated_milling_volumes.pdf",height=4)
par(mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
hist(RFQmillVolume,freq=TRUE, main=paste("Simulated milling volumes of products for a total of
",round(sims*months*mean(RFQnum)/G.numMC),"products"),
```

```
    xlab=expression(Volume ~ cm^{3}),ylab="Number of outcomes",col=rainbow(n=50, s = 1, v = 1, start = 0, end = 1, alpha = 0.5),
            breaks=50);dev.off()
#material cost
par(mfrow = c(1,1),mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
pdf(file = "plots/costofmaterials.pdf",height=4)
par(mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
hist(RFQsize[,]*G.RandMaterials[RFQmaterial[,]]*((1+RFQquality[,])^0.3)*1.5*
    (1+RFQmanuComplex[,])^2,freq=TRUE, main=paste("Simulated values for cost of materials for a total of
",round(sims*months*mean(RFQnum)/G.numMC),"quotes"),
xlab="Rand",ylab="Number of outcomes",col=rainbow(n=50, s = 1, v = 1, start = 0, end = 1, alpha = 0.5),
breaks=50);dev.off()
#tool cost
par(mfrow = c(1,1),mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
pdf(file = "plots/costoftools.pdf",height=4)
par(mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
hist((RFQmillVolume[,]/G.cm3PerTool[RFQmaterial[,]])*G.RandPerTool[RFQmaterial[,]]*
    ((1+RFQmanuComplex[,])^0.5)*(1+RFQquality[,])^0.5,freq=TRUE, main=paste("Simulated values for cost of tools for a total of
",round(sims*months*mean(RFQnum)/G.numMC),"quotes"),
xlab="Rand",ylab="Number of outcomes",col=rainbow(n=50, s = 1, v = 1, start = 0, end = 1, alpha = 0.5),
breaks=50);dev.off()

par(mfrow = c(1,1),mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
#max(colSums(MCP[,1,]);min(colSums(MCP[,1,])
for (j in 1:G.numC){
pdf(file = paste("plots/Reputationpermonth",j,".pdf"),height=4)
par(mar=c(3.95, 4.2, 3, 2), xpd=TRUE)
plot(1:(months+1),MCRep[j,1,],bg="white",pch=16,ylim=(c(0,1)),main=paste("Reputation at client ",j," for manufacturing companies"),
    xlab="Month",ylab="Reputation")
for (i in 1:G.numMC){
  points(1:(months+1),MCRep[j,i,],bg=rainbow(n=1,start=i/(G.numMC+1)+0.005),pch=26-i)
}
for (i in 1:G.numMC){
  lines(1:(months+1),MCRep[j,i,],col=rainbow(n=1,start=i/(G.numMC+1)+0.005),lty=i)
}
lines(1:(months+1),MCRep[j,i,],col="gold",lty=i)
text(x=c(0.9,0.9),y=MCRep[j,,1],1:G.numMC, col ="black",pos=2,cex=1)
#text(x=9,y=0.8,"Company nr.", col ="black",pos=2,cex=1);
dev.off()
}
#Lost to global market report
pdf(file = "plots/LostGlobal.pdf",height=4)
par(mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
plot(x=(1:months),y=rep(0,months),xlim=c(0,months),ylim=c(0,max(lostToGlobal/sims)),col="white",
    main="Potential work lost to the global market",xlab="Month",ylab="Rand lost",pch=16)
for (i in 1:G.numMC){
  #points(x=1:months,y=cashF[i,,j],pch=i,bg=rainbow(n=1,start=i/(G.numMC+1)+0.005))
  lines(x=(1:months),y=lostToGlobal/sims,lwd=3,col=rainbow(n=1,start=i/(G.numMC+1)+0.005))
  points(x=(1:months),y=lostToGlobal/sims,pch=26-i,bg=rainbow(n=1,start=i/(G.numMC+1)+0.005))
}
dev.off()

pdf(file = "plots/Util.pdf",height=4)
par(mar=c(3.85, 4.2, 3, 2), xpd=TRUE)
```

```
plot(x=1:months,y=rep(max(utilMC[,,]),months),   xaxt="n",   xlim=c(1,months),ylim=c(0,max(utilMC[,,])),main=paste("Simulated   utilisation   of
companies"),xlab="Month",ylab="% Utilisation",col="white",pch=16)
for (i in 1:G.numMC){points(x=1:months,y=utilMC[(RFQnumA-1),i,],bg=rainbow(n=1,start=i/(G.numMC+1)+0.005),pch=26-i)
                lines(x=1:months,y=utilMC[(RFQnumA-1),i,],lty=2,col=rainbow(n=1,start=i/(G.numMC+1)+0.005))
         text(x=i*months/G.numMC/1.2,y=max(utilMC[,,]),paste("Co.",i))
         points(x=i*months/G.numMC/1.2-2.3,y=max(utilMC[,,]),bg=rainbow(n=1,start=i/(G.numMC+1)+0.005),pch=26-i)
         axis(1, at=c(1:months),labels=(1:months), col.axis="black", las=0)}
dev.off();dev.off()
pdf(file = "plots/learn.pdf",height=4)
par(mar=c(4, 4.2, 3, 2), xpd=TRUE)
o<-1:100
oo<-1/(o^0.35+9)*10
gold2<-adjustcolor("gold",alpha.f=0.3)
plot(x=o,y=oo,bg="gold", ylim=c(0,1), pch=22,xlab="Number to manufacture",ylab="% Full cost",
    main="Cost reduction due to the different learning curves")
for (i in 2:4){points(x=o,y=(1/(o^(0.35+i/20)+9)*10),bg=gold2,pch=21)}
dev.off()
```

Appendix 2: Case studies to validate costs used in the simulations

Introduction to Appendix 2

This Appendix contains the completed case studies with comparisons to the R code costs and calibration of formulas to properly estimate the costs.

Validation of cost aspects in the simulation model

The following cases were completed from design to manufacture by the analyst to validate the costs simulated by the model. "’" are used to start a comment in the code.

The basic code used to calculate costs are based on the variables and formulas in R as shown in Appendix 1.

Case 1: micro fluidic application for research

The basic design of the part is shown in figure 1, where the central circle is 1 mm in diameter. The part was milled from perspex, 2mm thick. For work-holding, the perspex was fastened using double-sided tape. The planning and design aspects took about 90 minutes, most of which was spent in consultation with the client, since the original specification was not complete. To limit the torque on the double-sided tape, and limit the heat into the perspex, the centre hole was machined using a 203μm end mill.

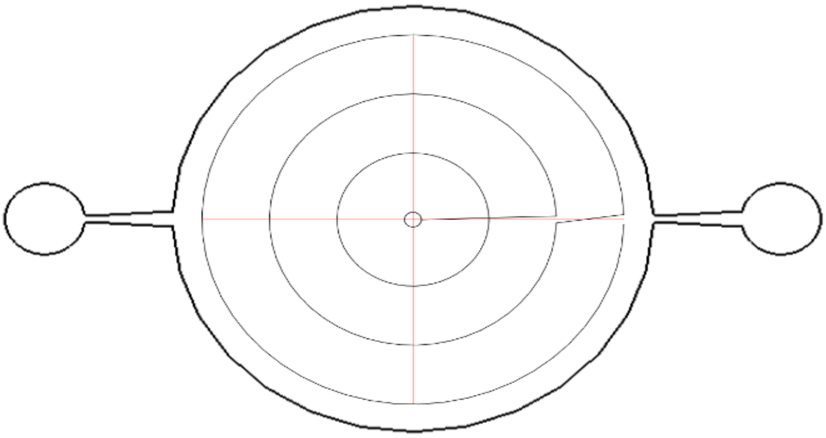


Figure 1: Case 1: micro fluidic product for research with partial tool path for the 203μm end mill

Figure 2: Case 1: micro fluidic product for research tool path for 25.4μm end mill

The tool path was a simple G02/G03 type arc command in x-y axis as shown in the figure. The two side holes were drilled using the same 203μm end mill. A second tool path was required using a 25.4μm end mill as shown in figure 2. The complexity of this part was estimated to be 0.6, where the index is from 0.5 as simple and 1 as extremely complex.

The following code was executed manually in R to get the various costs that the simulation would get if the part was required through a RFQ. The assign operator is $<-$ with a similar meaning as equals or $=$.

$> RFQmillVolume * G.RandMaterials[2] * ((1 + RFQquality)^{0.3}) * 1.5 + (1 + RFQmanuComplex)^2$

$[1]8.666427$

The result of R8.67 is considered realistic for the material cost of such a small micro-part. Logistics of materials, storage and such costs are added separately to projects based on overheads.

There is a time variable in the simulation code that estimates the time aspects of the manufacturing, based on volume, complexity of the part and the complexity of manufacturing. This time variable estimates the approximate time in hours that will be spent on the project per person or machine. It is then further adapted to be specific to design, management, operating, machining etc. Since the planning and design aspects took about 90 minutes, the following R code was run to estimate a design time cost the simulation would have used.

$> (timeC/2 * (1 + RFQproductComplex)^{0.3} + 1) * (1 + RFQquality)^{0.3} * DesignerSalary'CNCprogrammingordesignaspects$

[1] 450.8198

In the original code, the '(1+RFQquality)$^{0.3}$' code was not used. When running the code for the first time, a result of R159 was calculated. Upon further inspection of the formula, it was decided that the quality aspect should feature in the formula, since a higher quality aspect demands more care and accuracy during design and this will impact the design and planning time. Once this aspect was added, it was possible to calibrate it to give the same answer as the case study. This approach will be repeated with other case studies to get a reasonably calibrated formula that could work for most projects. Given that the designer salary is listed as R300 in the simulation, 90 minutes will give a cost of R450.

The machining on this part took 1 hour, of which about 20 minutes were spent in preparation, setup, setting of the zero position and tool changes. The R code to estimate a machining time cost were the following.

$> (timeC/2*((1+RFQmanuComplex)^{0.5})*(1+RFQquality)^{0.5}+1)* OperatorSalary'Manufacturingaspects, workholding, millingandfinishing$

[1] 271.3977

The result of R271 is slightly higher than what was experienced in the case study. By calibrating the wasted time aspect of the formula from 1 to 0.65, the following estimation gave a reasonable answer of R201, where 1 hour of work is currently billed at R200 in the model.

According to the relationship $(volumemilled)/(tooldiametre)^3$ for every tool, and cost per tool aspects, the following R code was used to calculate the estimated tool cost.

$> (timeC/G.hPerTool[RFQmaterial])*G.RandPerTool[RFQmaterial]* ((1 + RFQmanuComplex)^{0.5}) * (1 + RFQquality)^{0.5 \prime} Toolcost$

[1] 159.9309

This answer was considered reasonable, since the small 25.4 μm tool would be used only for one such part. The larger 203 μm tool would be used for multiple parts. The current cost per tool for this application and material combination is R112, so the calculated cost is in line with the expected case study value. even though more work might be performed with the same tools, the cost for the tools are loaded against the project to provide a buffer for tool breakage etc. In that case the formula might be required to be calibrated slightly higher. This aspect will be revised again after considering the other case studies.

The next aspect to evaluate is the indirect management cost. Since this is a quite standard and simple project, the involvement of management will be expected to be minimal. In a commercial venture, this might be completely different. The following R code estimated the management cost.

$> timeC/20*G.managementCost*((1+3*RFQmanuComplex)^{0.8})* (1 + 2 * RFQquality)^{0.8 \prime} IndirectManagementcost$

[1] 56.80551

The value of R56 represents about 6 minutes of management time, which seems quite low. For the actual case study inside a university set-up this is quite reasonable, but for a manufacturing company it is expected that it could be higher if the client has a high profile and could bring in larger projects. These aspects were not modelled and thus could be considered in future improvements.

Software is estimated to be used for about half the time of working on the project and the following R code estimated the software cost while considering complexity aspects of the product.

$> timeC/2 * G.softwareCost * ((1 + RFQmanuComplex)^{2}) * (1 + RFQproductComplex)^{2\prime} Indirectsoftwarecost$
[1] 19.65122

A cost of about R20 seems reasonable for the software cost in this case study. If this cost is expanded to a yearly figure, this would allow the company to spend about R40 000 per year on the design and manufacturing software. This is expected to be sufficient, though costs in this regard may vary considerably as well depending on the software solution chosen.

Property rent during 2015 in the Technopark area in Stellenbosch varied from about R100 to R200 per m^2. These figures are available widely in the media and must be updated when the simulations are required. Using an average cost of R150 per m^2, and a 16 m^2 space, the following estimated cost for space rent is envisioned for the case study.

