Digitalisation of shop-floor operations in the South African Tool, Die and Mould Making Industry

By

Mncedisi Trinity Dewa

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Supervisor: Dr. S Matope

Co-supervisor: Prof. AF van der Merwe

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Declaration

By submitting this dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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Abstract

This doctoral dissertation focuses on the digitalisation of shop-floor operations in the South African Tool, Die and Mould Making (TDM) industry through the development of a Mobile Data Collection (MDC) tool known as a Shop-floor Management System (SMS). Recent results of the benchmarking initiative in the South African TDM industry have shown that most firms struggle on the global market due to intense external competition and internal shortcomings. Digitalisation has been advocated as a possible solution that can improve the competitiveness of tooling companies in the 21st century. The recent rise of digital technologies makes digitalisation an achievable reality now. However, how does one adopt such a factor in a South African tool-room environment? This study aims to answer this question through a systematic method of analysis, design, development and testing of a solution. This research demonstrates the application of systems thinking by implementation of current technology in a tooling factory environment. The theoretical framework established by Professor Schuh for the "Fast Forward Tooling Approach" on digitalisation was employed in this study. A Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis of recent South African TDM industry benchmarking study results was conducted to decide on areas of deficiency which can be improved through digitalisation. A deficiency in the areas of shop-floor data collection and manipulation within most TDM firms was identified and selected as one of the major problems to be addressed. Thereafter, company visits were conducted to finalise the industry specific characteristics in the South African tooling industry and desired system goals were established. Mobile and web-based technologies were selected as a sustainable solution for near real-time data collection in production environments. Furthermore, an analysis followed of the tool production value chain through company visits of firms within the Western Cape Province. The sub-processes of cost estimation, process planning and job-card data collection were identified as areas which can be improved by digitalisation. Key parameters for each of the identified processes were derived through knowledge engineering and the Analytical Hierarchical Process (AHP) methodology was used to rank the identified parameters. Based on a decision matrix for development software platform selection, the AppSheet platform was chosen and utilised in the development of mobile data collection modules for the above-mentioned functions. Another decision matrix for selection of hardware tools was used to determine the appropriate input devices to be used for recording of shop-floor data by the tooling factory personnel. The 'Google Sheets' cloud computing platform was utilised for the development of the back-end database. Reports on cost analytics, resource performance and order progress status were generated by the system in real-time for process-planning, rescheduling and maintenance decisions. The system also facilitates alerts in cases of event changes within the tooling value stream process. The developed SMS was validated in a

selected company for various scenarios and cases. The system outputs show that the use of mobile devices and web-based cloud computing platforms for data collection and manipulation effectively improves the shop-floor real-time data collection and visibility of a tooling factory environment.

Opsomming

Hierdie doktorale proefskrif fokus op die digitalisering van werkswinkel bedrywighede in die Suid-Afrikaanse gereedskap industrie, ‘n Mobiele data versamelings stelsel vir bestuurbesluitneming in die gietstuk- en vormvervaardiginig bedryf word ontwikkel. Onlangse resultate van die inisiatief in die Suid-Afrikaanse TDM-bedryf het getoon dat die meeste firmas sukkel op die globale mark as gevolg van intense eksterne mededinging en interne tekortkominge. Digitalisering is 'n moontlike oplossing wat die mededingendheid van gereedskapmaatskappye in die 21ste eeu kan verbeter. Die onlangse ontwikkellings in nuwe digitale tegnologie maak digitalisering in die werkswinkel 'n haalbare werklikheid. Die vraag is; Hoe neem mens egter so 'n faktor in 'n Suid-Afrikaanse instrumentkameromgewing aan?

Die studie beoog om hierdie vraag te beantwoord deur middel van 'n sistematiese metode van analise, ontwerp, ontwikkeling en toetsing van 'n oplossing. Hierdie navorsing demonstreer die toepassing van stelselingenieurswese deur die implementering van huidige tegnologie. Die teoretiese raamwerk, wat deur professor Schuh vir die "Fast Forward Tooling Approach" op digitalisering voorgestel is, word in die studie gebruik. 'n Sterk, Swakpunte, Geleenthede en Bedreigings (SWOT) -analise van onlangse Suid-Afrikaanse TDM-industrie se beginpunt-studie resultate is uitgevoer om te besluit op tekortgebiede wat deur digitalisering verbeter kan word. 'n Tekort op die gebied van data-insameling en hantering van winkelvloere binne die meeste TDM-firmas is geïdentifiseer en gekies as een van die belangrikste probleme wat aangespreek moet word. Daarna is maatskappybesoeke gedoen om die bedryfspesifieke eienskappe in die Suid-Afrikaanse gereedskapbedryf te finaliseer en stelseldoelwitte vas te stel. Mobiele en webgebaseerde tegnologie is gekies as 'n volhoubare oplossing vir byna intydse data-insameling in die produksieomgewing. 'n Analise van die waardeketting van die gereedskapsproduksie is gedoen tydens maatskappybesoeke van firmas in die Wes-Kaapprovinsie. Die subprosesse kosteberaming, prosesbeplanning en werkkaart data-insameling is geïdentifiseer as gebiede wat deur digitalisering verbeter kan word. Sleutelparameters vir elk van die geïdentifiseerde subprosesse is afgelei. Die metode van analitiese hiërargiese prosesse (AHP) is gebruik om die geïdentifiseerde parameters te rangskik. 'n Keusematriks is gebruik om die ontwikkelingsprogramplatformkeuse te maak en die AppSheet-platform is gekies en aangewend. Dit is ontwikkel en toegepas op die mobiele data-insamelingsmodules vir bogenoemde funksies. Nog 'n keusematriks is gebreuk vir die keuse van hardeware-gereedskap om die toepaslike sensorapparate te bepaal wat gebruik word vir die meting van werkwinkeldata gebruik deur die gereedskapfabriek-personeel. Die Google Sheets-wolkrekenaarplatform is gebruik vir die ontwikkeling van die ‘back-end’ databasis. Verslae oor koste-analise, hulpbronprestasie en bestellingsstatus is deur die stelsel in-tyd vir prosesbeplanning, herskikking en instandhoudingsbesluite genereer. Die stelsel

waarsku die gebruiker in gevalle van veranderinge binne die gereedskapwaarde-stroomproses. Die ontwikkelde stelsel is deur 'n geselekteerde maatskappy gevalideer vir verskeie scenario's en gevalle. Die stelseluitsette toon dat die gebruik van mobiele toestelle en webgebaseerde wolkrekenaarplatforms vir data-insameling en manipulasie die werkswinkelvloer in-tyd data-insameling en sigbaarheid van 'n gereedskap-fabrieksomgewing effektief verbeter.

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Without your help, the research was not going to be successfully completed, thank you.

List of publications

Most of the findings in this Dissertation have been published as peer-reviewed conference proceedings and journal research papers. These papers are:

1. **Dewa, M.T.,** Matope, S., Van der Merwe, A.F., and Nyanga, L. (2014). An Empirical Analysis of Operational Disturbances and their Impact on Business Performance in Manufacturing Firms: Case Tooling Industry South Africa. *Proceedings of the 26th SAIIE conference* (pp. 1-15). Muldersdrift, South Africa. (3 citations)
2. **Dewa, M.T.,** Matope, S., Van der Merwe, A.F., and Nyanga, L. (2014). Holonic Control System: A Proposed Solution for Managing Dynamic Events in a Distributed Manufacturing Environment. *Proceedings of the 26th SAIIE conference* (pp. 53-67). Muldersdrift, South Africa. (2 citations)
3. **Dewa, M.T.**, Matope, S., Van der Merwe, A.F., Nyanga, L. and Masiyazi, L. (2014). Holonic Manufacturing Systems: Their Applicability in an African Environment. Proceedings of Joint Symposium IMSS 14 and CIE 44 (pp. 1-13). Istanbul, Turkey.
4. **Dewa, M.T.,** Matope, S., Van der Merwe, A.F., and Nyanga, L. (2014). A Web-Based Holonic Inventory Management System for Tool and Die Operations. Proceedings of Joint symposium IMSS 14 and CIE 44 (pp. 14-29). Istanbul, Turkey. (2 citations)
5. **Dewa, M.T.,** Van der Merwe, A.F., and Matope, S. (2015). Holonic Control System: Reference Design Architecture for South African Tooling Industrial Clusters. Proceedings of the 45th International Conference on Computers and Industrial Engineering (pp. 1-8). Metz, France.
6. **Dewa, M.T.,** Van der Merwe, A.F., and Matope, S. (2015). Towards a Competitive South African Tooling Industry. International Journal of Social, Behavioural, Educational, Economic and Management Engineering, 9(11), 2716-2721. (4 citations)
7. **Dewa, M.T.,** Van der Merwe, A.F., and Matope, S. (2016). A Holonic Approach to Reactive scheduling When Rush Orders Emerge. Proceedings of the 16th International Conference on Competitive Manufacturing (pp. 337-342). Stellenbosch, South Africa.
8. **Dewa, M.T.,** Van der Merwe, A.F., Matope, S. and Nyanga, L. (2016). Decision Support Heuristics for Cost Estimation Model of Injection Moulds. Proceedings of the 27th SAIIE conference (pp. 163-176). Stone Edge, South Africa. (1 citation)

Dedications

I dedicate this work to my loving wife Sharon Rumbidzai Dewa, and my awesome daughter, Isabel Thembinkosi Dewa. Thank you for believing in me and allowing me to be the man I am today. To my Lord and Saviour Jesus Christ, thank you. Indeed, in You I live, move and have my being.

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List of Abbreviations

AHP – Analytical Hierarchical Process

CAD – Computer Aided Design

CAM – Computer Aided Manufacturing

CPS – Cyber Physical System

CPAS – Cyber Physical Assembly System

DAS – Digital Assistance System

DAE – Data Envelopment Analysis

DTI – Department of Trade and Industry

ERD – Entity Relationship Diagram

GPS – Global Positioning System

ICT – Information and Communication Technology

IIoT – Industrial Internet of Things

INCOSE – International Council of Systems Engineering

IoMT – Internet of Manufacturing Things

IoT – Internet of Things

ISTMA – International Specialised Tooling and Machining Association

MDC – Mobile Data Collection

MTM – Methods Time Measurement

NTIP – National Tooling Initiative Programme

OEM – Overall Equipment Manufacturers

QFD – Quality Function Deployment

RFID – Radio Frequency Identification

SMEs - Small to Medium Enterprises

SMMEs - Small Medium and Micro Enterprises

SMS – Shop-floor Management System

SST – Self-service Technology

SWOT – Strengths, Weaknesses, Opportunities, Threats

TAS – Technical Assistance System

TDM – Tool Die and Mould Making

WCTI – Western Cape Tooling Initiative

WIS – Worker Information System

Glossary

Benchmarking: the sharing of strategic business knowledge through comparative studies of business processes with the aspiration to generate new and beneficial knowledge through long-term symbiotic participation (Malherbe, 2007).

Cyber Physical System: a complex system which intertwines the information and the real world. The information system is a twin representation of the real-world. They are characterized by the fact that computer networks and built-in controllers control (possibly, with the participation of a person) physical processes by means of feedbacks, i.e., physical processes exert influence on computations and computations exert influence on the choice and course of physical processes (Lee, 2008).

Digitalisation: the continual implementation of current Information and Communication technologies to improve operations or processes (Schuh et al., 2016).

Internet of Things: a system where items (objects) in the physical world, and sensors within or attached to these items are connected to the internet via wireless and wired internet connections (Doukas, 2012).

SWOT Analysis: an examination of an organization's internal strengths and weaknesses, its opportunities for growth and improvement, and the threats the external environment presents to its survival (Gretzky, 2010).

Chapter 1: Introduction

1.1 Background

Tool, die and mould manufacturing has long been considered a key industrial sector and it is the sole supplier of basic production equipment. Therefore, the Tool, Die and Mould Making (TDM) industry, in South Africa is a critical support industry to the broader manufacturing industry, bridging the gap between product development and series production (Figure 1). This makes the sector a high value-adding constituent in the supply of manufactured products by being the heart of component manufacturing and by forming the backbone of the manufacturing sector (Malherbe, 2007). TDM firms have been traditionally known to consist of Small, Medium to Micro Enterprises (SMMEs) of which many are family-owned businesses. The European tooling industry represents an annual turnover of approximately 13,000 million Euros and comprises of over 7000 companies, 95% of which are SMMEs (Henriques and Pecas, 2013). Likewise, over 90% of TDM firms in South Africa are small businesses in the range of SMMEs (Geyer and Bruwer, 2006).