$> timeC*(G.spaceRent)*((1+RFQmanuComplex)^{0.3})*(1+RFQproductComplex)^{0.6}* ((1 + RFQquality)^{0.3})\prime Indirectspacerentcost$
[1] 23.17279

If expanded to a yearly figure this gives a yearly rental cost of about R45 000 which is considered reasonable.

When all these costs are added together, the basic cost to the company is found to be R920.

Mark-up is generally considered to be from about 5 % on high volume goods to about 2000 % in high service specialist goods. In most manufacturing however, the mark-up is normally based on a cost-plus basis at a reasonable mark-up of 10% to 60% depending on various factors. For a specialised manufacturing company, it is possible to charge slightly higher mark-ups, maybe up to 400% if the are highly skilled. For the simulations the profit margins were generally limited to between 15% and 70%.

For this project, a mark-up of 67% was added, and the final cost is R1540 for the project. This is considered a very realistic price for the case study.

Case 2: electric circuit board guide application for research

The basic design progression of the part is shown in figure 3. On the left is the original design drawing from the client. The slots were meant as a guide for aligning wires that had to be soldered to a circuit board in the centre of the design. After consultation the design was revised to the open sided design shown manufactured on the right. During the assembly process, the feeding of up to 48 wires at the same time through the slots would be inefficient if not very frustrating. Having the slots open to sides allows the guide to be laid on the surface and the wires bent into position while observing under a microscope. The size of the slots are 500 μm and the complete guide is 5x5x1.5mm in size. Each slot is 100 μm deep and was milled with a 50.8 μm end mill, using two cuts of 50 μm deep each. The guide fits into a larger part that had to be machined as well, shown in 4. The four 3/4 circles in the corners of the guide hole is there to facilitate removal of the guide if required.

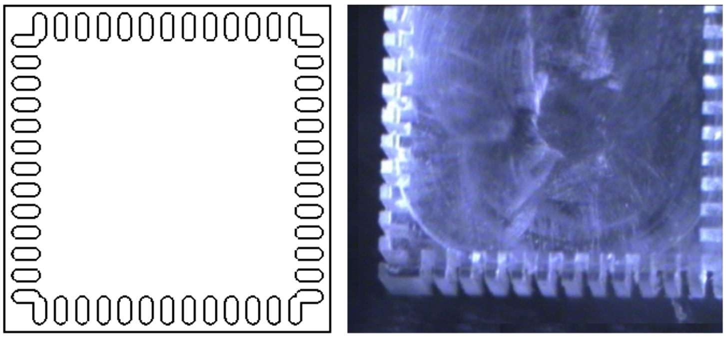


Figure 3: Case 2: micro 5x5mm guide for research with the original design on the left and the revised manufactured part on the right

The same process was followed as previously in R to get the various costs that the simulation would get if the part was required through a RFQ.

$> Cost[1]1569.408 > markup[1]1.690297 > quote1 < -markup*Cost > quote1$

[1] 2652.766

The total cost, markup and quote is considered realistic for the work done. The detail was as follows:

Material cost of R291 due to more expensive and larger volume as well as re-work experienced is considered realistic. Logistics of materials, storage and such costs are added separately to projects based on overheads.

The time variable in the simulation code that estimates the time aspects of the manufacturing, based on volume, complexity of the part and the complexity of manufacturing estimated the approximate time in hours that will be spent on the

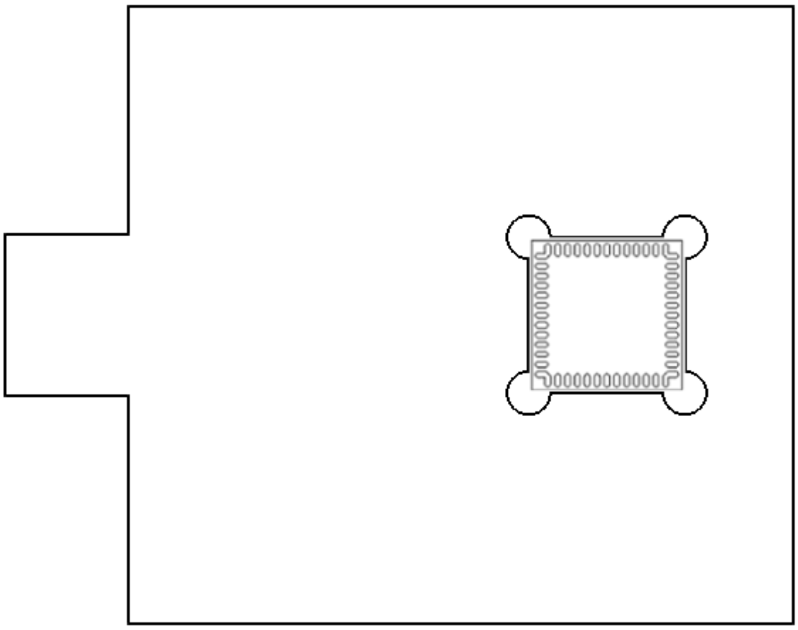


Figure 4: Case 2: the original design of the micro 5x5mm guide in the circuit board holding space design

project per person or machine. It is then further adapted to be specific to design, management, operating, machining etc. The planning and design aspects took about 4 hours on the case, while the estimated design time cost the simulation would have used was only 1.73 hours. This was mainly due to the redesign aspect that was required to make the assembly more user-friendly. It is considered that additional work will be required in such a case and that future work could attempt to simulate that variable. For the most case, this would not be part of a normal RFQ from a client.

Given that the designer salary is listed as R300/h in the simulation, 1.73 hours will give a cost of R521.

The machining on this part took 2.5 hours, of which about 60 minutes were spent in preparation, setup, setting of the zero position and tool changes. The R code to estimate a machining time cost gave the following result:

$> (timeC/2 * ((1 + RFQmanuComplex)^{0.5}) * (1 + RFQquality)^{0.5} + SU - 0.35) * OperatorSalary$

[1] 462.26

The result of R462 is slightly less than what was experienced in the case study with a cost of R500, but within reason. It may be observed that a new variable was introduced to keep track of the number of set-ups required as 'SU'. This allows case 1 to still give the same results since case 1 had one set-up only. The case cost of operator was for 1 hour of work billed at R200 in the model.

According to the relationship $(volumemilled)/(tooldiametre)^3$ for every tool, and cost per tool aspects, the following R code was used to calculate the estimated tool cost.

$> (timeC/G.hPerTool[RFQmaterial]) * G.RandPerTool[RFQmaterial] * ((1 + RFQmanuComplex)^{0.5}) * (1 + RFQquality)^{0.5}$

[1] 296.2663

This answer was considered reasonable, since the small 50.8 μm tool would be used only for one such part and the large number of entries into the part creates ample opportunities for the tool to break. The larger 2mm tool would be used for multiple parts. The current cost per tool for this application and material combination is R112, so the calculated cost is in line with the expected case study value. Even though more work might be performed with the same tools, the cost for the tools are loaded against the project to provide a buffer for tool breakage etc. In that case the formula might be required to be calibrated slightly higher. This aspect will be revised again after considering the other case studies.

The next aspect to evaluate is the indirect management cost. Since this is a slightly more complicated project than case 1, the involvement of management will be expected to be higher. The following R code estimated the management cost.

$> timeC/20 * G.managementCost * ((1 + 3 * RFQmanuComplex)^{0.8}) * (1 + 2 * RFQquality)^{0.8}$

[1] 110.1089

The value of R110 represents about 12 minutes of management time, which seems quite low. For the actual case study inside a university set-up this is quite reasonable, but for a manufacturing company it is expected that it could be higher if the client has a high profile and could bring in larger projects.

Software is estimated to be used for about half the time of working on the project and the following R code estimated the software cost while considering complexity aspects of the product.

$> timeC/2 * G.softwareCost * ((1 + RFQmanuComplex)^2) * (1 + RFQproductComplex)^2$

```
[1] 44.46537
```

A cost of about R45 seems reasonable for the software cost in this case study.

Property rent during 2015 values were described in case 1. Using an average cost of R150 per m^2, and a 16 m^2 space, the following estimated cost for space rent is envisioned for the case study.

$> timeC * (G.spaceRent) * ((1 + RFQmanuComplex)^{0.3}) * (1 + RFQproductComplex)^{0.6} * ((1 + RFQquality)^{0.3})$

```
[1] 43.91952
```

If expanded to a yearly figure this gives a yearly rental cost of about R45 000 which is considered reasonable.

When all these costs are added together, the basic cost to the company is found to be R1569.

Mark-up is discussed in case 1. For the simulations the profit margins were generally limited to between 15% and 70%.

For this project, a mark-up of 69% was added, and the final cost is R2653 for the project. This is considered a very realistic price for the case study.

Case 3: electric circuit board microwave filter application for research

The basic tool path of the part is shown in figure 5 and the part in figure 6. There are two tool paths shown for two tool sizes. The outer area and centre were cleared using a 1.2mm end mill. The slots were milled using a 200 μm end mill. A third 3mm tool was used to manufacture the base from aluminium and copper.

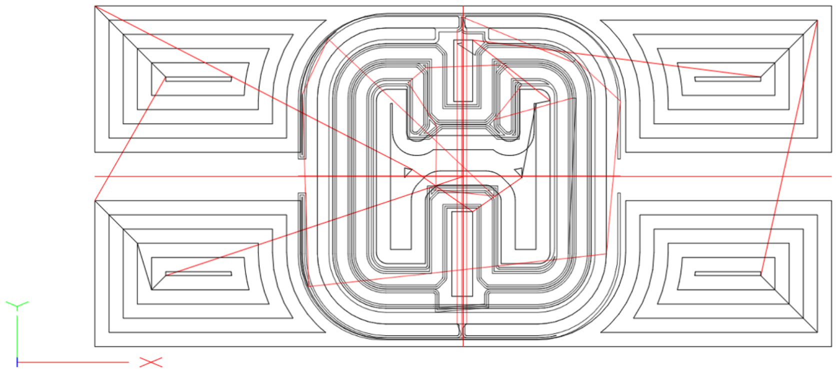


Figure 5: Case 3: micro milling tool paths for electronic circuit board microwave filter

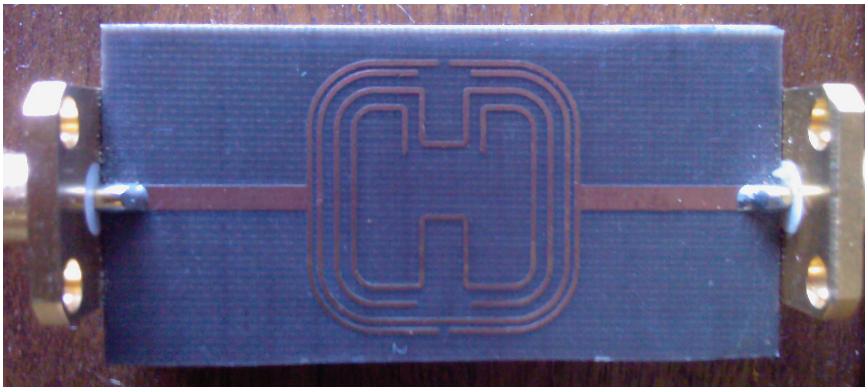


Figure 6: Case 3: micro milled electronic circuit board microwave filter

The same process was followed as previously in R to get the various costs that the simulation would get if the part was required through a RFQ.

$> Cost[1]4172.378 > markup[1]1.690297 > quote1 < -markup*Cost > quote1$
[1] 7052.56

The total cost, markup and quote is considered realistic for the work done. The detail was as follows:

Material cost of R132 is considered due to more expensive and larger volume is considered realistic. Logistics of materials, storage and such costs are added separately to projects based on overheads.

The time variable in the simulation code that estimates the time aspects of the manufacturing, based on volume, complexity of the part and the complexity of manufacturing estimated the approximate time in hours that will be spent on the project per person or machine. It is then further adapted to be specific to design, management, operating, machining etc. The planning and design aspects took about 4 hours on the case, while according to the estimated design time cost the simulation would have used 3.42 hours. This is considered close enough and realistic in the normal range of expected values.

Given that the designer salary is listed as R300/h in the simulation, 3.42 hours will give a cost of R1027.

The machining on this part took about 5 hours, of which about 60 minutes were spent in preparation, setup, setting of the zero position and tool changes. The R code to estimate a machining time cost gave a cost of R896 for a time of 4.48 hours, which is considered reasonable.

According to the relationship $(volumemilled)/(tooldiametre)^3$ for every tool, and cost per tool aspects, the estimated tool cost would be R1268 due to longer cutting times and more wear on the tools.

This answer was considered reasonable, since the small 200 μm tool was replaced twice to keep the quality of the cut high. The larger 2mm tool would be used for multiple parts. The current cost per tool for this application and material combination is R1268, so the calculated cost is in line with the expected case study value. Even though more work might be performed with the same tools, the cost for the tools and coolant are loaded against the project to provide a buffer for tool breakage etc.

The next aspect to evaluate is the indirect management cost. Since this is a more complicated project than case 1 and case 2, the involvement of management will be higher. The estimated management cost was calculated to be R471, representing almost an hour of the manager's time.

For the actual case study inside a university set-up this is quite reasonable, but for a manufacturing company it is expected that it could be higher if the client has a high profile and could bring in larger projects.

Software is estimated to be used for about half the time of working on the project and the estimated software cost while considering complexity aspects of the product was calculated to be R190. This seems reasonable for the software cost in this case study.

Property rent during 2015 values were described in case 1. Using an average cost of R150 per m^2, and a 16 m^2 space, the estimated cost for space rent for case study 3 is envisioned to be R188.

If expanded to a yearly figure this gives a yearly rental cost of about R45 000 which is considered reasonable.

When all these costs are added together, the basic cost to the company is found to be R4172.

Mark-up is discussed in case 1. For the simulations the profit margins were generally limited to between 15% and 70%.

For this project, a mark-up of 69% was added, and the final cost is R7053 for the project. This is considered a realistic price for the case study.

Case 4: aluminium microwave filter application for research

The rendered CAD file of the part is shown in figure 7. The basic plate with holes and levels were machined on a larger milling centre. The centre were shaped using a 1.8mm end mill and 2mm end mill. Six rough cuts were made each 1.5mm deep with the part submersed in an oil and water mixture. The tops of the pins were machined using a corner rounding 500 μm rounding radius end mill. Only the micro milling part of the manufacturing cost is estimated. Two parts were made as can be seen on the figure 8.

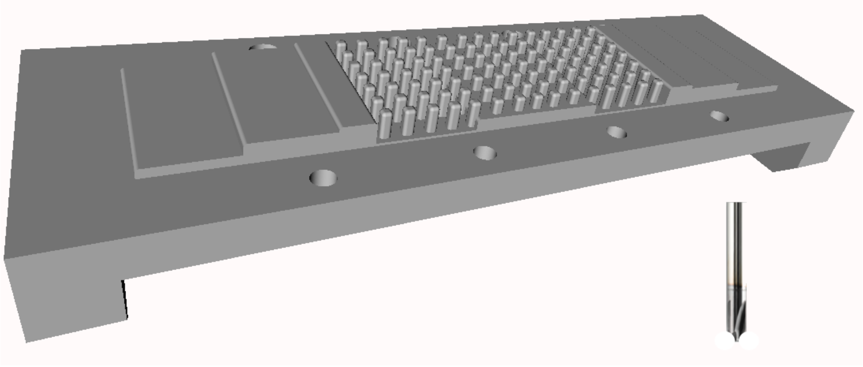


Figure 7: Case 4: CAD picture of a micro milled aluminium microwave filter and corner rounding milling tool

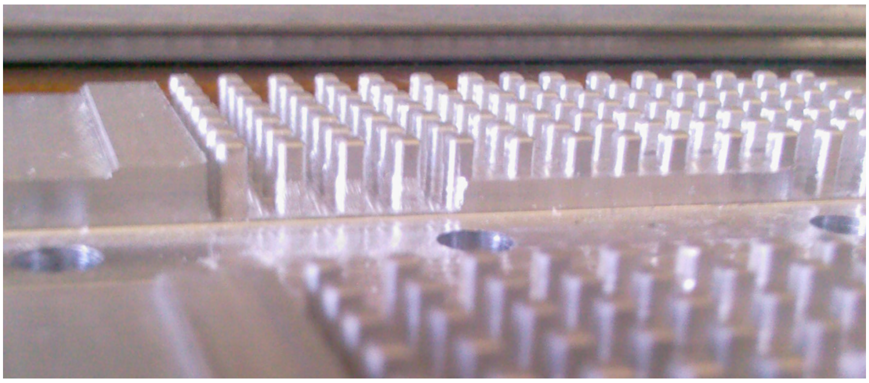


Figure 8: Case 4: two micro milled aluminium microwave filters after manufacture

The same process was followed as previously in R to get the various costs that the simulation would get if the part was required through a RFQ.

$> Cost[1]15149.61 > markup[1]1.414534 > quote1 < -markup*Cost >$ $quote1$

[1] 21429.64

The total cost, markup and quote is considered realistic for the work done. The detail was as follows:

Material cost of R1591 is considered reasonable due to more expensive material and larger volume. Logistics of materials, storage and such costs are added separately to projects based on overheads.

The time variable in the simulation code that estimates the time aspects of the manufacturing, based on volume, complexity of the part and the complexity of manufacturing estimated the approximate time in hours that will be spent on the project per person or machine. It is then further adapted to be specific to design, management, operating, machining etc. The planning and design aspects took about 10 hours on the case, while according to the estimated design time cost the simulation would have used 9.25 hours. This is considered close enough and realistic in the normal range of expected values.

Given that the designer salary is listed as R300/h in the simulation, 9.25 hours will give a cost of R2776.

The machining on this part took about 2 days, of which about 120 minutes were spent in preparation, set-up, setting of the zero position and tool changes. The R code to estimate a machining time cost gave a cost of R2620 for a time of 13 hours, which is considered reasonable. The second part was done quicker and since there was no added design cost, that could be left out. At this time the model only considers single parts, though batches will be considered for the future.

According to the relationship $(volumemilled)/(tooldiametre)^3$ for every tool, and cost per tool aspects, the estimated tool cost would be R4681 due to longer cutting times and more wear on the tools.

This answer was considered reasonable, due to multiple tool changes, specialised corner tools and such that had to be ordered from the global market. Even though more work might be performed with the same tools, the cost for the tools and coolant are loaded against the project to provide a buffer for tool breakage etc.

The next aspect to evaluate is the indirect management cost. Since this is a more complicated project than case 1 and case 2, the involvement of management will be higher. The estimated management cost was calculated to be R1819, representing about three-and-half hours of the manager's time.

For the actual case study inside a university set-up this is quite reasonable, but for a manufacturing company it is expected that it could be higher if the client has a high profile and could bring in larger projects.

Software is estimated to be used for about half the time of working on the project and the estimated software cost while considering complexity aspects of the product was calculated to be R942. This seems reasonable for the software cost in this case study.

Property rent during 2015 values were described in case 1. Using an average cost of R150 per m^2, and a 16 m^2 space, the estimated cost for space rent for case study 4 is envisioned to be R720.

When all these costs are added together, the basic cost to the company is found to be R15150.

Mark-up is discussed in case 1. For the simulations the profit margins were generally limited to between 15% and 70%.

For this project, a mark-up of 41.45% was added, and the final cost is R21430 for the project for the first part. This is considered a realistic price for the case study. For additional parts to be made, the design, management and space rent cost may be left out. This means that the second parts should cost R9835 to manufacture and with the mark-up could be sold for R13912.

Due to this case study an additional variable is added to the simulation to handle batching of parts.

Case 5: electric network cable crimping die application for manufacturing

This part was reverse engineered from a given part, and the different levels that had to be machined are shown in figure 9. The outer area and centre were cleared using a 2mm end mill. The pins and slots were milled using a 800 μm end mill. The material was brass due to a low wear requirement.

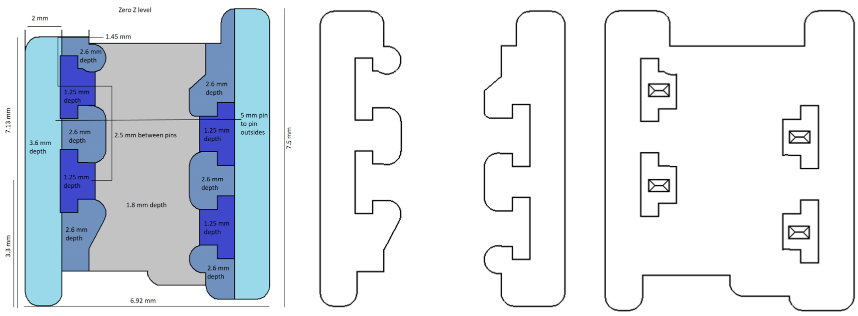


Figure 9: Case 5: electric network cable crimping die measurements and levels for micro milling

The same process was followed as previously in R to get the various costs that the simulation would get if the part was required through a RFQ.

$> Cost[1]795.5192 > markup[1]1.690297 > quote1 < -markup*Cost > quote1$

[1] 1344.664

The total cost, markup and quote is considered realistic for the work done. The detail was as follows:

Material cost of R21 is considered realistic due to the small volume of material. Logistics of materials, storage and such costs are added separately to projects based on overheads.

The time variable in the simulation code that estimates the time aspects of the manufacturing, based on volume, complexity of the part and the complexity of manufacturing estimated the approximate time in hours that will be spent on the project per person or machine. It is then further adapted to be specific to design, management, operating, machining etc. The planning and design aspects took about 4 hours on the case, while according to the estimated design time cost the simulation would have used 1.24 hours. This difference is due to the additional work required for reverse engineering and future models could consider calculating reverse engineering aspects. The current model assumed a RFQ that is complete with CAD files and specifications.

Given that the designer salary is listed as R300/h in the simulation, 1.24 hours will give a cost of R371.

The machining on this part took about 90 minutes, of which about 30 minutes were spent in preparation, setup, setting of the zero position and tool changes. The R code to estimate a machining time cost gave a cost of R346 for a time of 1.73 hours or 103 minutes, which is considered reasonable.

According to the relationship $(volumemilled)/(tooldiametre)^3$ for every tool, and cost per tool aspects, the estimated tool cost would be R35 due to short cutting times and less wear on the tools.

This answer was considered reasonable, but it might make sense to offset at least one new tool per project. This would mean that a minimum tool cost of R112 is assumed if the cost is calculated to be lower. Even though more work might be performed with the same tools, the cost for the tools and coolant are loaded against the project to provide a buffer for tool breakage etc.

The next aspect to evaluate is the indirect management cost. Since this is a simple project like case 1, the involvement of management was low. The estimated the management cost was calculated to be R12, meaning almost no management time.

For the actual case study inside a university set-up this is quite reasonable, but for a manufacturing company it is expected that it could be higher if the client has a high profile and could bring in larger projects.

Software is estimated to be used for about half the time of working on the project and the estimated software cost while considering complexity aspects of the product was calculated to be about R6. This seems reasonable for the software cost in this case study.

Property rent during 2015 values were described in case 1. Using an average cost of R150 per m^2, and a 16 m^2 space, the estimated cost for space rent for case study 5 is envisioned to be about R5.

When all these costs are added together, the basic cost to the company is found to be R796.

Mark-up is discussed in case 1. For the simulations the profit margins were generally limited to between 15% and 70%.

For this project, a mark-up of 69% was added, and the final cost is R1345 for the project. This is considered a realistic price for the case study.

Case 6: mould design for space frame injection moulded part

The complex tool path of the part is shown in figure 10. To machine the part various roughing operations were required. The roughing was done cleared using 3mm end mills and a 3mm balnose cutter. The final cut was done using a smaller step-over value of 200 μm to limit the surface roughness. A 800 μm balnose cutter was used on some small features. The material was aluminium for a test mould. In figure 11 the design of the moulded part is shown as a progression on the left and a top view of the mould on the right.

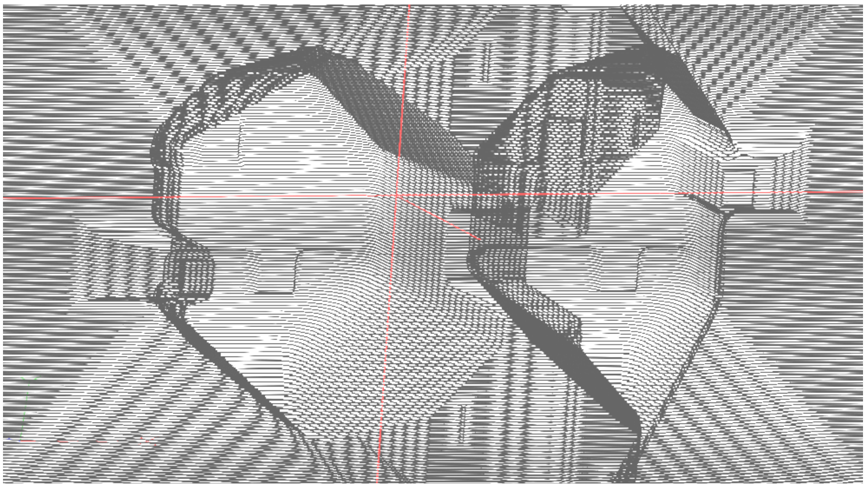


Figure 10: Case 6: complex micro milling tool paths space frame mould shape

The same process was followed as previously in R to get the various costs that the simulation would get if the part was required through a RFQ.