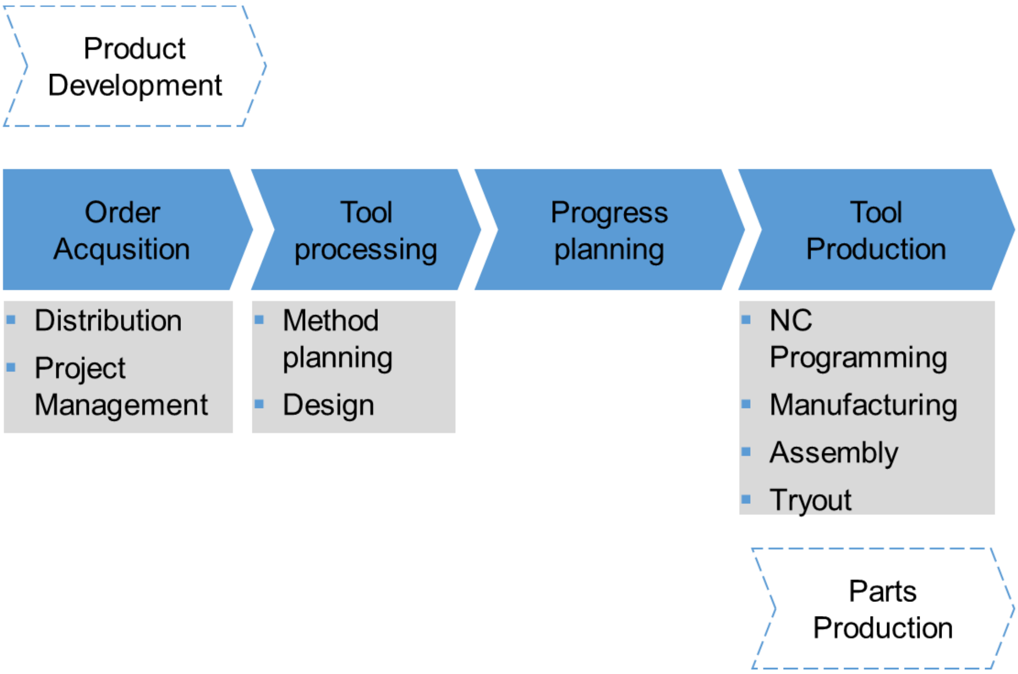

Figure 1: Tool, Die and Mould Making Industry Value Chain (adapted from Von Leipzig and Dimitrov, 2015)

The value chain of the TDM industry involves the processes shown in Figure 1 above: Order acquisition, tool processing and progress planning, and tool production. TDM operations are therefore traditionally known to be focused on a strong internal manufacturing process, making them knowledge and labour-intensive (Schuh, Pitsch, Komorek, Schippers and Salmen, 2014).

However, globalisation and the rapid growth in Information Communication Technologies (ICT) have changed views in the way production is being done in the TDM sector. Gaining a competitive edge is no longer solely determined by product quality and lower costs only, with customers of the tooling industry growing more demanding and rapidly changing their needs. There is a general consensus among researchers and industrialists that due date conformance and delivery reliability have also become major key success factors for firms which are successful in the TDM industry (Schuh et al., 2014 ; Schuh, 2011; Choi, Shin, Choi and Lee, 2010).

Consequently, successful TDM firms in Asia and Europe have changed their business strategies to design, manufacture and deliver products quickly and reliably to customers, thus giving them an edge in terms of lead times. This reality has caused some South African companies in the TDM sector to suffer as a result of global competition, thus hampering their profitability and growth. Records reveal that over 85 percent of the tools required by the local manufacturing sector are imported (Von Leipzig and Dimitrov, 2015), leaving the South African TDM sector with limited clientele.

Due to the challenges the South African TDM sector has faced in winning market share, the South African Government initiated the National Tooling Initiative Programme (NTIP) in March 2002. The NTIP, under the Department of Trade and Industry (DTI), was mandated to formulate strategies to revive the TDM sector. Two key programmes, namely the Skills Development Programme and the Enterprise Development Programme, were launched by the NTIP so as to improve the sector's competitiveness. Since then, an Enterprise Development Programme value chain for improving the status of the tooling industry was established, as shown in Figure 2.

Figure 2: Enterprise Development Programme Value Chain (adapted from McEwan, 2016)

As part of the work, the NTIP Enterprise Development team, in collaboration with academic institutions of higher learning, conducted a benchmarking programme (third stage of the value chain) for the South African TDM industry. The purpose of the benchmarking programme was to establish the status of the sector before strategic interventions could be designed and implemented. As revealed in an Engineering Artisan article ("state of benchmarking", 2012), results of the benchmarking study showed that most of the South African TDM industry companies observed would not survive global competition. The study also confirmed that product time-to-market was a key success factor to global competitiveness; hence there was a need for firms in the TDM industry to increase the flexibility and velocity of manufacturing while maintaining product quality.

Figure 3: NTIP/WBA Intervention projects industrialisation framework (adapted from McEwan, 2016)

Results of the recent benchmarking study of the South African tooling industry also reflected that companies are failing to compete in terms of production lead times. Based on the benchmarking results, an intervention projects industrialisation framework (fourth stage of the value chain shown in – Figure 2) was proposed by the NTIP, as illustrated in Figure 3. This framework cited twelve key strategic areas to improve the South African tooling sector. This dissertation focuses on a contribution to the *shop-floor management* part of this framework. This is mainly because the Managing Director of AfriMold, Mr. Ron MacLarty, was quoted by Engineering News online in October 2012 stating that the challenges that tool-making companies in South Africa face are mainly due to weak business practices in contract management, planning, production and project management (an implication of poor shop-floor management) (Moodley, 2012). The TDM sector in South Africa has been facing many challenges in satisfying customer demand on time over the past decade. Delivery due dates are not being met as promised and the firms are currently slower than their competitors. It was recommended that to solve the dilemma, the South African TDM industry must embark on collaborative manufacturing and improve on their tool-room visibility (Geyer and Bruwer, 2006).

Attempts are therefore being made to form industrial tooling clusters, which facilitate collaborative manufacturing. The "made-in-house" mind-set is gradually changing to a more collaborative mentality with various organisations teaming up to speed up product development and manufacturing. However, despite these efforts, South African TDM firms still lag behind in the global market place. A study by Schuh et al. (2015) on the concept of "Fast Forward Tooling" identified nine critical success factors tool-making firms can implement to improve their global competitive position. One of the factors suggested is that of "digitalisation", which has the potential to significantly improve the competitiveness of a tooling enterprise, thereby becoming the basis for other success factors (Figure 4).

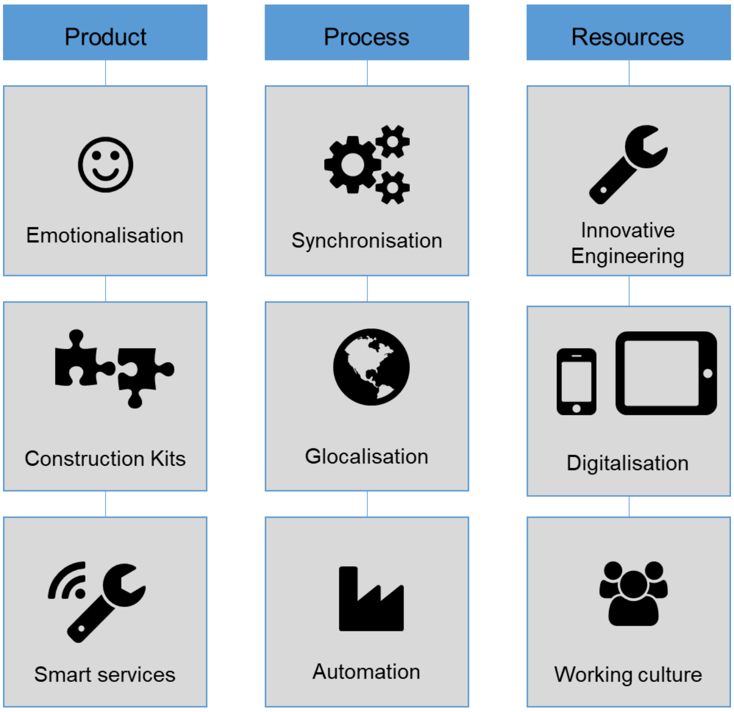

Figure 4: Fast Forward Tooling success factors (adapted from Schuh et al., 2015)

With the recent growth in ICT technology, such as Internet of Things (IoT) devices, it is now possible to apply the concept of digitalisation, thus improving the flexibility, agility, efficiency and productivity of operations in a tooling environment (Schuh, Pitsch, Salmen and Rittstieg, 2016a). Eventually, events leading to shop-floor disturbances can be continuously monitored and controlled before they negatively affect business operations. Furthermore, collaborative value-chain networks can be established easily using available digital technologies. According to Business Insider estimates, by the year 2020, approximately 20 billion devices will be connected to the internet, with 40% of these being IoT devices (Samuelson, Lanman and Pocek, 2015), as shown in Figure 5. The NTIP has realised the need for the development of Cyber Physical Systems for the local tooling industry to move into the fourth industrial revolution (Industry 4.0), a paradigm driven by the ability of everyday objects being able to connect to the internet. These systems are known to support strategic and operative decision-making based on quantitative performance or parameter indicators.

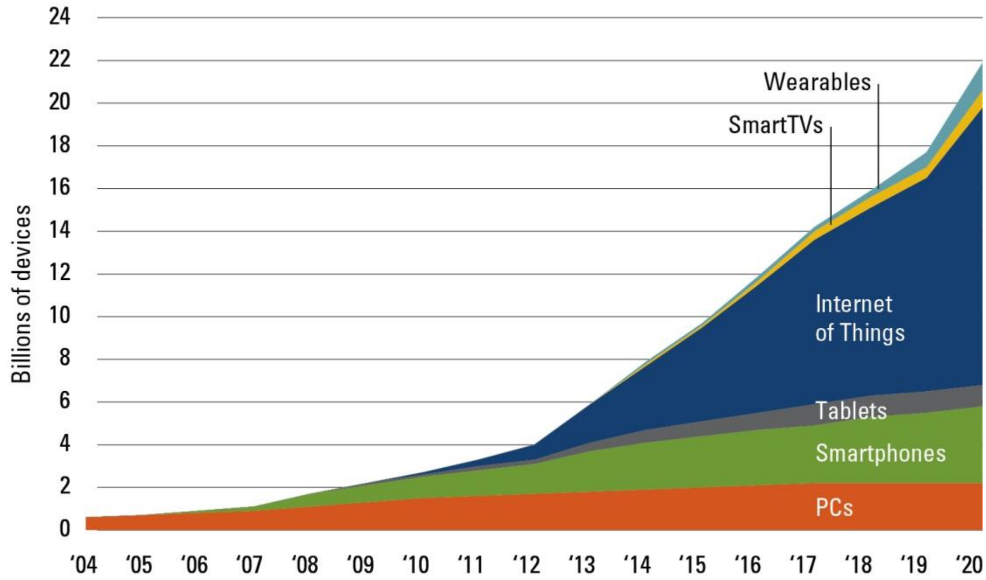

Figure 5: Growth in IoT devices (Samuelson et al. 2015)

According to Schuh, Kuhlmann, Pitsch and Komorek (2013), the IoT devices will greatly impact the way toolmakers will perform production in the 21st century. However, the application of IoT or current ICT technology is yet to be fully explored in terms of its relevance in the digitalisation of shop-floor operations in the South African TDM industry. Hence, the potentials of digitalisation are yet to be explored by South African tooling companies in a comprehensive manner. This research attempts to fill this gap by developing an IoT framework (a system) for the digital transformation of operations on the tool room shop-floor while accessing its applicability in the South African TDM sector.

1.2 Problem statement

Though the availability of digital technologies has increased in an exponential way within the 21st century, there is a slow industrial adoption in manufacturing companies, especially by SMMEs (Ebner, Buvat, Schneider-Maul, Kvj and Klade, 2013). This is mainly because these production firms tend to shy away from the digitalisation concept, due to misconceptions on the cost or impact implications of adoption. As a result, many firms follow the "watch and see" approach (Schumacher, Erol and Sihn, 2016). Due to the vast diversity of operations and products in the TDM industry, there are no complete or standard digital solutions on the market for toolmakers. Eventually, tool-making firms should develop their own personalised solutions (Schuh et al., 2016a). As a result, the potential benefits of digitalisation are yet to be explored by South African tooling companies in a comprehensive way.

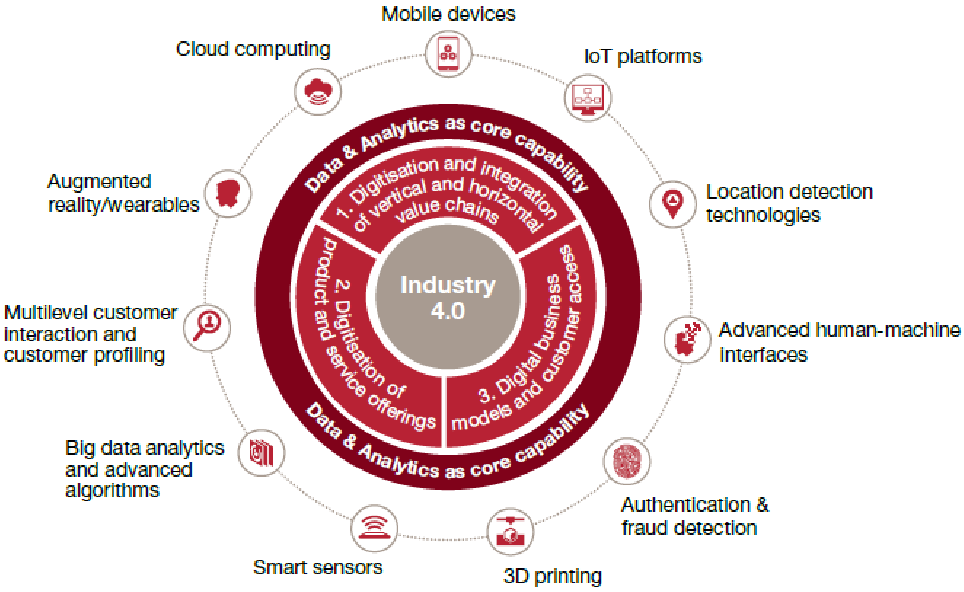

Figure 6: Industry 4.0 Framework and supporting digital technologies (Reinhard, Jesper and Stefan, 2016)

The Industry 4.0 framework, established by Reinhard et al. (2016), is used in this study to formulate the hypothesis. In this study, different classes of currently available digital technologies, which can potentially improve manufacturing operations, were outlined (Figure 6). Based on this framework, the hypotheses for the study are:

H_1: IoT platforms can be utilised for digitalisation of business operations in the South African tooling industry

H_2: Location detection technologies can be utilised for digitalisation of business operations in the South African tooling industry

H_3: Advanced human machine interfaces can be utilised for digitalisation of business operations in the South African tooling industry

H_4: Authentication and fraud detection technologies can be utilised for digitalisation of business operations in the South African tooling industry

H_5: 3D printing technologies can be utilised for digitalisation of manufacturing in the South African tooling industry

H_6: Smart sensors can be utilised for digitalisation of business operations in the South African tooling industry

H_7: Big data analytics and advanced algorithms can be utilised for digitalisation of business operations in the South African tooling industry

H_8: Mobile devices can be utilised for digitalisation of business operations in the South African tooling industry

H_9: Multilevel customer interaction and customer profiling technologies can be utilised for digitalisation of business operations in the South African tooling industry

H_{10}: Cloud computing platforms can be utilised for digitalisation of business operations in the South African tooling industry

H_{11}: Augmented reality wearables can be utilised for digitalisation of business operations in the South African tooling industry

The alternative hypothesis for the study is:

H_a: The above-mentioned technologies are inapplicable for digitalisation of business operations within the South African tooling industry.