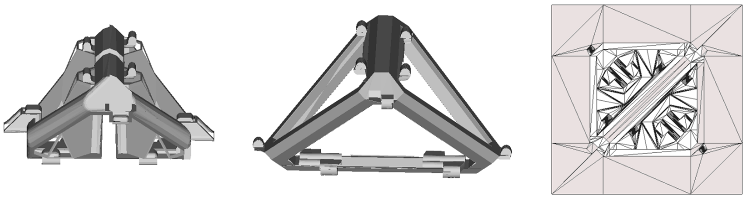


Figure 11: Case 3: design progression of the space frame from left to right and a top view of the mould on the right

$> Cost[1]10758.9 > markup[1]1.591873 > quote1 < -markup * Cost > quote1$

[1] 17126.8

The total cost, markup and quote is considered realistic for the work done. The detail was as follows:

Material cost of R132 is considered due to more expensive and larger volume is considered realistic. Logistics of materials, storage and such costs are added separately to projects based on overheads.

The time variable in the simulation code that estimates the time aspects of the manufacturing, based on volume, complexity of the part and the complexity of manufacturing estimated the approximate time in hours that will be spent on the project per person or machine. It is then further adapted to be specific to design, management, operating, machining etc. The planning and design aspects took about 4 hours on the case, while according to the estimated design time cost the simulation would have used 3.42 hours. This is considered close enough and realistic in the normal range of expected values.

Given that the designer salary is listed as R300/h in the simulation, 3.42 hours will give a cost of R1027.

The machining on this part took about 5 hours, of which about 60 minutes were spent in preparation, setup, setting of the zero position and tool changes. The R code to estimate a machining time cost gave a cost of R896 for a time of 4.48 hours, which is considered reasonable.

According to the relationship $(volumemilled)/(tooldiametre)^3$ for every tool, and cost per tool aspects, the estimated tool cost would be R1268 due to longer cutting times and more wear on the tools.

This answer was considered reasonable, since the small 200 μm tool was replaced twice to keep the quality of the cut high. The larger 2mm tool would be used for multiple parts. The current cost per tool for this application and material combination is R1268, so the calculated cost is in line with the expected case study value. Even though more work might be performed with the same tools, the cost for the tools and coolant are loaded against the project to provide a buffer for tool breakage etc.

The next aspect to evaluate is the indirect management cost. Since this is a more complicated project than case 1 and case 2, the involvement of management will be higher. The estimated the management cost was calculated to be R471, representing almost an hour of the manager's time.

For the actual case study inside a university set-up this is quite reasonable, but for a manufacturing company it is expected that it could be higher if the client has a high profile and could bring in larger projects.

Software is estimated to be used for about half the time of working on the project and the estimated software cost while considering complexity aspects of the product was calculated to be R190. This seems reasonable for the software cost in this case study.

Property rent during 2015 values were described in case 1. Using an average cost of R150 per m^2, and a 16 m^2 space, the estimated cost for space rent for case study 3 is envisioned to be R188.

If expanded to a yearly figure this gives a yearly rental cost of about R45 000 which is considered reasonable.

When all these costs are added together, the basic cost to the company is found to be R4172.

Mark-up is discussed in case 1. For the simulations the profit margins were generally limited to between 15% and 70%.

For this project, a mark-up of 69% was added, and the final cost is R7053 for the project. This is considered a realistic price for the case study.

Conclusion on the case studies

The case studies brought various issues to light, such as the need to model multiple or batch products. For these products, the design cost, management cost and space rent cost may be reduced or left out. There might also be a learning curve that makes large batches less expensive.

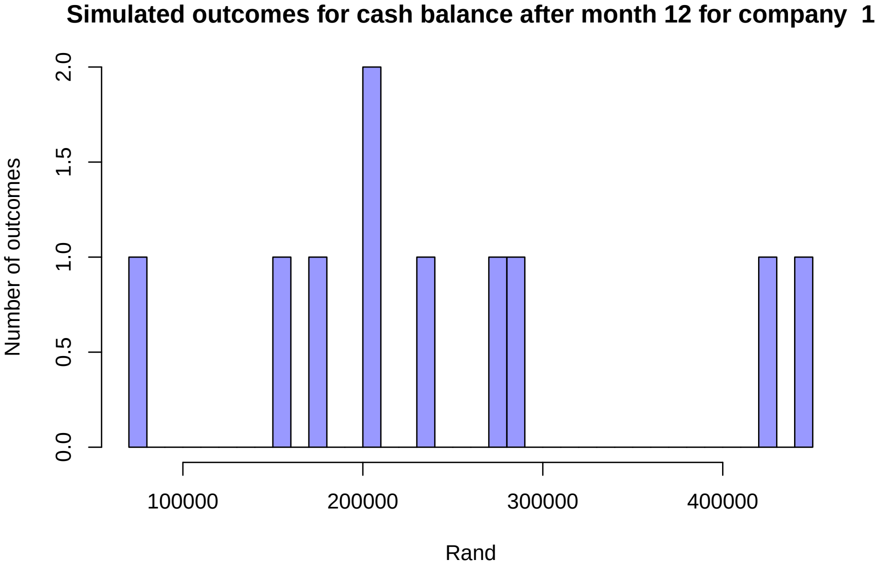
If the client has a high profile management might be more involved to bring in larger projects. These aspects were not modelled and thus could be considered in future improvements.

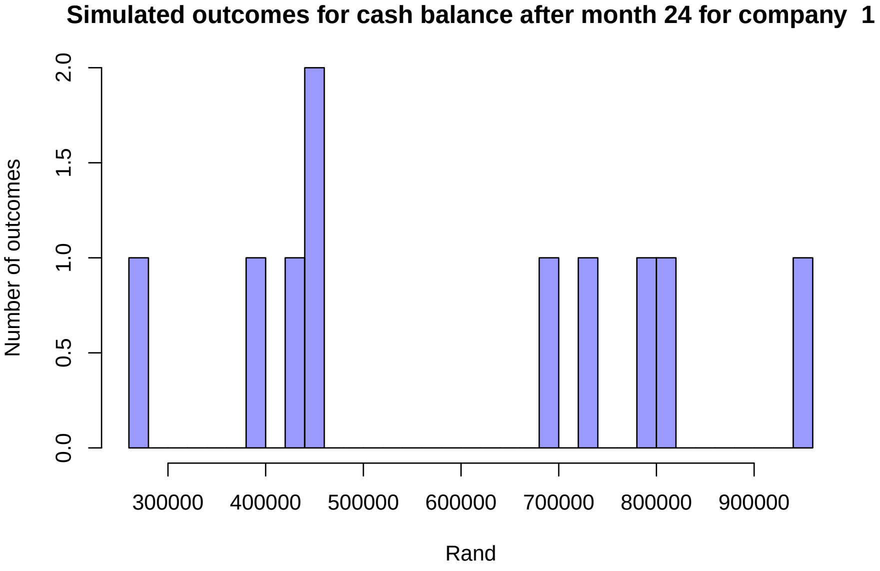
Additional work required for reverse engineering was not considered and future models could consider calculating reverse engineering aspects. The current model assumed a RFQ that is complete with CAD files and specifications.

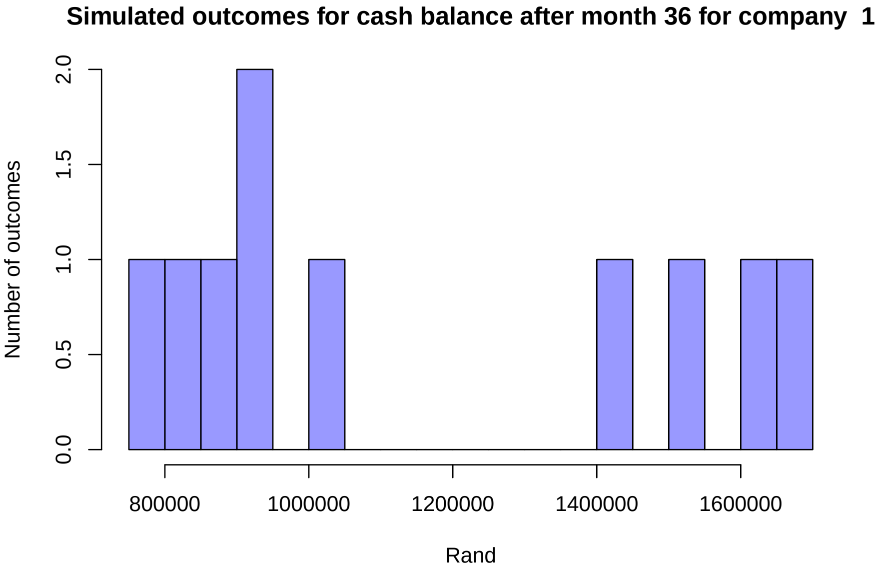
Appendix 3: Graphs and tables from a single run of the simulation program

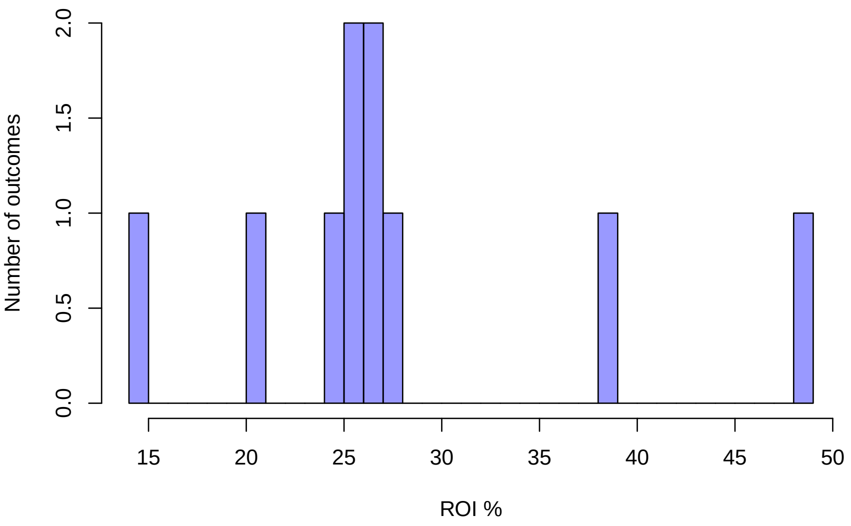
Introduction to Appendix 3

This Appendix contains graphs and tables from a single run of the simulation program. To limit the space taken in this document, only three competing companies are set up in the parameters and only 48 months are used to output the RFQ's. In the simulation parameters it may be chosen to use 10, 20 or more competing companies if this is realistic. Also, the market may be set up to generate a lot more RQF's per month, but in this case it was limited to 4. The outputs are used as described in the results chapter. These may be used to compare how multiple companies competing will change the awarded tenders to every company, as well as the impact on work lost to the global market.