1.3 Research question and sub-questions

The main question for the research is how can current information and communication technologies or IoT devices best be strategically employed to ensure digitalisation of shop-floor operations within the South African TDM industry?

The associated research sub-questions are as follows:

1. What is process or operational digitalisation?
2. Which business processes on the South African TDM shop floor can be improved by digitalisation?
3. Which digital technologies currently available on the market can be employed to improve the efficiency and productivity of shop-floor operations in the South African TDM industry?
4. How can the digital (shop-floor management system) solution be designed, developed and tested?
5. What strategies need to be employed to effectively deploy and use the system in a South African tool-room environment?

A breakdown of the above mentioned research sub-questions is given in Appendix 1-1.

1.4 Research statement

Current ICT devices or IoT tools can be designed and strategically employed to aid in digitalisation within the South African tooling industry, thus improving the sector's operational excellence, agility (response to internal and external changes), and product time-to-market (competitive position).

1.5 Research aim

The aim of the research is to digitalise shop-floor operations in the South African tooling industry by designing, developing, testing and validating a digital solution specifically for the TDM Industry in South Africa using current ICT or IoT devices. The goal will be to use modern technologies to do the same things toolmakers do on a daily basis in a dramatically more efficient and effective way. The developed system will serve as a Cyber Physical System for global decision-making with the goal of improving the sector's operational excellence, flexibility, agility, and product time-to-market.

1.6 Research objectives

To answer the stated research questions and achieve the aim for this study, the objectives of the study will be:

i. To define the concept of digitalisation in the context of shop-floor operations in the tooling industry.
ii. To derive the industry specific characteristics of the South African tooling industry through a SWOT analysis of benchmarking results and research context definition.
iii. To determine the current operational practices employed by firms in the South African TDM industry, together with the operational disturbances affecting the sector.
iv. To conduct a system requirements analysis and design, so as to establish system needs, users, functions and input parameters.
v. To determine the appropriate software platforms and hardware devices for the envisaged digitalisation solution.
vi. To design, develop and test the module subsystem components before deployment.
vii. To deploy and validate the final system prototype with end users by conducting use-case studies using selected products within tooling companies.

1.7 Research road map

To implement a digital transformation of business operations, a systematic approach is required (Krishnan, Pujari and Sarkar, 2015). The first objective will entail a thorough synthesis of the available literature on digitalisation. Various secondary sources will be used to establish the state of the art in the field of digitalisation within the tooling industry. According to Webster and Watson (2002), this stage will help in establishing progress made to date and gaps in the body of knowledge regarding the field of study. The output of this stage will be a working definition of the digitalisation concept in the context of tooling in South Africa.

According to Schuh et al. (2016a), the industry specific characteristics of the tool-making firm must be established first before any digital solutions are developed or implemented. Hence, the second objective will involve derivation of the observed characteristics of the South African TDM industry. During this phase, published results on the current benchmarking exercise in the South African tooling industry will be used for the determination of areas where possible improvements can be realised through digitalisation. At this stage, a SWOT analysis will be used for strategically selecting problem areas to focus on. According to Kime (2008), a SWOT analysis can be an effective decision-making instrument in the initial phases of a study. The output of this stage will be a decision on a problem area experienced by South African TDM firms which can possibly be addressed by digitalisation.

In the third objective, the current shop-floor operational practices employed in the South African TDM sector will be identified. This will be achieved through a questionnaire survey and site visits of specific selected companies. During the visits, work flow analysis and interviews will be used as the method of data collection. Targeted firms within the Western Cape Tooling industry will be visited during arranged benchmarking schedules and interviews done with the owners and workers at the companies. The purpose of the survey and visits will be to understand the currently employed operational methods with regard to running a tooling business with the aim of identifying processes which will benefit immensely from digitalisation. The output of this stage will be an operational description document which outlines the roles, operational processes, documents and limitations of the current system of operation. This output will be compared with published works to validate the value chain model established.

The fourth objective marks the genesis of the development stage of the solution. The specific processes requiring digitalisation will be identified for the purposes of deriving key input parameters. The method of knowledge engineering will be employed at this stage, with specific selected experts in the tooling industry visited and interviewed. The Delphi, or expert-opinion, method will be used in the careful selection of the field experts in tooling. The experts' knowledge on key parameters to consider, derived from these interviews, will be used to develop a digital blueprint of the system functionality for the solution to be developed. Engineering tools such as the Analytical Hierarchical Process (AHP) approach and correlation analysis will be employed to rank identified key parameters and derive relationships for the envisaged model.

To attain the fifth objective, which involves appropriate selection of the software and hardware components for the digital solution, a decision matrix will be employed to weigh different available alternatives. The optimal components that will be selected should meet set criteria which include cost, flexibility and quality requirements.

The sixth and seventh objectives, which involve system design, development, testing and validation, will be conducted using the software optimally selected during the fourth stage of implementation. In building the system model, the researcher should understand the:

- factors affecting today's tooling business environment;
- Industrial policies in South Africa;
- manufacturing environment and culture in South Africa;
- work-load levelling and line balancing rules; and
- Web-based information exchange frameworks.

The system will be tested within one of the tooling companies visited during the development and validation stages.

1.8 Significance of the research

The TDM industry provides machine tools and equipment required to fabricate most products in the Automotive and Packaging industries. Due to its position in the supply chain, the sector plays a significant role in contributing to the quality, cost and time-to-market of all manufactured products. This makes the sector pivotal to the South African economy by being the heart of component manufacturing and by forming the backbone of the manufacturing sector. Due to its importance, the South African government has realised the evident need to restructure and develop the TDM industry. The main reasons for this interest in the industry are:

1. Records, as highlighted by Geyer and Bruwer (2006), reveal that approximately 90% of the South African tooling industry companies comprise of Small, Medium or Micro Enterprises (SMMEs). According to Malherbe (2007), SMMEs are the economic backbone of developing economies and account for approximately 60% of all employment in South Africa, with a contribution of 40% to the South African Gross Domestic Product (GDP). In addition, the SMMEs are often the vehicle by which entrepreneurs from all socio-economic levels gain access to economic opportunities (Malherbe, 2007).
2. The value adding of tooling in the economy is high (estimated 1:19). For every R 1 million invested in TDM equipment and technology, over 250 million components could be manufactured, making the industry an important value-added catalyst in the South African economy (Geyer and Bruwer, 2006).

Thus, the output of this research will benefit the TDM industry in South Africa. Furthermore, this will eventually benefit the manufacturing sector that depends on the TDM sector, and the South African economy will be significantly boosted.

1.9 Contribution to engineering body of knowledge

The main contribution to knowledge and engineering will be the development of a digital solution which suits the environment of companies in the TDM sector in South Africa. In addition, the developed framework will address specific identified needs and criteria for the South African tooling context. This will result in the preservation of expert knowledge in the field of tooling. An extension to the literature on digitalisation and Industry 4.0 will be another major contribution of the research to the body of knowledge.

1.10 Limitations and assumptions of the study

Due to time constraints, it will be impossible to assess all firms in the TDM sector in South Africa. As such, only tooling industry firms forming an industrial cluster in the Western Cape Province will be used in the study for testing the designed system. The term “digitalisation” is broadly defined and can mean different things to different groups. In this research a “people-centred” approach to digitalisation is employed. This implies that the concept will only be used to enhance the productivity of shop-floor workers by assisting them with more efficient production methodologies.

1.11 Ethical implications of the research

The population of this study is a selected sample of manufacturing enterprises forming an industrial cluster in the TDM Industry within the Western Cape province of South Africa. The companies which will consent to participate in the study will only be used in this study.

The aspects to be considered in this research are:

- User requirement information collected from system users will be utilised for the purposes of this research only and specific companies revealing their needs will be protected.
- The system design will be done in accordance with the International Council of Systems Engineering (INCOSE) guidelines.
- The research will comply with the University’s guidelines on ethical aspects of scholarly and scientific research. As such, ethical clearance, as well as consent of the participants, will be obtained for the purposes of doing the research.

Since the research involves direct interaction with companies and data collection from the firms, the data collection instruments were sent, to be assessed and approved for obtaining an ethical clearance certificate (see Appendix 1-2).

1.12 Chapter Overview

Chapter 1 introduces the readers to the aim and objectives of the study. Chapter 2 contains the literature the researcher reviewed throughout the study. Chapter 3 presents the research design and methodology employed, whilst Chapter 4 presents the requirements analysis and design of the Shop-floor Management System (SMS). Research results of the system development are discussed in Chapter 5 and the validation of the system using case studies is presented in Chapter 6. Finally, Chapter 7 concludes the research report with a summary and opportunities for further research.

1.13 Conclusion

This chapter summarises the main research question which will be addressed in this dissertation. The background of the study and the research problem are outlined and the objectives which will be accomplished in the study are stated with a brief description of the methodology which will be followed for each objective. Chapter 2 will present the literature reviewed in the field of digitalisation and South African tool-making context.

Chapter 2: Literature Review

2.1 Introduction

In the 21st century, all production enterprises face a fundamental shift from a vendor-oriented market to a customer-oriented market (Wortmann, Muntslag and Timmermans, 1997). This places a demand on manufacturing organisations to change their way of doing business by shortening product life-cycles, reducing costs and maintaining production of quality products. Customers are the driving force of the business world. It is common knowledge in the business world today that customers are the life blood of organisations. Lack of customers or a depletion of the customer base has seen some businesses fold at an alarmingly fast rate (Dewa, Mhlanga, Masiyazi and Museka, 2013). Therefore, the question that remains for sustained survival in the cutthroat business environment is: What needs to be put into place to ensure that customers stay?

The growing instability in the business arena, advancement in Information Communication Technologies (ICT) and increased global competition have placed a demand on manufacturing enterprises to change their ways of doing business (Ongori and Migiro, 2013). Consequently, new paradigms for configuring manufacturing systems have emerged. Current market trends require production firms to possess the ability to respond to frequent product changes, shop-floor disturbances with shorter production runs, lower inventory levels and higher productivity (Giotopoulos, Kontolaimou, Korra and Tsakanikas, 2017). As a result, these requirements warrant systems which can constantly adapt and are highly flexible. Flexibility and the ability to anticipate then respond to changes as they emerge are increasingly becoming fundamental characteristics that all businesses should possess to survive global competition. One of these emerging ideas is that of digitalisation (Brennen and Kreiss, 2014). This chapter reviews the most recent critical literature with regard to digitalisation, the paradigm of Industry 4.0, IoT devices and their relevance in improving operations in the TDM industry in South Africa in particular.The following section introduces the concept of digitalisation and also outlines how it is relevant to the South African TDM sector. Recent benchmarking results are also used to reflect on possible areas which can be impacted by digitalisation.

2.2 Digitalisation

In this section, the concept of digitalisation is introduced as a potential initiative to improving the competitiveness of TDM operations. The benefits of digitalisation are outlined and technologies supporting digitalisation are also explained before state of the art research on digitalisation within the global tooling industry is shown. Justification is given as to why this concept is relevant in the tooling industry now. Eventually, the research gap is also outlined.

2.2.1 Concept of Digitalisation

Digitalisation can be viewed as the implementation of current modern ICT to improve production processes, efficiency and productivity (Schuh et al., 2016). The concept has been advocated for having the potential to significantly improve the competitiveness of any manufacturing enterprise (Oesterreich and Teuteberg, 2016). According to Stolterman and Fors (2004), digitalisation or digital transformation refers to the changes associated with the application of digital technology in all aspects of human society (Parviainen, Tihinen, Kääriäinen and Teppola, 2017). The concept differs from that of digitisation which refers to the conversion of analogue or manual processes to digital ones. Brennen and Kreiss (2014) defined the concept of digitalisation as “the adoption or increase in use of digital or computer technology by an organization, industry or country”. Unfortunately, the rate of adoption of digital technologies in the manufacturing sector has been slow with most firms using a “wait and see” approach (Park, 2015). However, the few companies who have implemented digital solutions have experienced success stories. Therefore, tool-making firms ought to view digital solutions as an opportunity rather than as a threat (Schuh et al., 2016a).

Digitalisation is to be viewed as an on-going process rather than as a one-stop destination as firms ought to continually evaluate what is worth digitalising. This is mainly because digital technologies evolve on the market at a quick pace in a globalised world. To be successful, one has to keep up with current technological trends and pilot small solutions incrementally to inspire workers while improving competitiveness.

2.2.2 Digitalisation scope

The concept of digitalisation has been reckoned to apply to different scenarios and applications in the business world. The available literature records three different views of digitalisation: The process-level, product-level and supply-chain views. In the process-level view of digitalisation, new digital tools are adopted to streamline business activities and processes by reducing manual steps (Parviainen *et al.*, 2017), while the product-level view focuses on the ability to turn existing products or services into digital variants, thus offering a competitive advantage over other tangible products (Henriette, Feki and Boughzala, 2015). Furthermore, the supply-chain view of digitalisation only focuses on the use of digital technologies to connect suppliers and customers, radically transforming business procedures through connectivity. Since this study focuses on the digitalisation of shop-floor operations in a tooling environment, only the process-level view applies in this study. Through process-level digitalisation, real-time information is made readily available for decision makers within an organisation (Reinhard et al., 2016).

Figure 7 illustrates the scope of processes involved when digitalisation occurs in a firm. The basis for digitalisation is the recording of data, and there is a lot of data one can find in a manufacturing environment. Hence, the concept enables the recording of information from manufacturing processes as well as serial production. After the data is collected, it is then processed into smart data or information which is presented in a meaningful way for managers and decision makers to make decisions (Schuh et al., 2016a). This permits the establishment of unique know-how or sustainable knowledge. As a result, a company will possess expert knowledge which can be used for future decision-making and may be commercialised.

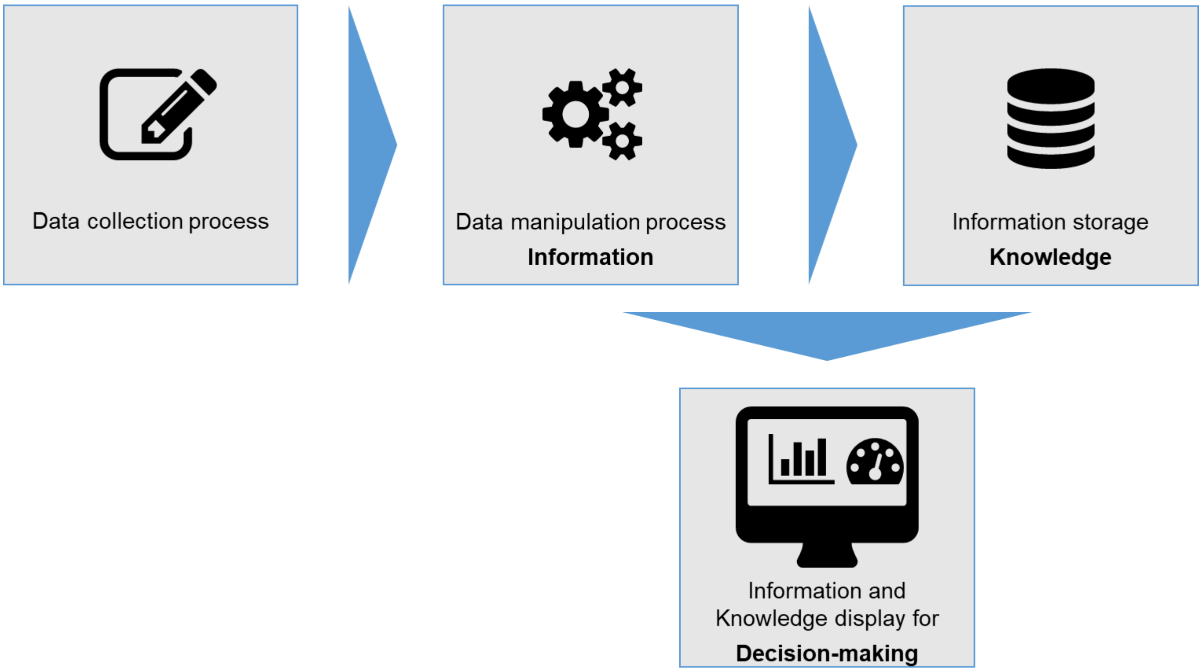

Figure 7: Digitalisation Scope (concept adapted from Schuh et al., 2016a)

During the implementation of digitalisation, companies should address a few questions for the venture to be effective. These questions include:

1. Which business processes are likely to experience immense benefits from digitalisation?
2. What knowledge or information is required to make daily operational decisions?
3. Which data must be collected to generate the required information?
4. What are the sources of the required data?
5. Which digital technologies can be used for data collection, manipulation and information display?

2.2.3 Benefits of Digitalisation

The digitalisation effort pays off in a lot of ways. Firstly, digitalisation improves the process transparency which is a key step to more efficiency and profitability (Satyavolu, Setlur, Thomas and Iyer, 2015). Anything recorded can be easily measured, tracked and monitored. Secondly, since digitalisation ensures the processing of data into real-time information, often referred to as smart data, informed decision-making by production managers is supported. Eventually, the productivity of the enterprise is considerably improved since decisions can be made quickly based on the readily available information (Oesterreich and Teuteberg, 2016). The productivity improvement will result in a substantial reduction in time spent by employees searching for information, as workers spend most of their time on activities that produce value. As a result, all employees become more efficient when working in an optimised process. Thirdly, with informed decisions made at all levels of the value chain, the costs associated with incorrect information and erroneous decisions are greatly eliminated (Stancioiu, 2017). Moreover, the business integration is significantly improved by digitalisation, helping firms to significantly reduce time spent on interruptions while simultaneously enhancing product or service quality (Brettel, Friederichsen, Keller and Rosenberg, 2014). This is crucial in the TDM industry where there are no complete or standard solutions on the market for tool-making firms. As such, each company is supposed to develop its own solution as they all have varied applications and business context scenarios. Enterprise Resource Planning (ERP) solutions on the market usually do not fit well in a tooling environment, as they are offered with more modules than required. As a result, buying one is very expensive and extra costs may be incurred in efforts to adapt the system to the business rules of the company using it. According to Schuh et al. (2013), digitalisation can aid in collaborative work within the tooling industry by ensuring seamless communication within value creation networks. Eventually the product time-to-market is improved while the customer focus is enhanced (Zawadzki and Żywicki, 2016).

According to Schuh et al. (2016a), digitalisation in the context of tooling has to be adapted to industry specific characteristics. Hence there is a need to determine the industry specific characteristics of a group before selecting and implementing the appropriate digital technologies. In a study on establishing a framework for digitalisation in production firms, Krishnan et al*.* (2015) outlined four dimensions digitalisation can address in manufacturing. The operational excellence of a production firm can be enhanced as productivity and efficiency across processes and functions grow. Furthermore, a firm’s agility or adaptation, its response to internal and external changes (disturbances), is improved. The dimension of innovation and customer centricity are also enhanced in a firm by digitalisation.

2.2.4 Limitations and misconceptions of digitalisation

Though digitalisation has the potential to significantly improve operations, there are a few shortfalls which need to be addressed. The internet is one of the central technologies in digitalisation. As a result, data security of sensitive information remains a challenge that is yet to be adequately resolved (Iwaya, 2016). Furthermore, workers with a low computer or digital literacy require sufficient training before they can implement or use any digital solutions (Richter, 2017). These factors can slow down the acceptance or possible adoption of digital solutions. Digital transformation of business operations has often been perceived by business owners as a costly venture (Ebner and Bechtold, 2012). As a result, a majority of SMMEs do not consider trying to implement any new technology into their businesses. However, the cost of some digital devices have significantly reduced on the market and the Do-It-Yourself (DIY), open source devices have opened new opportunities for innovative designs at little or no cost at all (Nevo and Chengalur-Smith, 2017; Upasani, 2016). Furthermore, digitalisation is often confused by some to mean the same thing as automation. According to Henriette et al. (2015), process automation is only one part of the entire digitalisation framework. This perception only focuses on the process-level view of digitalisation, yet the concept also includes the product-level and supply chain level as discussed earlier in section 2.2.2.

As a result, another misconception workers usually have is that digitalisation may lead to the loss of jobs if manual processes are reduced by semi-automated methodologies. In contrast, digitalisation should be viewed as a way of making processes better and more effective rather than replacing human labour (Parviainen et al., 2017). The next section will give a brief overview of the disruptive characteristics of employing new technologies.

2.2.5 Disruptive digital technologies

Organisational survival depends on the ability to make rapid and continuous changes to keep up with the pace of technological advancements (Brown and Eisenhardt, 1997). However, the introduction of a new technology in business operations poses a number of implications. Work by Christensen (1997) cited that any new technology can either be sustaining or disruptive. Sustaining technologies are incremental improvements to an existing established technology while disruptive technologies significantly alter the way businesses operate through displacing an established technology or way of doing things. As a result, in most cases, introduction of new technologies to improve business operations brings in some “disruptive characteristics” (Christensen, 1997).

Examples of disruptive technologies include the way desktop computers displaced typewriters; cell phones displaced the landline telephone and the way Email transformed the face of communication, largely displacing letter writing and disrupting the postal industry. Disruptive technologies are known to reshape the manner in which organisations operate, thereby increasing the strategic use of information technology (Garrison, 2009). However, though adoption of disruptive technologies can radically improve the face of a business, they carry both positive and undesirable characteristics.

2.2.5.1 Nature and positive Impact of disruptive technologies

Since all disruptive technologies start off without any proven practical application, there is usually uncertainty in their value (Dewar and Dutton, 1986). The benefits of implementing a disruptive technology can only be realised in the process of time. Consequently, manufacturing organisations tend to be reluctant in adopting them until there is a track record of their benefits from others. Secondly, disruptive digital technologies often lead to a phenomenon known as "cannibalism"; a process which requires a company to reallocate resources, develop new procedures and routines which alter organisational strategy (Garrison, 2009). As a result, managers in most firms are known to reject disruptive technologies so that they can remain focused on their current business strategy. Furthermore, disruptive digital technologies may result in organisational restructuring or re-orientation.

Disruptive technologies carry different implications for companies, workers, customers, and industries. Customers are usually poised to benefit the most as new technologies allow cheaper, or free, and more sophisticated goods and services to emerge (Ko, Kim and Lee, 2009). The effects on firm workers may include some advantages, such as increased efficiency and workplace flexibility (Campatelli, Richter and Stocker, 2016). Companies in general will benefit from labour costs savings through increased labour efficiency and the transition of some tasks to computers and machines (Chin, Chan and Gupta, 2007).

2.2.5.2 Disruptive characteristics of digital technology

Though digital technologies offer a promise of improved internal efficiencies and creation of external opportunities (Parviainen et al., 2017), they also carry some negative implications. These implications, also coined as "disruptive characteristics", can be realised at a business, organisational or shop-floor level. In a Global survey conducted on 4800 business executives, managers and analysts by Deloitte, 76% of the respondents indicated that digital technologies will disrupt their industry greatly or moderately in the near future (Kane, Palmer, Philips, Kiron and Buckley, 2015).

Firstly, digital technology introduction alters the operational methods employed on the shop-floor (Vodanovich, Steinhuser and Honnola, 2017). Manual or routine tasks can get replaced by automated systems. As a result, the role of workers is redefined, thus placing a huge demand on the requisite skills required. Employees can find difficulty in adjusting in terms of the competence levels demanded as tasks are changed and new roles are created (Henderson, 2006). Eventually, the need for training, education and re-skilling emerges for workers to keep up to pace with the changes (Ullrich, 2016). Furthermore, with digital solutions redefining task execution, some jobs may be displaced leading to unemployment in some cases. Consequently, the social and cultural dimension of the working environment can be affected by digital transformation in a manufacturing environment (Schumacher, Sihn and Erol, 2016). Secondly, organisations can experience challenges due to the adoption of digital technologies. Digital transformation affects many parts of the organisation including business strategy (Kane et al., 2015), business models and company culture (Kagermann, 2015). The firm's management will have to adopt change management strategies in response to the changes. As a result, the products or services offered to customers are changed thus potentially ending existing businesses while creating new ones (Karimi and Walter, 2015).

Thirdly, digital technologies can result in changes in a firm's operating environment. An existing established industry may be rendered obsolete with a new vendor displacing another. Much like labour, some industries may be displaced as existing products and services become obsolete, free, or unprofitable (Karimi and Walter, 2015). However, Christensen (1997) indicated that during seasons of disruptive transition, organisations that have succeeded deliberately ignored the possible risks of disruptive digital technologies. Instead, these firms find ways of introducing them to change business operations. A thorough understanding of the currently available digital technologies can assist in eliminating the above mentioned shortcomings and misconceptions regarding digitalisation. The next section will give a brief overview of some of the common classes of currently available digital technologies.

2.2.6 Current digital technologies

With the cost and power in computing dropping exponentially each year into the range of cents and milliwatts respectively, digital technologies are currently becoming common and ubiquitous. It is now very possible to grant internet connectivity to numerous small and unimaginable objects, and this reality has ushered the world into an era called the "Internet of Things" (IoT) (Mattern and Floerkemeier, 2010). The concept was first coined by Ashton (2009) in the year 1999, when he painted a picture of a vision where computers could collect data on their own without the need of any human effort or contribution. In his account he argued that:

If we had computers that knew everything there was to know about things—using data they gathered without any help from us—we would be able to track and count everything, and greatly reduce waste, loss and cost. We would know when things needed replacing, repairing or recalling, and whether they were fresh or past their best. (Ashton, 2009)

He went on to suggest that Radio Frequency Identification (RFID) and sensor technology were capable of making this vision a reality. With the promise of improved productivity and efficiency through the proposed concept, the world of manufacturing has since embraced the IoT concept, with some scholars naming it the "Industrial Internet of Things" (IIoT) (Prasanth, Rumi and Soundar, 2017) and some the "Internet of Manufacturing Things" (IoMT) (Cutler, 2014). This concept, based on Cyber-Physical Systems (CPS), has now ushered the manufacturing world into the fourth industrial revolution, called "Industry 4.0" (Stancioiu, 2017). For manufacturers to prepare themselves to be competitive enterprises, there is an increased need to look at how these advanced ICT can boost their value creation activities and improve their position on the market (Guzman, 2015).