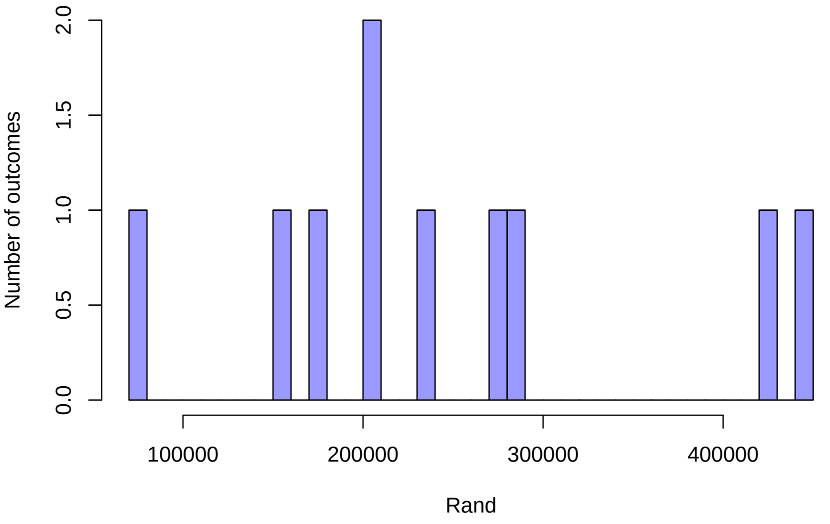

Simulated outcomes for cash balance after month 12 for company 1


Simulated outcomes for cash balance after month 24 for company 1

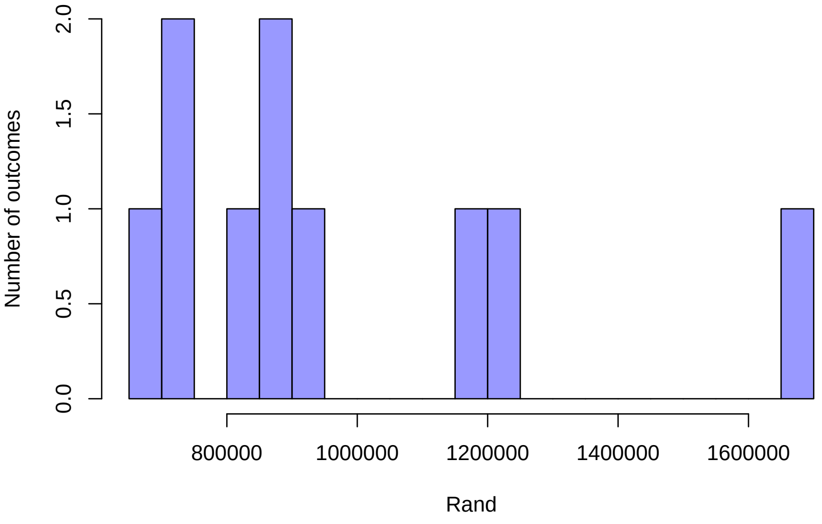

Simulated outcomes for cash balance after month 36 for company 1



Simulated ROI outcomes for company 1

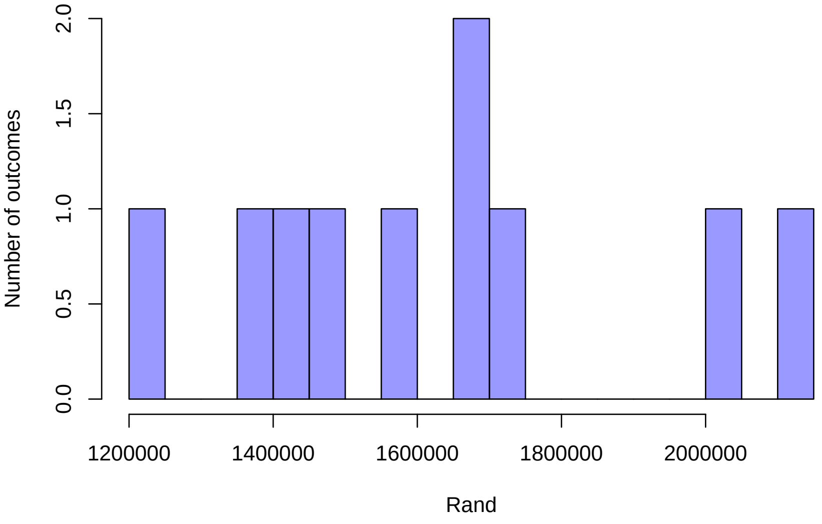


Simulated outcomes for cash balance after month 12 for company 1

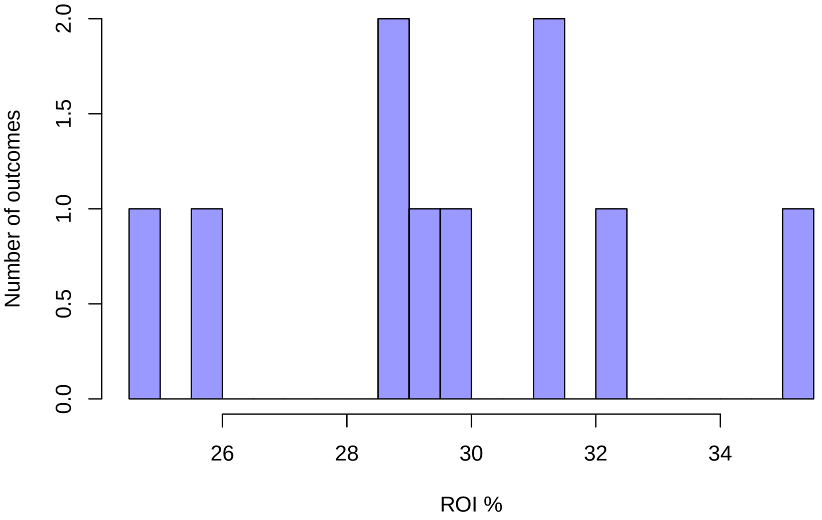


Simulated outcomes for cash balance after month 24 for company 2

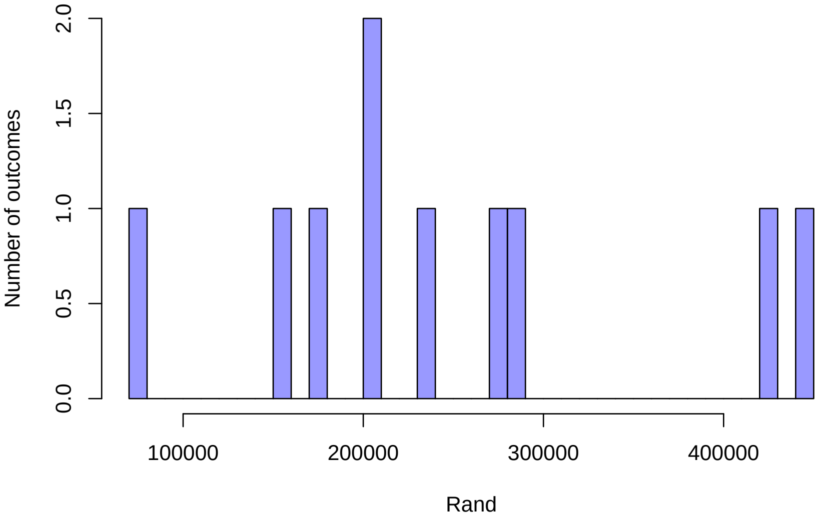
Simulated outcomes for cash balance after month 36 for company 2

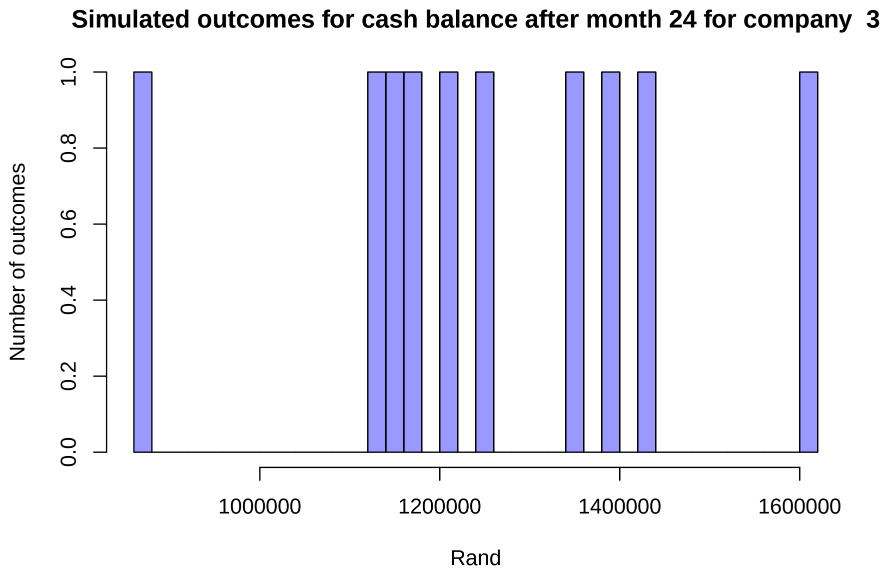


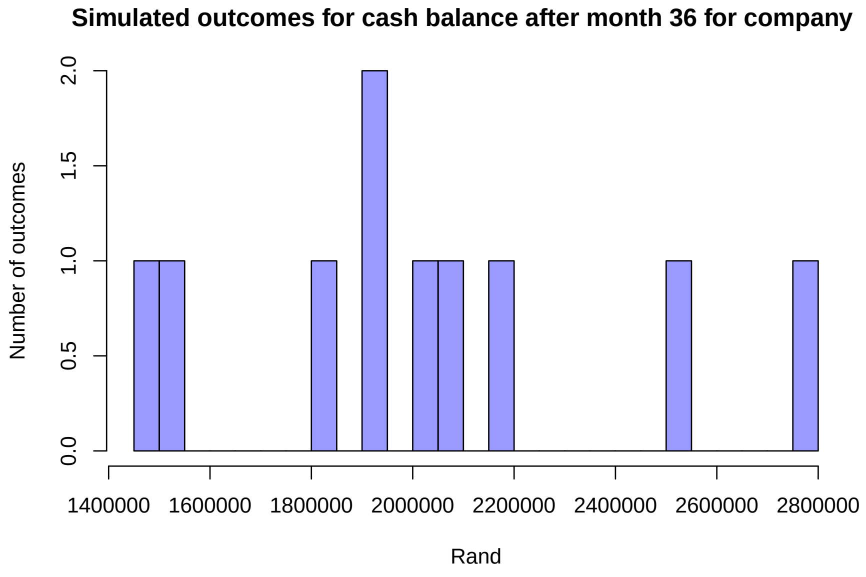
Simulated ROI outcomes for company 2

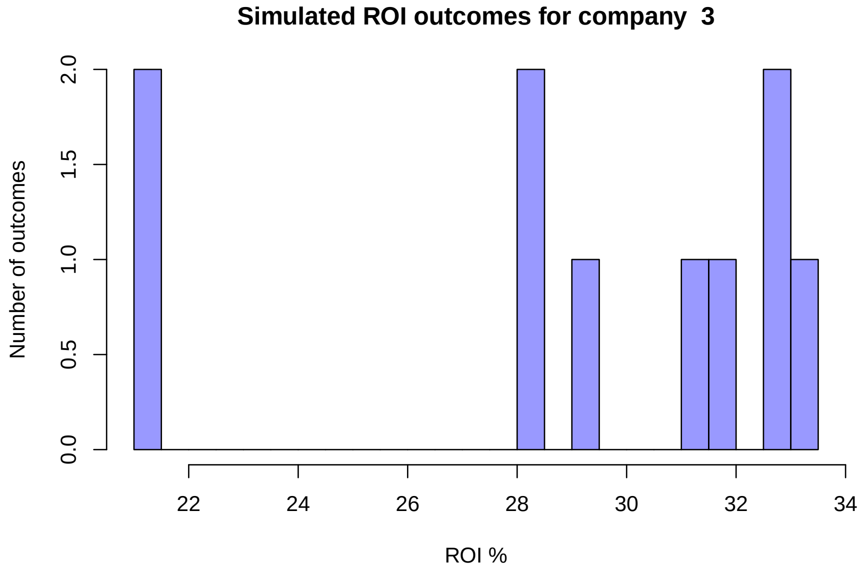


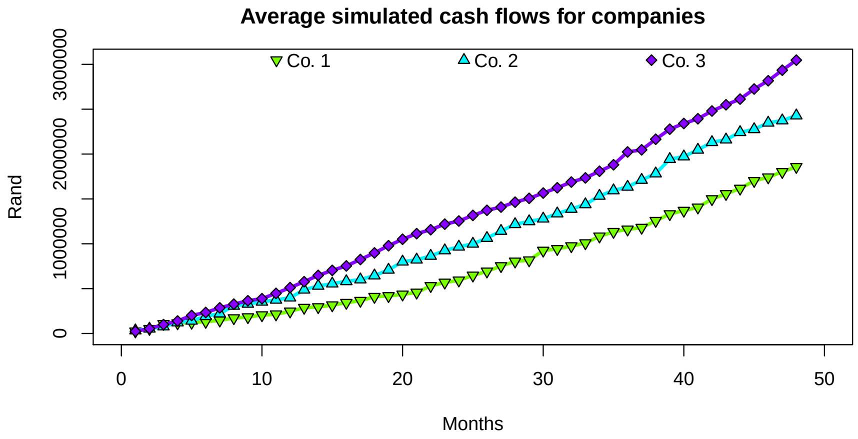
Simulated outcomes for cash balance after month 12 for company 1

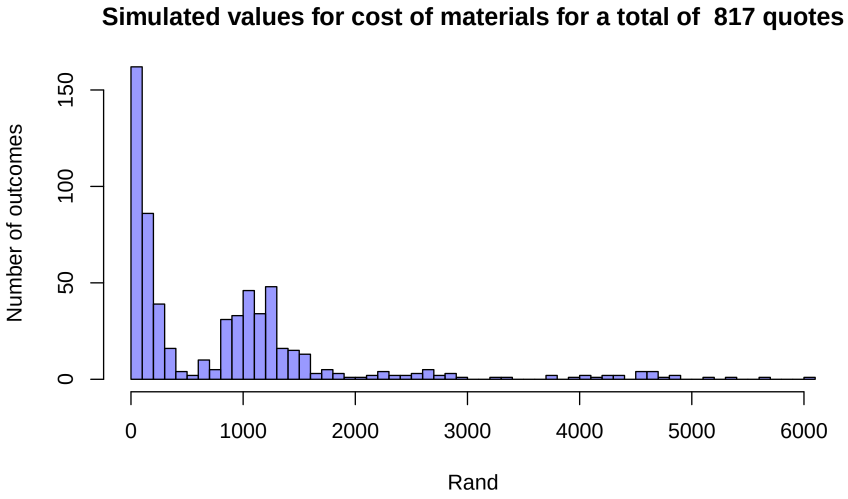


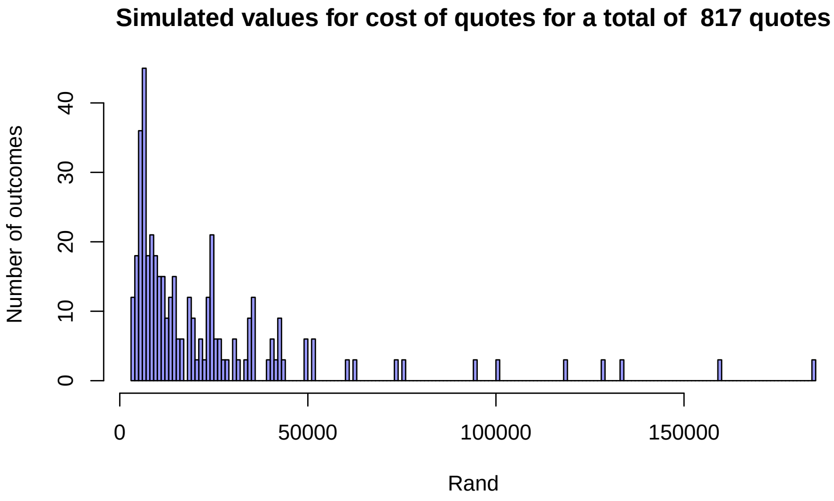

Simulated outcomes for cash balance after month 24 for company 3
Number of outcomes
0.0
0.2
0.4
0.6
0.8
1.0
1000000
1200000
1400000
1600000
Rand

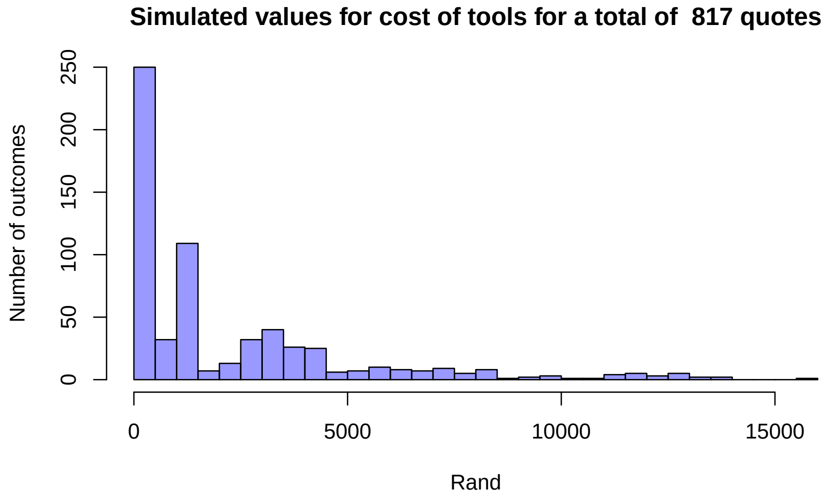

Simulated outcomes for cash balance after month 36 for company 3
Number of outcomes
0.0
0.5
1.0
1.5
2.0
1400000
1600000
1800000
2000000
2200000
2400000
2600000
2800000
Rand

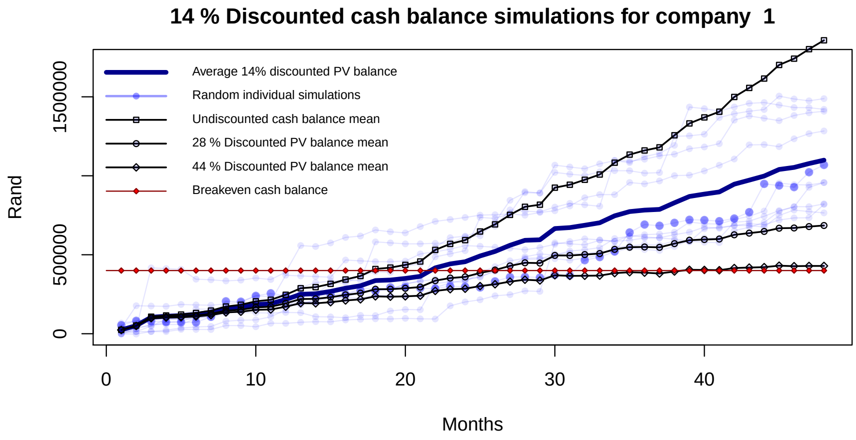

Simulated ROI outcomes for company 3
Number of outcomes
0.0
0.5
1.0
1.5
2.0
22
24
26
28
30
32
34
ROI %

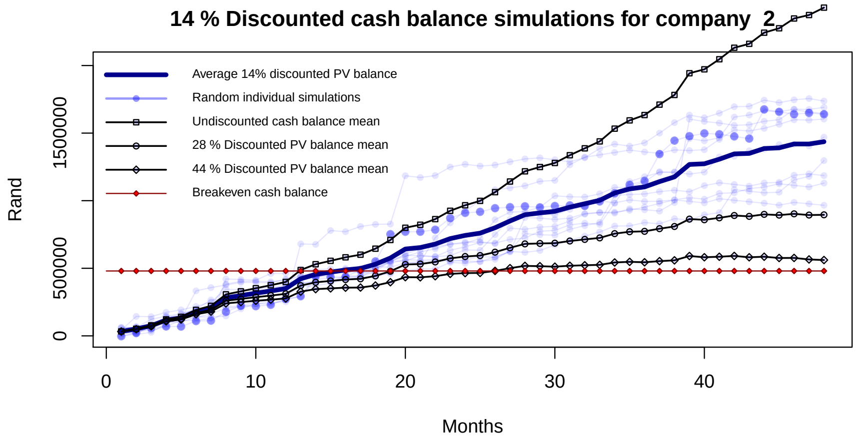

Average simulated cash flows for companies
Co. 1
Co. 2
Co. 3
Rand
0
1000000
2000000
3000000
0
10
20
30
40
50
Months

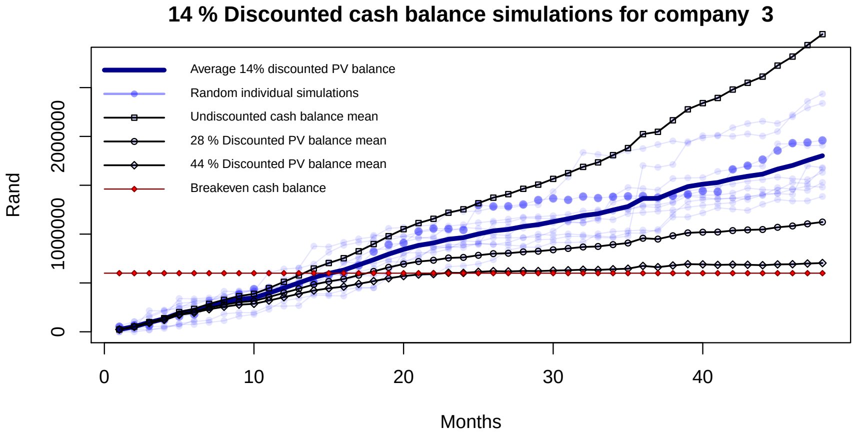

Simulated values for cost of materials for a total of 817 quotes
Number of outcomes
0
50
100
150
0
1000
2000
3000
4000
5000
6000
Rand


Simulated values for cost of quotes for a total of 817 quotes