2.2.6.1 Digital technologies for value chain integration

Cloud computing platforms, IoT networks, mobile devices and wearables facilitate the integration of business processes thus making firms realise new models and ways of trading. The IoT is the network of physical objects around us that contain electronic components, software, sensors and networking systems that allow these objects to exchange and acquire information. Hence, an IoT framework comprises of everyday physical objects with attached sensors which send big data streams to the internet for information analytics via a communications or networking channel (Doukas, 2012). To converge this world of devices together in a more efficient way, IoT platforms have emerged (Ray, 2016). These are readily available online tools for linking sensors to the cloud with analytics capabilities as well. These include the Google cloud, Thingworx, Microsoft Azure, and Jasper (Cisco) platforms (Lamont, 2017).

More recently, mobile devices like smartphones and tablets have become ubiquitous in everyday life (Trucano, 2014). These gadgets have become readily available at low prices, causing a growth in usage in the 21st century. Modern smartphones have become programmable. They also come with a growing number of embedded sensors, such as a digital compass, an accelerometer, gyroscope, GPS, microphone and camera (Vieira and Vieira, 2015). As a result, the range of data these devices can handle is enormous, including types like text messages, GPS, barcodes, QR-codes, pictures or images, audio and video (Park, 2015). Furthermore, nowadays, mobile devices can browse the internet, making them easily part of a global network of other objects. Mobile data can be accessed anywhere at any time, in near real-time (Jung, 2011). Mobile devices are well-suited for applications in which the data collection is repeatedly done, conducted in a distributed way and a large percentage of the data types collected are quantitative in nature (Satterlee, McCullough, Dawson and Cheung, 2015).

Wearables and augmented reality are two technologies that look poised to empower the worker of tomorrow to be extraordinarily efficient and productive through contextual computing capabilities (Elvins and Todd, 1998). These applications are used for maximising the contextual awareness of an individual through providing real-time information, which is fundamental for decision-making. A majority of applications for this technology exist in the medical field where human monitoring systems for pulse rate, body temperature and exercise habits have been developed (Chandra, 2016; Abbasi, Ur-Rehman, Qaraqe and Alomainy, 2016). However, the major drawbacks for the adoption of this technology include limited battery lifespan of devices, design and aesthetics of wearables, data privacy and management, and interoperability among solutions and vendors (PR Newswire, 2016). Furthermore, the cost of implementing such technologies is very high, while a majority of vendor-oriented integration issues remain unresolved (Newman and Clark, 1999).

According to Mell and Grance (2011), Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g. networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction. This model of technology is a broad field of study with numerous resources which allow the sharing of data over distributed systems. Google has the most commonly used cloud computing resources in the form of Google drive (Carretero and Blas, 2014). Microsoft Azure is another commonly used platform for Windows users (Jennings, 2009). Cloud computing platforms have a wide usage in many domains, including business (Shroff, 2010), healthcare and manufacturing (Hung, Lin, Quoc Huy, Yang and Cheng, 2012).

2.2.6.2 Digital technologies for product and service offerings

Smart sensors, customer profiling and big data analytics software offer new product variants and services in the digital world. A number of technologies, which enhance the interaction of customers with products and services that companies offer, are emerging on the market (Meuter, Bitner, Ostrom and Brown, 2005). These solutions allow customers to define the product design during the conceptualisation stage and also order items online without having to visit a firm or store (Meuter, Ostrom, Roundtree and Bitner, 2000). Application areas for this class of technology include the use of self-service technologies (SSTs), such as telephone banking, automated hotel checkout, and online investment trading, whereby customers produce services for themselves without assistance from firm employees. With the volume and speed of data generated by computers and the internet growing exponentially each year, the field of big data has grown and attracted much attention in academia (Rajaraman, 2016). The field involves the use of data streams for inferential decision-making. As a result, many domain applications for big data technology have emerged and these include; supply chain management (Shahriar, Wamba, Gunasekaran, Dubey and Childee, 2016), manufacturing (Zhong, Xu, Chen and Huang, 2017) and healthcare (Yichuan and Nick, 2017). A major drawback in the wide adoption of big data analytics technologies is the issue of data security (Zhenning, Frankwick and Ramirez, 2016).

With the ability to embed intelligence in systems made easier in the 21st century, smart sensors are also emerging on the market (Meijer, 2008). These devices can make decisions based on the data they obtain through instrumental recording. Smart sensors have been used widely in academia and research with applications in the transportation and logistics industry (Moreu, 2017), manufacturing (Nihtianov, 2017), security (Acho, 2017) and healthcare (Gaggioli et al., 2013) amongst many other examples.

2.2.6.3 Digital technologies for business models and customer access

Location and detection technologies together with advanced human interfaces, 3D printing and authentication detection technologies are another class of current digital devices. With the Global Positioning System (GPS) technology freely and readily available nowadays, the tracking of object position is now possible. In the early 19th century, barcode technology was commonly employed to record and communicate locational information for objects. However with the advancement of electronic gadgets, RFID technology is also growing in usage within the manufacturing sector (Nambiar, 2009). These technologies allow Automatic Identification (Auto ID) and tracking of objects while collecting specific data of parts moving in an environment (Ting, Tsang and Tse, 2013). Location detection technologies like RFID devices are known to have many applications in supply-chain related problems, such as creating an Internet of Things framework (Welbourne et al., 2009), distributed manufacturing control (Barenji, Barenji and Hashemipour, 2014) and mass customisation production (Zhong, Dai, Qu, Hu and Huang, 2013) . The major drawbacks in the implementation of RFID technology have been as a result of proximity challenges, the effect of metal and water on RFID waves (Barenji et al., 2014) and the high cost of implementation (Welbourne et al., 2009). Due to the high implementation costs, SMMEs rarely use these technologies on the shop floor. With the growth of embedded sensors in industrial equipment, human-machine interfaces for the real-time analytics of machinery performance have become a present hour reality (Teramoto and Onosato, 2001). Advanced human-machine interfaces are common on current industrial machines with numerous applications, which include motion study (Inoue, Okuda, Tani and Mae, 2001), and manufacturing (Jeong, *et al.,* 2013). The high rate of cybercriminal activities and need for security in specific fields make authentication and fraud detection technologies critical. The retail payments have the highest usage of these technologies (Summers, 2009). Other applications are found in internet banking (Bignell, 2006) and security systems (News Bites, 2014). Rapid prototyping has become a key stage in the product development cycle and 3D printers have emerged on the market to fill this gap. Their usage has been broad in fields of construction (Honiball, 2010), manufacturing (Long, Pan, Zhang and Hao, 2017) and medicine (Christensen and Rybicki, 2017; Hirsch, Vincent and Eisenman, 2017; Leng et al., 2017; Costa, Nosach and Harding, 2017 and Radenkoic, Solouk and Seifalian, 2016). The next section discusses the state-of-the-art in the field of digitalisation. Models and methodologies employed in the digital transformation of operations will be explored for the purposes of selecting an appropriate approach for the study. Furthermore, the application of digitalisation concepts in the TDM industry to date will be reviewed.

2.2.7 State of the art

The digitalisation of different parts of business operations to support workers results in the development of Digital Assistance Systems (DAS) (Hold and Sihn, 2016) and Technical Assistance Systems (TAS) (Kruger, Lien, and Verl, 2009). Hinrichsen, Riediger and Unrau (2016) defined an assistance system is a technical system that receives and processes information from its environment in order to support people carrying out their tasks. While DAS are computer systems which organise and present information in a way to support operator decision-making (Reisinger, Komenda, Hold, and Sihn, 2018), TAS are able to perform human physical tasks. The purpose of DAS are to bridge the gap between the information an operator has and the one required to conduct a task through detailed digital representation of information (Spillner, 2015). As a result, DAS reap benefits in reducing the time required to train workers, search for production information while minimising operational errors, and improving work in stressful scenarios (Zaeh et al. 2007). The conceptualisation of the system requirements is usually the first crucial stage in developing DAS (Yang and Plewe, 2015). The need for a DAS must be established for the technical requirements to be generated (Hold and Sihn, 2016). As a result, success of the design process depends on the selection and adoption of relevant structured methodologies for defining requirements (Dewa, Matope, Van der Merwe, Nyanga and Garikayi, 2013). This makes the digitalisation of production processes a challenging exercise which requires a strategic and systematic approach (Oks, Fritzsche and Lehmann, 2016). Unfortunately, the current literature lacks sufficient information on models or methodologies for the strategic digitalisation of processes (Monostori, 2014). Some researchers have identified gaps in the available literature regarding approaches for the systematic identification of information that users' need for the appropriate selection of technologies and development of assistance systems (Hannola, Steinhuser, Richter, Schafler and Laceuva-Perez, 2018; Hold, Erol, Reisinger and Sihn, 2017). While the technical digital instruments are well-known (as shown in Section 2.2.6), the steps required in bringing about digital transformation remain widely unclear. Consequently, companies become reluctant in taking the necessary phases to introduce digital devices in their value chain (Wang, Torngren and Onori, 2015). This section focuses on comparing the most current major methodological developments in the design and development of DAS. The comparison will aid in the selection of the appropriate design approach which can aid in the digitalisation of shop-floor operations in the South African TDM industry. To fully understand the concept of assistance systems and methodologies developed to date, a systematic literature review was conducted on the Scopus and Web of Science search engines. To avoid an ad hoc list of publications, the search filters were set using the theme words, "assistance systems", "design of digital assistance systems", "design of technical assistance systems", "design of Worker Information Systems (WIS)" and "ICT implementation methodologies". To obtain the most current work in the field, the search was limited to journal and conference publications between 1995 and 2018. The initial search yielded 12 304 articles. After a thorough analysis, only 60 relevant publications were used in the synthesis.

According to Geiser (1997) four interdependent models, task, user, interaction, and environment, can be used and should be distinguished when designing DAS. These models or approaches support the process of deriving requirements and roughly conceptualising an assistance system. The task model helps identify the processes or decisions which can be supported by DAS. Figure 8 illustrates the different aspects each model addresses during the conceptualisation of DAS.

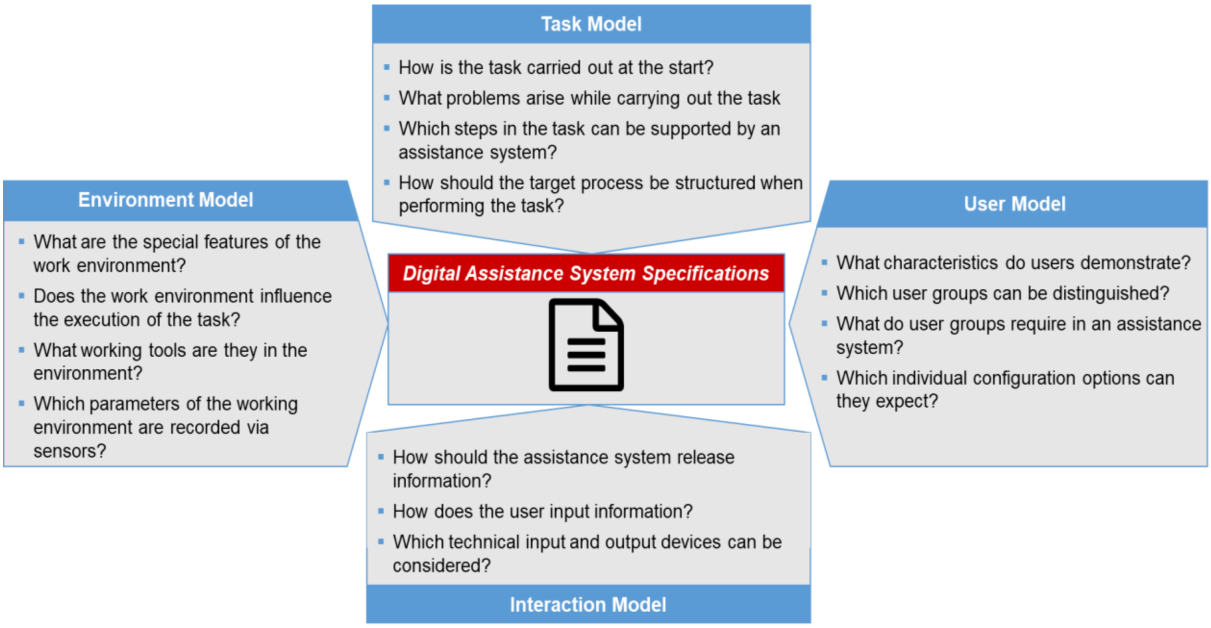

Figure 8: Model approaches for conceptualising Digital Assistance Systems (Geiser, 1997)

A task-centred approach focuses on the relationship between characteristics of assembly tasks, the qualitative and quantitative evaluation of their complexity, and the derivation of requirements for digital assistance systems (Wiesbeck, Zaeh, Rudolf and Vogl, 2006). As such, the task model helps the developer in identifying processes or decisions which require the support of an assistance system. This is achieved through listing all tasks contributing to process, questioning users on the tasks which pose problems and observing workers while they execute tasks (Geiser, 1997). Furthermore, specific characteristics can be used to determine the tasks which require support. The output of this specific model can aid in answering the second research sub-question (identification of TDM operations requiring digitalisation) in this dissertation (see Section 1.3).

While the task model focuses on business processes, the user model can guide the DAS developer in identifying system users with the aim of distinguishing user groups. A user-centred approach focuses on employing user groups for informing the requirements of a DAS based on their specific needs and characteristics (Ho, Yamaguchi, Kawagishi, sato-Shimokawara, and Tagawa, 2013). This is crucial as some users may not require DAS to support their operations. Furthermore, different operators have different needs they may require from DAS. As such, the output of this model can aid in addressing the fourth research sub-question (configuration options for the required digital solution to meet user needs) in this dissertation (see Section 1.3).

System users (for example assembly operators) may have different system requirements. As a result, how each group interacts with DAS, with regards to input and output information, may differ. The interaction model guides the developer in deriving required user experience with the new technologies. As a result, the optimal technologies which fit the derived specification can be selected, tested and implemented (Hold, Ranz, Sihn and Hummel, 2016). Consequently, the interaction model details can aid in addressing the third research sub-question (identification of the appropriate technologies to use for digital transformation) in this dissertation (see Section 1.3).

In some cases, users may require external environmental input parameters like pressure and temperature reckoned by the DAS. The environmental model defines how the system automatically detects these parameters through digital sensors (Zaeh, et al. 2007; Korn, 2014). This also guides the technology selection process (third research sub-question). However, unlike other approaches, the environmental model is not a mandatory part of all DAS as it is only required when context-specific data must be captured via sensors (as per requirements).

Available scholarly literature has different models for developing DAS based on the above-mentioned generic framework. However, some approaches have methodologies which tend to emphasise a particular model. Hence, the above-stated framework for developing DAS was employed to compare different approaches developed and used to date. Table 1 represents different models researchers have proposed for building digital assistance systems. Hold, Erol, Reisinger and Sihn (2017) developed and suggested a holistic model for the planning and evaluation of DAS by focusing on tasks characteristics, operator individual skills, qualifications and competence levels. The model employs the Method Time Measurements (MTM) methodology (Bokranz and Landau, 2012) during the initial stages of mapping assembly operation tasks; hence making it a task-centric approach which makes consideration to user characteristics and interaction needs. The methodology assists engineers to plan adequately for the design Cyber Physical Assembly Systems (CPAS) while accessing the productivity and economic benefits of the system.

Furthermore, in a related work, Hold, Ranz, Sihn and Hummel (2016) developed a three-step model which helps engineers to design a CPAS which integrates technical and digital assistance systems (see Table 1). The methodology also employs the MTM methodology (task-centric approach) and aids engineers in deciding tasks which can be done by robots or have to be shared between human operators and robots, thus supporting operators in assembly systems.

Table 1: Models for DAS design and steps in each methodology

Model and author(s)	Methods (basis)	Steps in the methodology (model)
Planning and Evaluation of DAS (Hold et al., 2017)	Methods-Time Measurement (MTM) and Quality Function Deployment (QFD)	1. Systematic identification of information needs. • Evaluation of component/product complexity • Evaluation of workstation complexity • Evaluation of human workload • Evaluation of human reliability 2. Configuration of the information and assistance system. • Identification of the technical possibilities and components 3. Evaluation of the system with regards to productivity. • Decision support in regard of configuration and investment of DAS
Planning Operator Support in CPAS (Hold et al., 2016)	Task precedence mapping Methods-Time Measurement (MTM)	1. Manual assembly process design 2. Identification of tasks for technical assistance 3. Identification of necessities for digital assistance
Process model for the implementation of DAS (Kleineberg et al., 2017)	REFA standard (Hinrichsen and Riediger, 2016)	1. Analysis and project scoping – current state analysis. 2. Finalise targets – recording of usage requirements. 3. Rough planning – recording detailed work flow and information flow requirements. 4. Detailed planning – iterative selection and design of software and hardware. 5. Realisation – System procurement and training of personnel 6. Implementation – implement the system
Design and introduction of assembly assistance systems (Hinrichsen et al., 2017)	DIN EN ISO 9241-210:2011-01 (A standard for the Ergonomics of human beings System interaction)	1. Determination of factory-specific requirements – based on staff, organisational/managerial and technical aspects. 2. User-centered design to ensure usability and acceptability. • Needs based hardware selection • Creation of users and user rights • Evaluation and preparation of data according to informational requirements. • Integration of the digital system into the existing IT infrastructure. 3. System introduction – technical implementation, system testing and roll-out.
Human-centered design methodology (Nelles et al., 2016)	BS EN ISO 9241-210 (Ergonomics of human-system interaction – Part 210)	1. Identification of user-context. 2. Specification of user requirements. 3. Creation of design solutions. 4. Evaluation of design solution.

Since the successful implementation of assistance systems requires an active handling of the change process, it depends on buy-in from system users (workers). Only when workers view the assistance system as an asset which adds value to their operational needs are they likely to use it. In response to this need, Kleineberg, Eichelberg and Hinrichsen (2017), developed a six stage process model (see Table 1) for the implementation of DAS. The approach is based on the REFA standard defined in work by Hinrichsen and Riediger (2016), and follows a user-centered design and implementation process which involves participation of workers at all levels (executives, work councils, design team and shop-floor workers) in the development process. This bottom-up approach enhances acceptance and use of the final developed solution (Farooq and O'Brien, 2015).

In another contribution on the development of a projection-based assistance system for maintaining injection molding tools, Hinrichsen, Riediger and Unrau (2017) used a design model based on the DIN EN ISO 9241-210:2011-01 (2011) standard (Ergonomics of human beings System interaction). The methodology facilitates the design and introduction of assembly assistance systems and uses a three stage methodology illustrated in Table 1. The steps in the method adopt a user-centered system design approach to ensure the usability and acceptance of the assistance system by workers. After problem analysis, requirements are derived in the first stage using factory specific information based on the staff, organisational/managerial and technical aspects. The information is then used in the subsequent steps to design and introduce the assistance system.

Similarly, a four-step approach for human-centered design of interactive systems in the context of production planning and control was developed by Nelles, Kuz, Mertens and Schilick (2016). The model starts with the identification of the user-context which accounts for the users, tasks and the environment. This information is used to derive requirements in the second stage before the blue print design is developed and the system evaluated in the third and fourth stages respectively. The approach uses the BS EN ISO 9241-210:2010 (2010) standard (Ergonomics of human-system interaction – Part 210) as a reference guide methodology. Since the approach starts with paying attention to the user-context, the model is a user-centric one which takes into consideration the interaction model too.

The analysis shown in Table 2 summarises the comparison of the five identified models for building DAS using the framework by Geiser (1997). The first two models (by Hold et al., 2017 and Hold el al., 2016) are mainly task-centric, while the remaining three (by Kleineberg et al., 2017; Hinrichsen et al., 2017 and Nelles et al. 2016) employ a user-centric approach

Table 2: Comparison of Models for DAS design

Model and/or Methodology		**Design approach**											
		Task model			User model			Interaction model			Environment model		
Model for:	Methodology or approach	Task identification	Task characteristics	Partial or all tasks	User groups identification	User characteristics	User needs identification	Information input protocol	Information display methodology	Technology considerations	Environment characteristics	Available tools in the environment	Environmental parameters
Planning and evaluation of DAS in CPAS (Hold et al. 2017)	*MTM (Methods Time Measurement methodology) and Quality Function Deployment (QFD)*	●	●	●	◒	○	◒	◒	◒	◒	◒	○	○
Integrating TAS and DAS (Hold et al. 2016	*MTM (Methods Time Measurement methodology)*	●	●	●	◒	◒	○	○	◒	○	○	○	○
Participative Implementation of DAS (Kleineberg et al. 2017	*REFA standard*	○	○	◒	●	●	●	◒	○	○	○	○	○
Design and introduction of assembly assistance systems (Hinrichsen et al. 2017)	*DIN EN ISO 9241-210:2011-01 (Ergonomics of human beings System interaction)*	◒	○	○	●	●	●	○	●	◒	●	○	○
Human-centered design of interactive systems (Nelles et al. 2016)	*Human-centered design approach (BS EN ISO 9241-210)*	◒	○	○	●	●	●	◒	○	◒	●	○	○

Key

○ Weak emphasis ◒ Moderate emphasis ● Strong emphasis

As illustrated in Table 3 (summary comparison), models for development of DAS have been mainly applied in the context of manual assembly operations. Two approaches mainly used in realising these technical systems employ a task-centric approach (first two models) and the user-centric approaches (last three models). Task-based approaches (like the planning and evaluation model by Hold et al. 2017) make use of quantitative data collection and analysis methods like the MTM methodology which helps improve system productivity while reducing operational costs. Furthermore, the approach can give results on the economic feasibility of the developed DAS. However, a major shortcoming for the task-centric approach is that human factors like safety and ergonomic needs can be easily overlooked in the derivation process, thus compromising on the acceptance of the DAS by operators. The task-centric approach is also well suited for assembly tasks, where there is a specific scope of operations. Manual assembly operations usually entail set-up, handling, joining, controlling, and adjusting and auxiliary tasks (Hinrichsen et al., 2016). As a result, task-based approaches are difficult to implement in contexts where the product-mix is very wide resulting in numerous complex tasks.

Table 3: Comparison of DAS design models summary

Model author(s)	**Major approach**	**Application area (context)**
Hold et al. (2017)	Task-centric with user and interaction consideration	Cyber Physical Assembly systems
Hold et al. (2016)	Task-centric	Cyber Physical Assembly systems
Kleineberg et al. (2017)	User-centric	Manual assembly and manufacturing processes
Hinrichsen et al. (2017)	User-centric	Injection molding tool operations
Nelles et al. (2016)	User Centric	Production planning and control

On the other hand, user-centric approaches (like the worker participative model by Kleineberg et al. 2017) employ a strategy which requires consistent consultation with system users. User-centered approaches have been successfully implemented to develop assistance systems in the domains of transportation systems (Landau, 2002), healthcare systems (Ziefle and Rocker, 2009) and environmental monitoring systems (Rocker, 2013). Since they employ human factor engineering principles, the acceptance and implementation of the final solution is enhanced (Rocker, 2013). Furthermore, human factors like safety and ergonomic needs are catered for in the early stages of the development process. This is crucial since the user-friendliness and design interface of the technical devices employed in the DAS are a key factor to the ease of use of the application. Consequently, user-based approaches significantly reduce operator training times thus improving the organisational productivity. A major shortfall to the user-based approaches is that since the data collection and analysis approach is purely qualitative, some key quantitative factors like productivity cannot be measured. As a result, the user-based approach cannot account for the account for the economic use of the developed assistance system. The chosen approach for digitalisation of processes will always depend on the application area or the context of the problem. Hence, determination of industry specific characteristics (Schuh et al. 2016) is a key step in selecting the appropriate approach.

The characteristics of an assistance system can be described using a morphology box. The purpose of the morphology method is to present a solution description by breaking down a complex situation into individual categories and their characteristic values. Through a morphology, the characteristic values of specific assistance systems can be presented relating the individual features of the characteristics. Hinrichsen et al. (2016) developed a morphological box for describing the features of a developed assistance system in the context of manual assembly operations. The box will be adapted and used in the study to describe the digital system to be developed (SMS).

Assistance systems can be classified in terms of their areas of application (Lusic, Fischer, Bönig, Hornfeck and Franke, 2016). These areas of application can include manual assembly, maintenance, inspection, costing or logistics. Depending on the application domain and the type of system being supported, physical or informational assistance may be required. Physical assistance involves the use of robotic systems to assist in tasks which can be difficult of strenuous on workers (Müller, Vette, Mailahn, Ginschel and Ball, 2014) while informational assistance involves availing task related data to workers so as to support decision-making and reduce production errors (Rainer and Cegielski, 2011). Furthermore, the type of system supported determines the assistance system installation requirements. The assistance system can either being stationery, mobile, hand-held or wearable (Schenk M., Mecke R., Grubert J., Berndt D. and Sauer S., 2010). This will eventually influence the data transfer medium used in the system, which can either we wired, in a localised environment, or wireless, in a distributed setting (Fischer, Lusic, Bönig, Hornfeck and Franke, 2014). The tasks supported by the assistance system can also be employed as a classification criteria. Hinrichsen et al. (2016) only used assembly operations in the description and went on to distinguish support of all or some of the operations. However in some contexts, the production tasks may differ depending on the area in which the assistance is required. Furthermore, the interaction requirements of system users can also be employed in distinguishing assistance systems. The type of human interface (Geiser, 1997), input information recorded (Reinhart, Berlak, Weber, Spangler, Ermisch and Stawinoga, 2001) and information output shown (Gustafsson, 2000), define the interaction characteristics of an assistance system. Similarly, the system users also contribute the system characteristics in terms of the need for configuration and recognition by operators while using the system (Hinrichsen et al., 2016). Finally, some assistance systems may require the recording of environmental information. As a result, situational and motion detection by sensors may be needed. In such cases, the need to reconfigure the workplace facility has to be evaluated while monitoring the compatibility of the assistance devices with the systems already existing in the business ecosystem.

Table 4: Morphological analysis of a designed Digital Assistance Systems (Hinrichsen et al. 2016)

CHARACTERISTICS	**CHARACTERISTIC VALUES**						
TYPE OF SYSTEM SUPPORT	Physical				Informational		
TYPE OF DIGITAL ASSISTANCE SYSTEMS	Stationery (fixed installation)	Mobile (mobile installation)			Hand device	Wearable -Head -Upper body -Arms/Hands -Legs/Feet	
DATA TRANSFER	Linked by cable				Wireless		
TYPE OF SUPPORTED OPERATIONS	Joining	Handling		Adjusting	Controlling	Auxiliary processes	Setting up the Assembly system
SCOPE OF PROCESS SUPPORT	Partial process(es)				Total process		
HUMAN-MACHINE INTERFACE	Unimodal				Multimodal		
TYPE OF INFORMATION OUTPUT	Visual (optical)			Auditory (acoustic)		Tactile-kinesthetic (tactile)	
TYPE OF VISUAL INFORMATION OUTPUT	On-screen display			Representation in the working area		Working area display superimposed over the assembly object	
SCOPE OF VISUAL INFORMATION OUTPUT IN THE WORKING AREA	No output	Selective presentation		Limited display of symbols, images and drawings		Extensive presentation of items such as images, videos and animations	
TYPE OF THE INFORMATION INPUT/SYSTEM CONTROL	Manual (via actuators)	Verbal (voice control)			Gesturing (tracking system)	Automatic (sensory)	
SCOPE OF USER CONFIGURATION	Set configuration of information input and output			Individual configuration of information output		Individual configuration of information input and output	
USER RECOGNITION	None			Registration and uploading of user profiles		Automatic registration and uploading of user profiles	
SITUATION/MOTION DETECTION	None		Via measurement sensors		Via optical sensors	Other	
COMPATIBILITY/INSTALLATION EFFORT	Entire workplace has to be newly configured		Basic adjustments made to the workplace		Minor adjustments made to the workplace	No adjustments made to the workplace	
FLEXIBILITY IN RECONFIGURING THE WORKPLACE	Substantial adjustments to be made to the main hardware		High software reconfiguration effort (done by qualified specialists)		Average software reconfiguration effort (done by specialists on site)	Low software reconfiguration effort (done by user on site)	

The implementation of current ICT or DAS in the TDM industry has been slow, with some researchers having successfully implemented solutions in TDM firms using current ICT. Efforts to create such information systems for the TDM sector are on-going. A majority of the applications developed to date have utilised web-based technologies to create collaborative frameworks. Li, Wang, San, and Seng (2005) developed a web-based collaborative portal which facillitates joint production. Likewise, Silva, Roque and Almeida (2006) developed a web-based decision support system for a tool-room environment. Choi et al., (2010) created a collaborative solution which facilitates quality management while Hu, Zhou and Li (2010) developed an online portal for product development in toolmaking. Little work and development has been done for the South African TDM sector.