Number of outcomes
0
10
20
30
40
0
50000
100000
150000
Rand


Simulated values for cost of tools for a total of 817 quotes
Number of outcomes
0
50
100
150
200
250
0
5000
10000
15000
Rand


14 % Discounted cash balance simulations for company 1
Average 14% discounted PV balance
Random individual simulations
Undiscounted cash balance mean
28 % Discounted PV balance mean
44 % Discounted PV balance mean
Breakeven cash balance
Rand
0
500000
1500000
0
10
20
30
40
Months

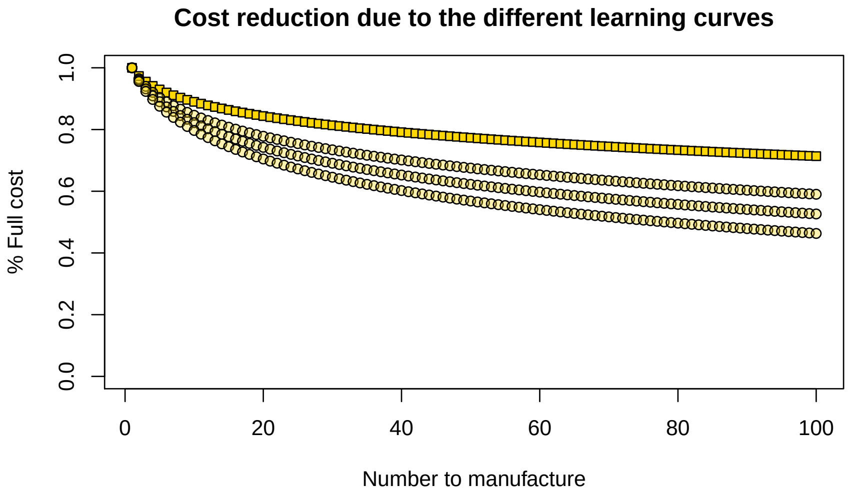

14 % Discounted cash balance simulations for company 2
Average 14% discounted PV balance
Random individual simulations
Undiscounted cash balance mean
28 % Discounted PV balance mean
44 % Discounted PV balance mean
Breakeven cash balance
Rand
0
500000
1500000
0
10
20
30
40
Months

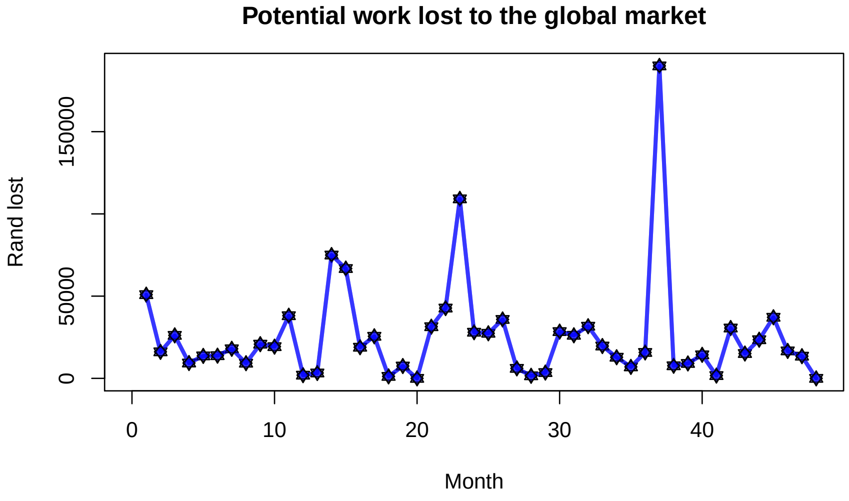


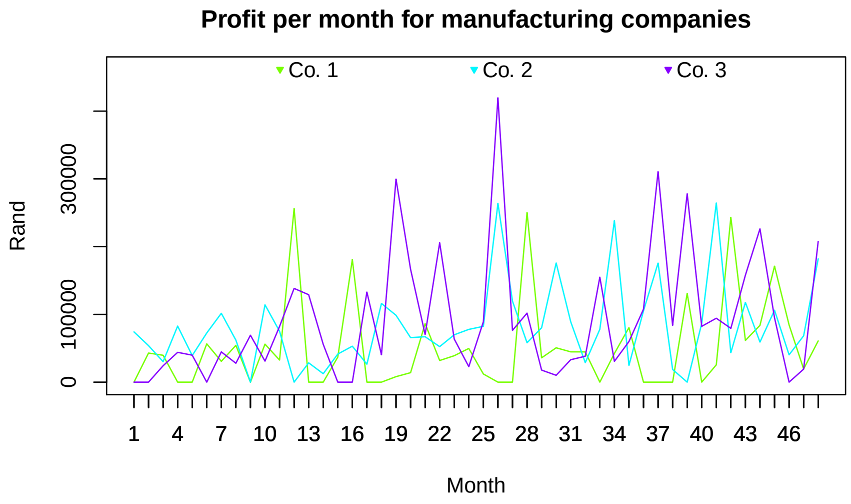
Manufacturing company 1	Rand
Total income revenue	3873261
− Cost of sales	1415269
Gross profit	2457992
− SG and A expenses	601303
Operating profit	1856689
+ Interest	73740
Profit before tax	1930429
− Income tax	540520
Profit	1389909

Manufacturing company 2	Rand
Total income revenue	5796872
− Cost of sales	1874297
Gross profit	3922575
− SG and A expenses	589490
Operating profit	3333086
+ Interest	117677
Profit before tax	3450763
− Income tax	966214
Profit	2484549

Manufacturing company 3	Rand
Total income revenue	6501282
− Cost of sales	2038689
Gross profit	4462593
− SG and A expenses	764277
Operating profit	3698316
+ Interest	133878
Profit before tax	3832194
− Income tax	1073014
Profit	2759180







Manufacturing sector Automotive

Project 1 Value R: 50367

Material volume/item 40.5939 and number to manufacture 2

Material Steel stainless

Material Price R 1278

Quality 0.85

Product Complexity 0.9181

Milling volume 14.0856

Manufacturing Complexity 0.8967