Implementation of new technology in a manufacturing environment is a complex task which requires the use of appropriate methodologies (Evans, Lohse and Summers, 2013). Methodologies for digital technology-selection (based on the interaction model by Geiser, 1997) and adoption have evolved over the past years. It is therefore crucial to explore the different technology selection methods employed to date. Kleindorfer and Partovi (1990) suggested a technology-selection framework applicable in a manufacturing environment using competitive strategy analysis. In this method, a company defines its key performance objectives then selects technologies based on the criterion.

In other studies, Data-Envelopment Analysis (DEA) was used to develop a technology-selection model by Khouja (1995). Sambasivarao and Deshmukh (1997) utilised a Decision Support System developed using economic, multi-attribute and risk evaluation approaches for the selection of technologies. In other studies, Torkkeli and Tuominen (2002) developed a core-competency approach for technology selection. In their work they documented a seven step process of sequential steps for technology selection. The past decade has seen the use of decision models like the Analytical Hierarchical Process (AHP) for technology selection frameworks. This is seen in examples like work by Punniyamoorthy and Ragavan (2003), Chang, Wu, Lin and Chen (2007), Jaganathan, Erinjeri and Ker (2007) and Evans, Lohse and Summers (2013). Though the stated methodologies are easy to follow and implement, their main shortcoming is that they were implemented within a single company in each case. As a result, they may not give the desired results for an industry or group of companies' analysis.

A technology-selection methodology known as action research proposed by Farooq and O'Brien (2015) addresses these challenges by suggesting an empirical approach for a group of companies. In this approach, companies are visited by the researcher to obtain system requirements from the technology users during the framing phase and expert knowledge is obtained during the selection and implementation phase. As a result, the researcher's participation in the technology-selection decision making aids in an optimal decision. Krishnan et al. (2015), suggested a similar approach which utilises a systematic procedure, which involves analysis, design, development and testing for the digital technology selection and implementation. The later methodology (action research) works well in a distributed production environment like in tooling.

Methodologies for software development of digital solutions have also evolved over the years. The waterfall approach (Cerpa and Verner, 1996) has traditionally been the most commonly used approach in which the entire development process is divided into sequential phases. The method is known to have tight control, formal reviews and sign-off for each stage. Though the waterfall approach has an orderly sequence of steps which are simple to follow, it is an inflexible, slow and often cumbersome approach to development. Due to these challenges, rapid prototyping approaches like the agile approach have emerged (Chapman, White and Woodcook, 2017). In the agile approach, the development exercise is divided into small, sub projects. This renders the development exercise quick with consistent user feedback. However, the approach demands for consistent interaction with solution end-users. Due to the merits of the agile approach, this study will use the methodology during the solution development phase. An understanding of the TDM industry domain is therefore paramount before digitalisation can be fully implemented in the field. The following section focuses on the nature of the TDM sector together with some competitive strategies proposed for the industry in available literature.

2.3 The World of Tooling

The importance of the TDM industry to the growth and existence of the manufacturing sector cannot be under-estimated as TDM firms have been known to play a pivotal role in the growth and development of the manufacturing sectors in most economies. Their output contributes significantly to the quality, cost and delivery speed of final manufactured parts (Canis, 2012; Eduardo, 2004). According to International Specialised Tooling and Machining (ISTMA) statistics, up to 50% of any manufactured component's cost competitiveness is governed by tooling (Williamson and McEwan, 2013). This puts the TDM sector at the heart of component manufacturing. Choi et al., (2010) specified the importance of tool, die and mould quality since these are used for the repetitive production of manufactured parts. Poor TDM products eventually result in defective parts. Furthermore, the fabrication of tools is a rate-determining step in the production process, thus affecting delivery speed. The production of tools is a complex activity which requires a lot of expert knowledge and sound judgement. Due to the demand for customised, unique products, the process of tool-making requires great innovation, making it highly dependent on the craftsmanship of the toolmaker. The success of a project therefore depends on the experience and levels of skills of the workers doing the job. This makes tool making a skills or people-driven exercise. The skills required in the TDM value chain include tool designers, project managers, toolmakers, cost estimators and many more specialised roles.

The Automotive sector is one of the major clients of the TDM industry. Recent trends in the automotive sector due to globalisation have also affected production in the TDM industry, as shown in Figure 9. Clients are now demanding more customised products within shorter product life cycles. Maintaining high levels of quality and due date conformance are now key for the firms in the automotive industry to remain competitive. However, these trends result in new demands for the local tool-making companies, which have to deliver their components with the greatest precision, speed-to-market and reliability. Hence, with global competition intensifying in the tooling industry, firms are now seeking sustainable business practices which will make them stand out on the market.

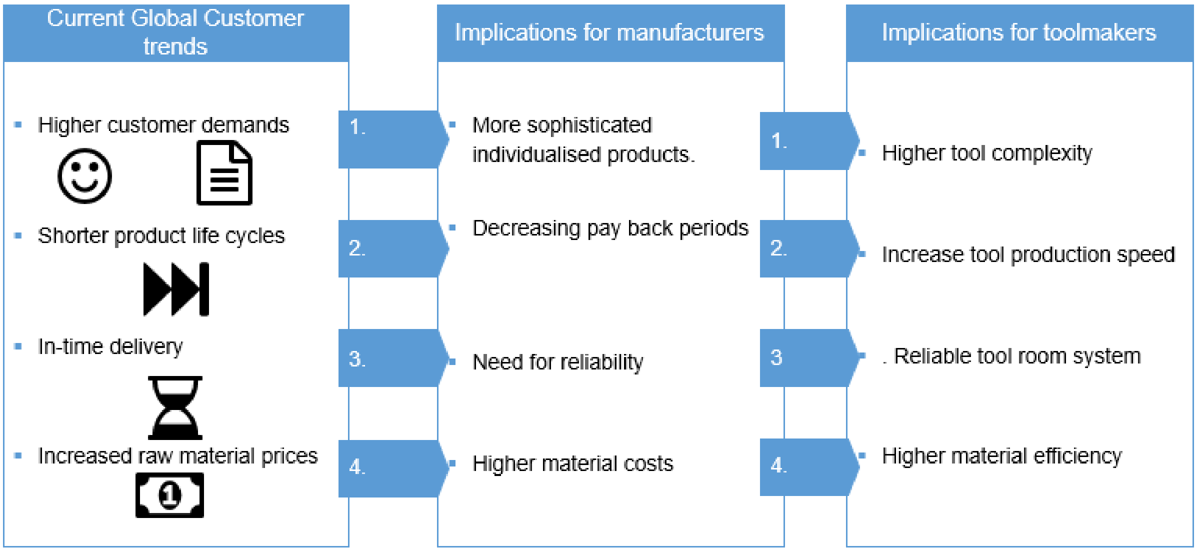

Figure 9: Global Trends in Automotive Industry and their impact on the tooling Industry (adapted from Rittstieg and Garms, 2011)

Tool-making firms which align themselves to these current demands stand out on the market and attract more clientele than those who lag behind. A global survey conducted by Schuh et al. (2016b) on the different tool making firms (located in the 20 most important countries in the World of Tooling) classified the different firms based on their market share and competence levels using a “World of Tooling” radar. The survey classified TDM firms into four categories, which are:

- **Allstars:** a cluster of companies with a high tooling competence and a big market share.
- **Established:** a cluster of tool-making firms with a high tooling competence and a medium market size.
- **Rookies:** a cluster of tool-making firms with a medium tooling competence and a small market size.
- **Rising Stars:** a cluster of tool-making firms with both a low tooling competence and a small market size.

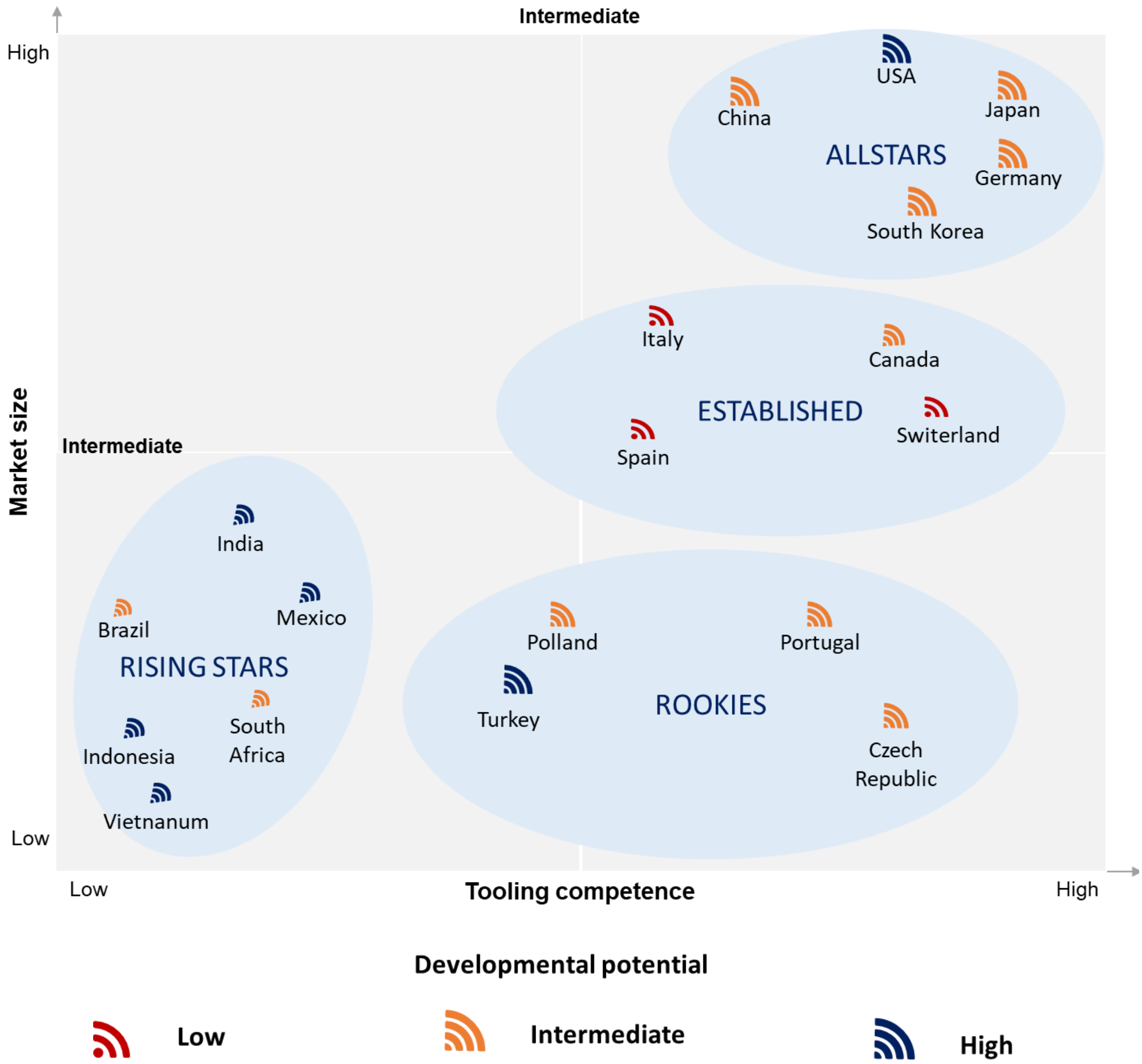

Figure 10: World of Tooling Radar (adapted from Schuh et al., 2016b)

The South African TDM sector was classified within the “Rising Star” category of the radar in the study, as depicted by Figure 10. It is clearly evident that the South African TDM sector has an intermediate potential to develop and improve its status into becoming a globally recognised competitor – that is, attaining Allstar status. The question remaining which arises is: what can a TDM firm do to attain Allstar status? The next section introduces some of the common global competitive strategies recommended in the literature. Much literature exists on methods in which toolmakers can position themselves in a competitive way on the global market. Besides digitalisation, the concepts of collaborative production and agility (flexibility) during production stand out. The following section focuses on the collaborative production strategy.

2.3.1Collaborative manufacturing in the TDM industry

Collaborative manufacturing can be defined as combining resources, skills and information together across a group of participating firms so as to improve capacity and flexibility, and reduce production lead times (Cleveland, 2003). The strategy of collaborative manufacturing is gaining popularity in the TDM industry, a sector characterised by intense global competition. Toolmakers have realised the need to focus on their core competencies and narrow their scope of value addition, hence teaming up during the fabrication of parts. These collaborative teams, also known as value creation networks (Schuh et al., 2013) or industrial clusters, need to collaborate effectively for successful order processing and delivery. Clustering of activities and firms has proven to be an effective strategy with some tooling clusters developed in nations like Portugal, Thailand and China (Schuh et al., 2016b). Unfortunately, although collaborative manufacturing can be a very effective business strategy, it is not always easy to implement. A study by Wegehaupt (2004) reveals that there is a very high failure rate of collaborative projects in the manufacturing industry.