Manufacturing sector Automotive

Project 2 Value R: 175970

Material volume/item 33.8561 and number to manufacture 14

Material Steel stainless

Material Price R 979

Quality 0.7

Product Complexity 0.8224

Milling volume 11.9246

Manufacturing sector Dental
Project 3 Value R: 66532
Material volume/item 133.6403 and number to manufacture 1
Material Steel stainless
Material Price R 3340
Quality 0.9
Product Complexity 0.7397
Milling volume 46.801
Manufacturing Complexity 0.683

Manufacturing sector Research
Project 4 Value R: 17128
Material volume/item 40.5474 and number to manufacture 1
Material Steel hot rolled
Material Price R 83
Quality 0.8
Product Complexity 0.8383
Milling volume 14.105
Manufacturing Complexity 0.8544

Manufacturing sector Dental
Project 5 Value R: 34929
Material volume/item 37.519 and number to manufacture 1
Material Titanium
Material Price R 1007

Manufacturing sector Implants

Project 6 Value R: 53815

Material volume/item 143.9558 and number to manufacture 2

Material Steel cold rolled

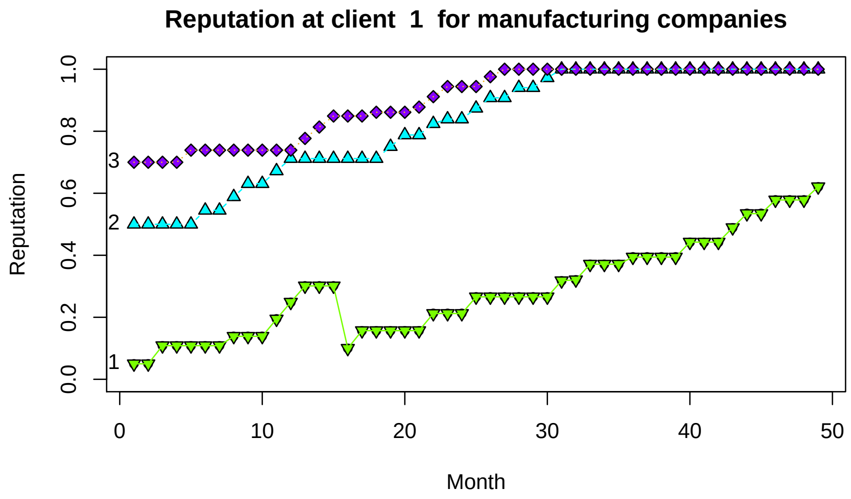
Material Price R 89

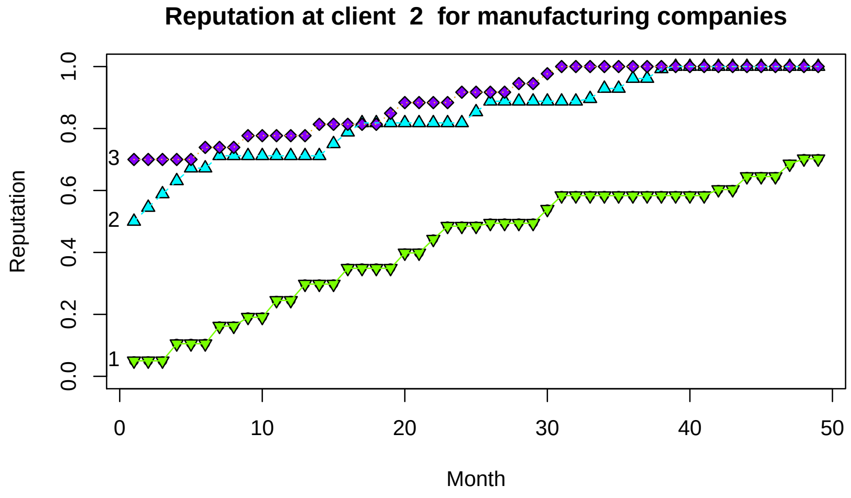
Quality 0.95

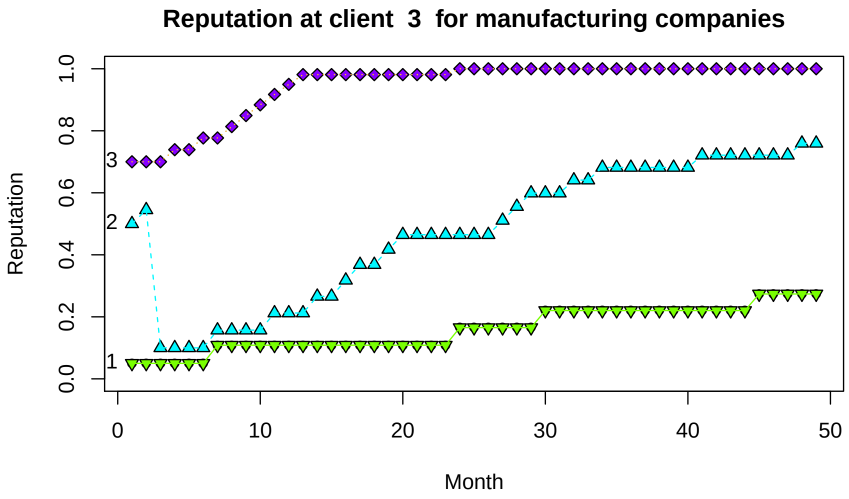
Product Complexity 0.68

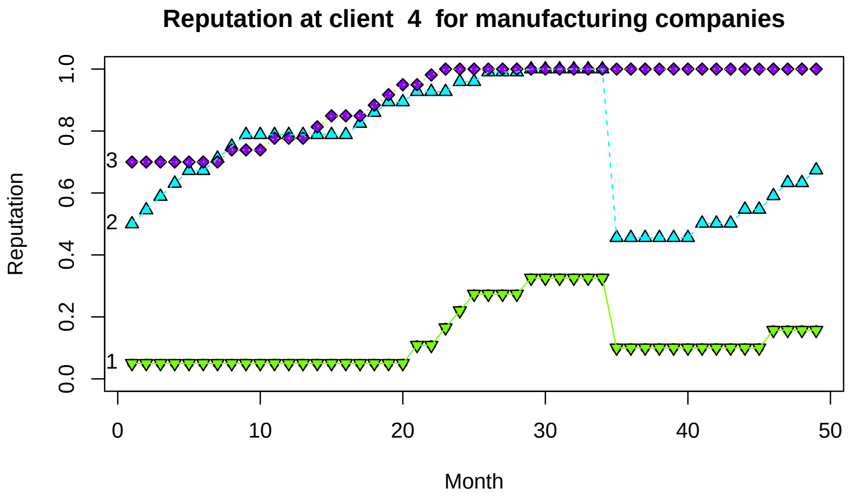
Milling volume 51.6739

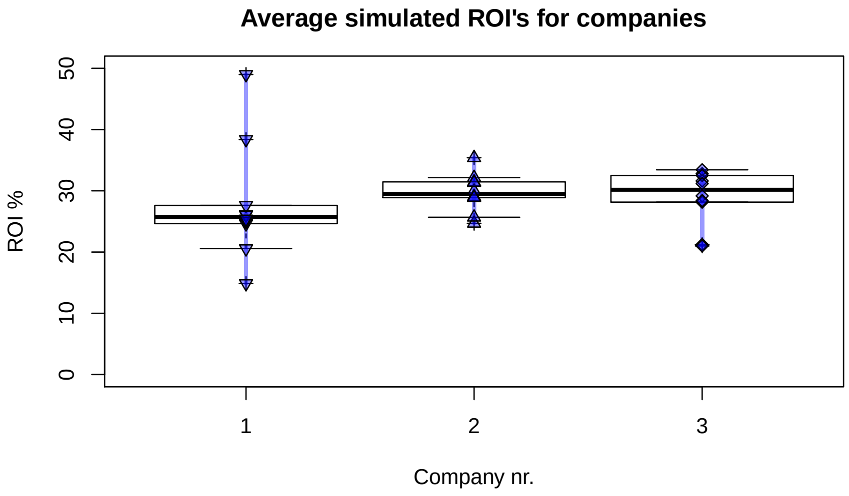
Manufacturing Complexity 0.659

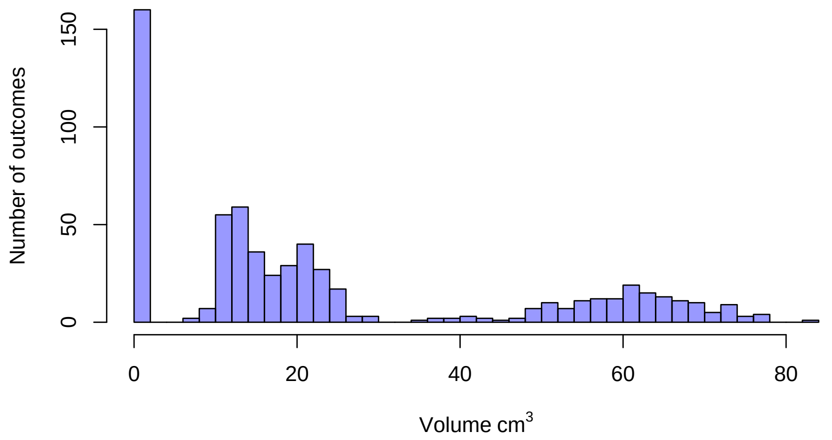

Reputation at client 1 for manufacturing companies


Reputation at client 2 for manufacturing companies

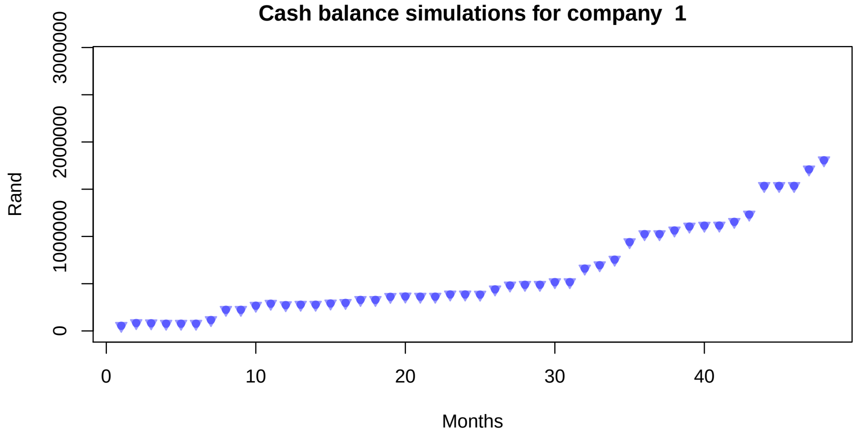

Reputation at client 3 for manufacturing companies
Reputation
0.0
0.2
0.4
0.6
0.8
1.0
3
2
1
0
10
20
30
40
50
Month


Reputation at client 4 for manufacturing companies
Reputation
0.0
0.2
0.4
0.6
0.8
1.0
3
2
1
0
10
20
30
40
50
Month

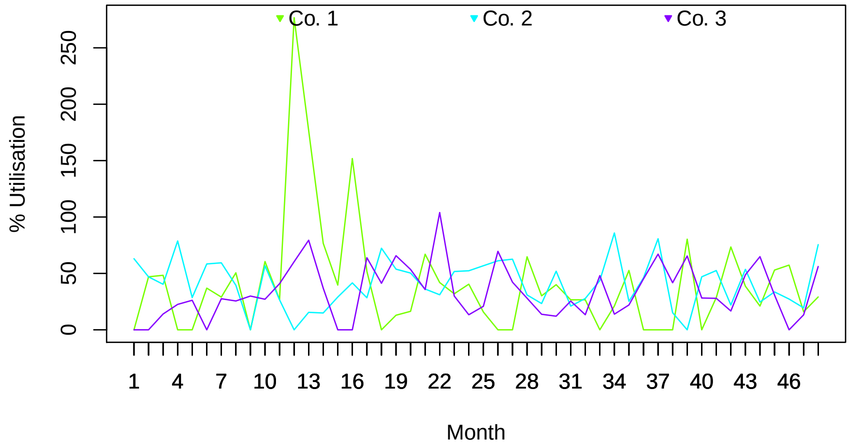

Average simulated ROI's for companies
ROI %
0
10
20
30
40
50
1
2
3
Company nr.



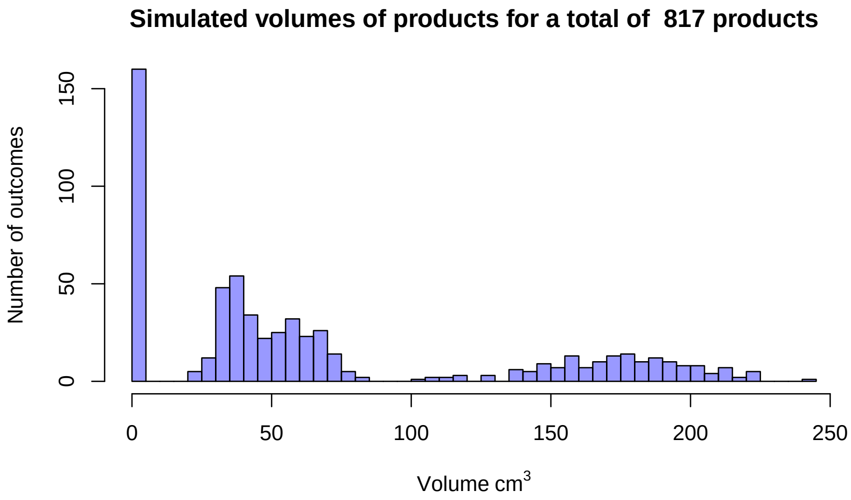
Simulated milling volumes of products for a total of 817 products



Cash balance simulations for company 1



Simulated utilisation of companies


Simulated volumes of products for a total of 817 products
Number of outcomes
0
50
100
150
0
50
100
150
200
250
Volume cm³

Appendix 4: Insight Maker simulation

Introduction to Appendix 4

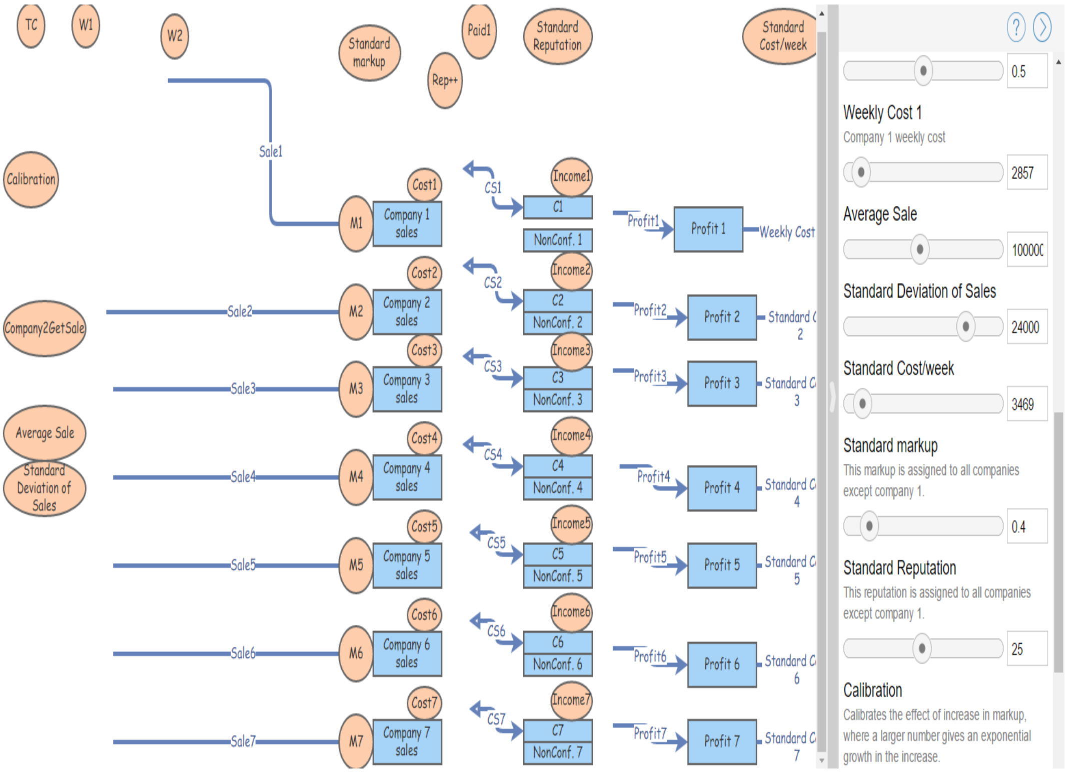
This appendix contains three screen shots from the Insight Maker website. The reader should take note that the model is a simplified version of the R model and is meant to allow the user to get a feel for the logic of the simulation, without adding all the complexities.

The first figure 12 shows a process view of the simulation with tenders being awarded using a similar logic as in R. The model has variables that may be set using the slider values to the right.

The first graph figure 13 shows the profit simulation for company 1 in a scenario where the company is barely making a profit on average. Due to the variability of the specific simulation it may be observed that the risk of making a loss is about at 40

The second graph figure 14 shown the building of reputation over weeks instead of months. Company 1 is the new company and starts at a much lower reputation than the current companies.

The model may be used by clicking on this link: https://insightmaker.com/insight/57050/Clone-of-Success-of-New-Business-in-Competitive-Environment



0.5

Weekly Cost 1

Company 1 weekly cost

2857

Average Sale

10000C

Standard Deviation of Sales

24000

Standard Cost/week

3469

Standard markup

This markup is assigned to all companies except company 1.

0.4

Standard Reputation

This reputation is assigned to all companies except company 1.

25

Calibration

Calibrates the effect of increase in markup, where a larger number gives an exponential growth in the increase.

Figure 12: Model process outlay on Insight Maker

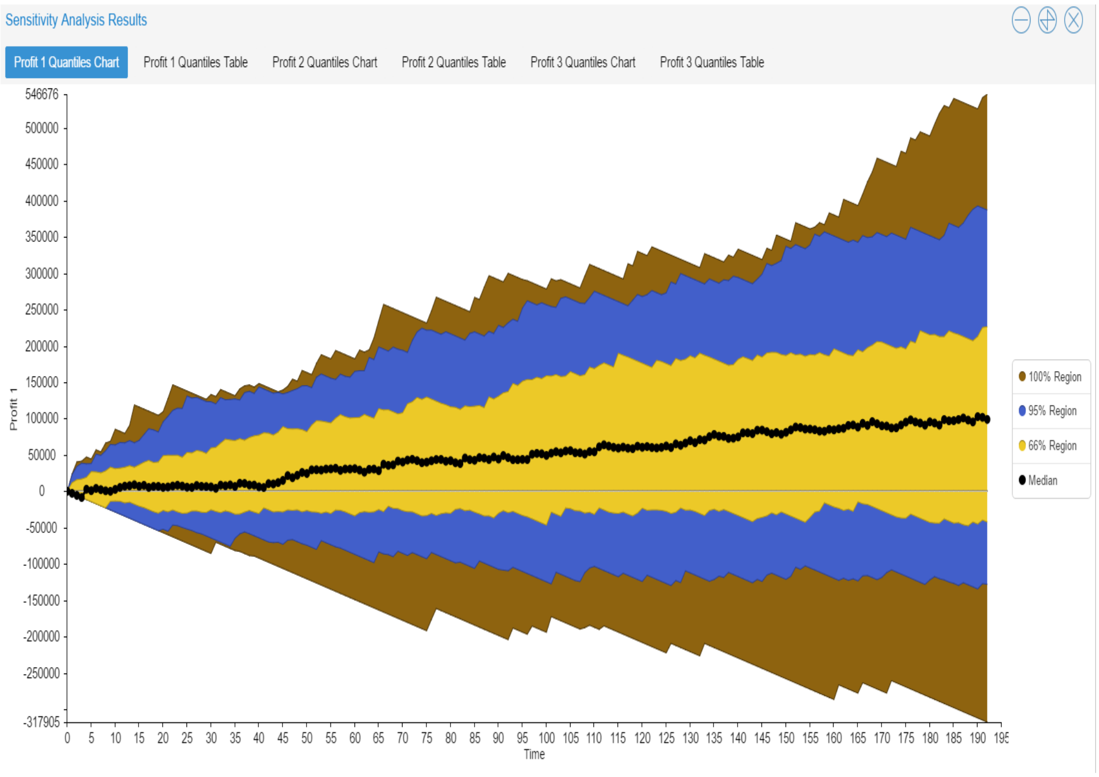


Figure 13: Simulation output showing Income over time, with various probabilities

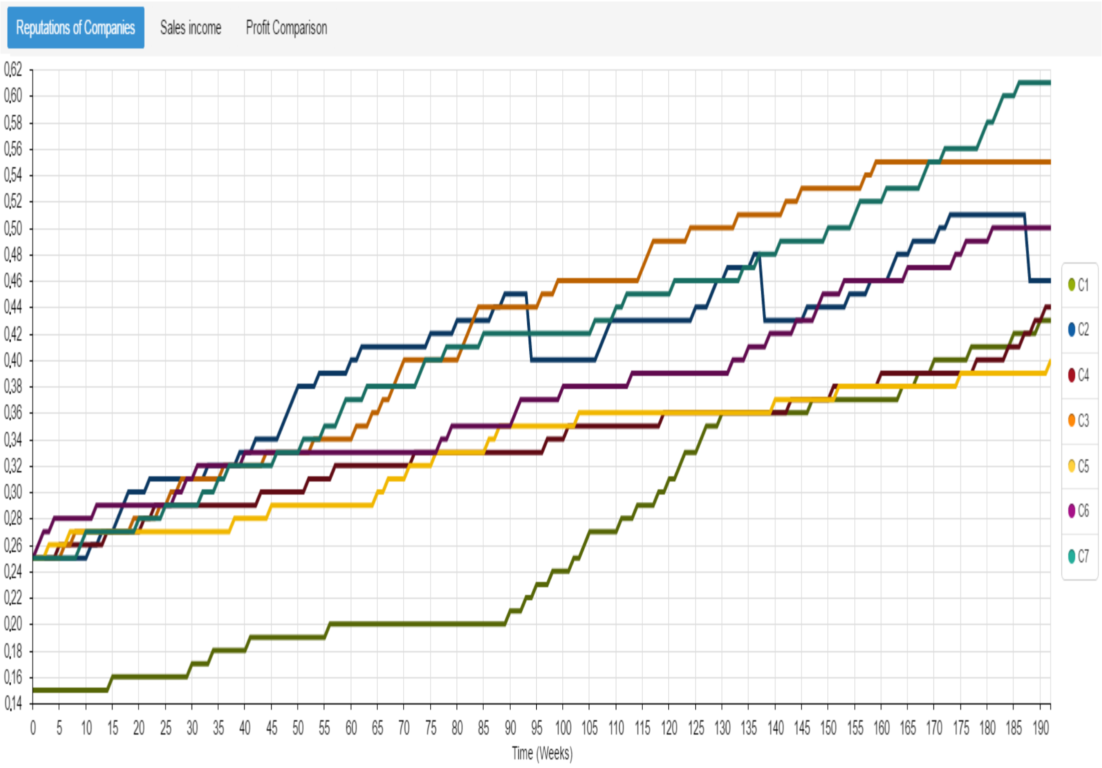


Figure 14: Simulation output showing reputation over time, for seven companies