2.3.1.1 Rationale for collaborative manufacturing in tooling

The concept of collaborative manufacturing benefits toolmakers in a lot of ways. With global competition intensifying in the TDM industry, firms are seeking sustainable business practices which make them stand out on the market. A majority of firms in the South African TDM sector are small, family-run firms with approximately 10 – 15 employees. According to Geyer and Bruwer (2006), about 90% of firms in the South African TDM sector constitute of SMMEs, with the Automotive and Packaging industries being their biggest clients. However, these companies lack sufficient resources and capacity for voluminous work. Due to the capacity constraints that most TDM firms face (Dewa, Van Der Merwe and Matope, 2015a), the South African Department of Trade and Industry (DTI) and the Tooling Association of South Africa

(TASA) have realised the evident need to formulate a collaborative network of TDM firms in the form of industrial clusters. This initiative can aid in making the local TDM industry match the capacity base of its competitors and gain market share. The NTIP and TASA have been working at establishing six industrial clusters in different provinces and sub-clusters with specific specialties (Williamson and McEwan, 2013). The goal of this initiative is to create a single point of entry for clients of the South African TDM industry. Besides the capability to handle big contracts, the benefits of collaborative production include improved production speed and enhanced team productivity and communication. Furthermore, the initiative of collaboration improves delivery responsiveness, firm agility and customer service (Ashmore et al., 2004). The individual firms within the network can thus focus on their core competencies and excel in their operations. In the end, the firms are not forced to spend huge sums of money to procure new equipment, since they can tap into the network's resources.

2.3.1.2 Success factors for collaborative manufacturing

To gain market share, the South African TDM sector can embark on collaborative production so as to address the volume of work associated with large projects (e.g. from the automotive industry) in short periods. However, the full implementation of the idea of cluster collaboration places a demand on the partnering firms which would have to change their business models (Henriques and Pecas, 2013). All collaborating firms must adapt their operational methods to fit the features of an industrial collaboration. This section outlines the different factors which make collaborative manufacturing successful, as identified by other researchers in previous studies. A study by Willen and Zuazua (2011) illustrated six success factors for effective collaboration of firms, as summarised in Figure 11.

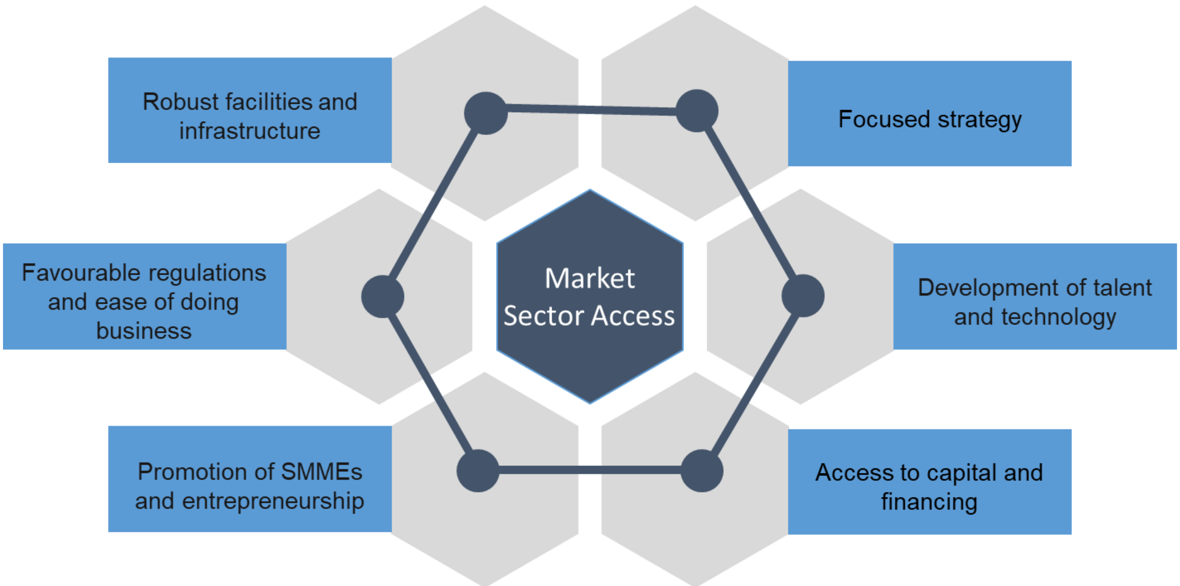

Figure 11: The discerning success factors for clustering (Willen and Zuazua, 2011)

Favourable regulations in doing business with robust facilities and infrastructure were identified as the qualifying enabling factors. The other four factors (access to capital, promotion of SMMEs, development of talent/technology and a focused strategy) were classified as differentiating success factors as illustrated in Figure 12. Based on the six success factors defined in research conducted over 50 case studies by A T Kearney, five factors can be derived. These factors are classified as cultural, operational, structural, technological and financial.

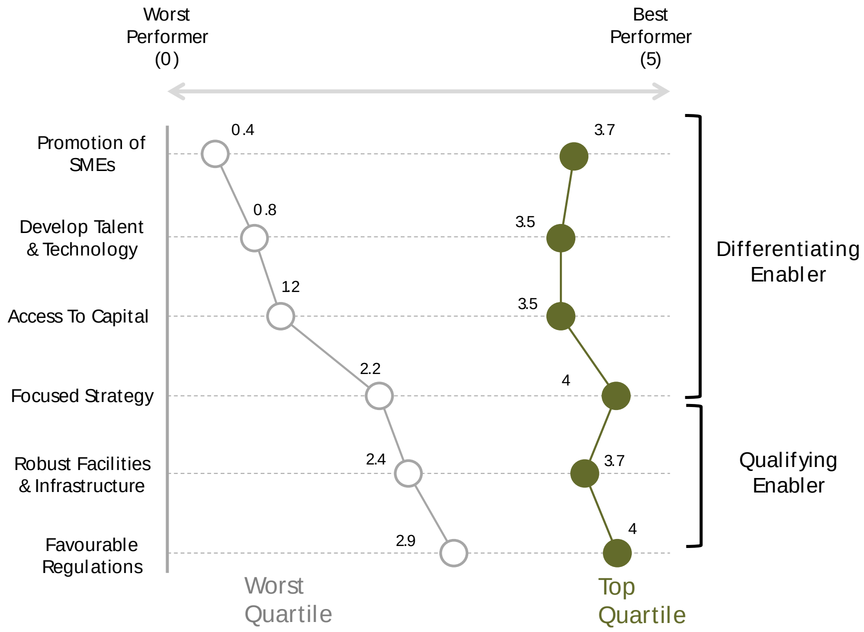

Figure 12: Distribution of success factors (Willen and Zuazua, 2011)

For a collaborative venture to be successful, participating firms need to have a different organisational culture. Hence, cultural success factors play a crucial role for collaboration to occur. McClellan (2004) identified the element of trust to be fundamental to any collaborative venture. This is because all parties in the network share company-sensitive data and so need to be assured that the information will be used for the attainment of the industrial cluster's objectives only. To build this trust within a cluster, firms must be dedicated and fully supportive of the cluster's common vision. A focused strategy should be well defined and communicated to all the cluster participants. Hence, the participating firms should also share common goals and objectives. Finally, the group of collaborating firms must share common manufacturing and business practices. There is therefore a need for benchmarking and training of certain minimum standard production world-class practices, such as lean manufacturing or agile production to create this common view.

Operational success factors also contribute to efficient collaboration factors. Real-time visibility of the available skills and resources within an industrial collaboration is vital. It is therefore critical for all participants, as well as the cluster coordinator, to know the resources available within the network of collaborating firms. Hence, firms must be willing to define their key competencies and specify the resources they can offer. This is an uncommon practice since organisations are normally secretive about their capacity and skills. Thus, this step will require a paradigm shift. Firms must be willing to make their operations visible and their information accessible to all partners within the framework. Organisations must be willing to release reliable information on their production data, logistics information, quality assurance, yield statistics and inventory data to the project coordinators. This will enable project managers to have a clear picture of what is available and can be done. This information can be rendered available and accessible to all partners within the collaborative framework.

The structural orientation of a production network also has immense implications on how successful collaborative ventures can become. Schuh et al. (2014) added that efficient project management by a cluster coordinator is also crucial to successful collaboration during tool making. Production tasks need to be assigned and coordinated effectively for successful contract management in a manner which satisfies the customers. Real-time production data is therefore a must. A summary of these success factors, together with the action plans for their attainment, is fully illustrated in Table 5. In addition to toolmakers collaborating amongst themselves, they have to effectively collaborate with their suppliers and the customers requiring their services. Favourable laws and regulations must be established to allow ease in trade and communication within a cluster. Furthermore, companies must also be willing to introduce modern information exchange mediums.

Effective collaboration within an industrial cluster is therefore compromised if the mode of information transfer is slow or inappropriate and the quality of the data exchanged is poor. Furthermore, frequent changes in production information can result in many errors, bottlenecks and manufacturing delays. These scenarios are capable of complicating matters during collaborative production. Furthermore, technology is at the heart of efficient collaboration. The sharing of information and resources is at the heart of collaboration in manufacturing. This is because the TDM sector is a knowledge-intensive industry, which involves numerous transactions between toolmakers, manufacturers and their suppliers (Schuh et al., 2014). A lot of production data is exchanged per order. Hence, accurate and timely manufacturing information is a critical factor for efficient collaboration. This makes online access to information an important feature during collaborative production.

Table 5: Success factors for effective collaboration

Category	Success Factors	Action Plan
Cultural	• Focused strategy • Trust • Cooperative efforts • Alignment of goals • Dedicated to the common vision • Common manufacturing and business practices	• Benchmarking and training of world class manufacturing practices within the industrial cluster.
Operational	• Core competence definition • Resource visibility • Production data accessibility • Information reliability	• Willingness to share information and data across partnering firms
Technological	• Web-based; online • Networking • Digitalisation • Development of talent and technology	• Development of web-based information systems for collaborative manufacturing.
Structural	• Efficient project management • Implementation of similar standards • Legal structuring • Robust facilities and infrastructure	• Coordination of the cluster's activities by an assigned project manager • Continuous review of performance and progress
Financial	• Access to capital • Promotion of SMMEs	• Application for grants • Financial support from the private sector

Yalniz and Kirda (2003) highlighted the need for information technologies which support collaboration of toolmakers. Schuh et al. (2013) refers to this factor as “digitalisation”, which implies the use of recent Information and Communication Technologies (ICT): wireless, mobile and web-based systems for the efficient sharing of production data. Information systems for collaboration need to allow for platform-independence, distributed-monitoring and distributed-control. Furthermore, skills development and human resource upgrade is required. Workers within the partnering firms must be trained on the new business practices and granted sufficient time to adapt to the new business models. Finally, availability of sufficient funds to support collaborative ventures is a key success factor. The firms partnering in a cluster will have to go through numerous changes outlined in the above success factors, something that can only be achieved with sufficient funding in place. The structural, technological and operational factors will require substantial capital injection for them to be implemented; hence, the government must be willing to grant finances to the collaborating firms for the upgrade. The private sector can also play a pivotal role in assisting the small firms with funding to build their systems and processes in an optimal manner, which will support collaboration. Another effective competitive strategy is that of agility and flexibility during TDM production. The following section outlines the importance of this factor.

2.3.2 Operational disturbances in the TDM industry

Agility refers to the flexibility a firm possesses with regard to responding to internal and external disturbances. For this important characteristic to be realised, the most prevalent operational disturbances affecting a sector needs to be further explored. This will ensure that the digital solutions developed will address or keep track of the identified operational risks. A majority of South African TDM firms struggle in the area of delivery due date conformance. In their study, Islam, Tedford and Haemmerle (2006) revealed that, in order to meet customer due dates or improve delivery time-to-market, high levels of overall system reliability need to be maintained. However, almost all manufacturing organisations face undesirable and unwanted setbacks in their day-to-day operations. These setbacks, referred to as "operational disturbances" in this dissertation have the potential to negatively impact business performance. In work done by Mital and Pennathur (2004), Monostori, Szelke and Kadar (1997) and Barroso and Wilson (2000), it was observed that events like the late delivery of raw materials and rush orders can lead to operational disturbances, which render the shop-floor system unavailable and unreliable, and delay the production of orders. To deal with these operational disturbances effectively, companies in the TDM sector need a systematic way to identify and manage these setbacks.

2.3.2.1 Operational disturbances explained

A manufacturing entity is a complex system which includes many functional areas that are mutually dependent on each other from procurement of raw materials to the dispatch of finished products. The failure of one function can greatly impact the other functions. At times, system failure results from operational disturbances. These internal and external disturbances alter the state of the system at any given time, rendering it unreliable and thus compromising production goals. Islam, Tedford and Haemmerle (2008) defined an operational disturbance as: *An undesirable or unplanned event that causes the deviation of system performance in such a way that it incurs a loss.* In other studies, they used the terms "setbacks", "disruptions", "errors", "failures", "production risks determinants" (Islam and Tedford, 2012) and "unwanted events" (Islam, 2012) interchangeably to refer to these disturbances. The consequences of operational disturbances may be experienced through wastage of time and raw materials, resulting in high production costs, longer lead times and poor product quality.

2.3.2.2 Disturbance mapping

Every operational disturbance, regardless of size, is caused by some event and results in a consequence which negatively affects business performance, flow of operations and worker health and safety (Figure 13). Events leading to operational disturbances may be triggered from external factors emanating from a firm's suppliers and customers or from internal factors resulting from incorrect production practices on the shop floor.

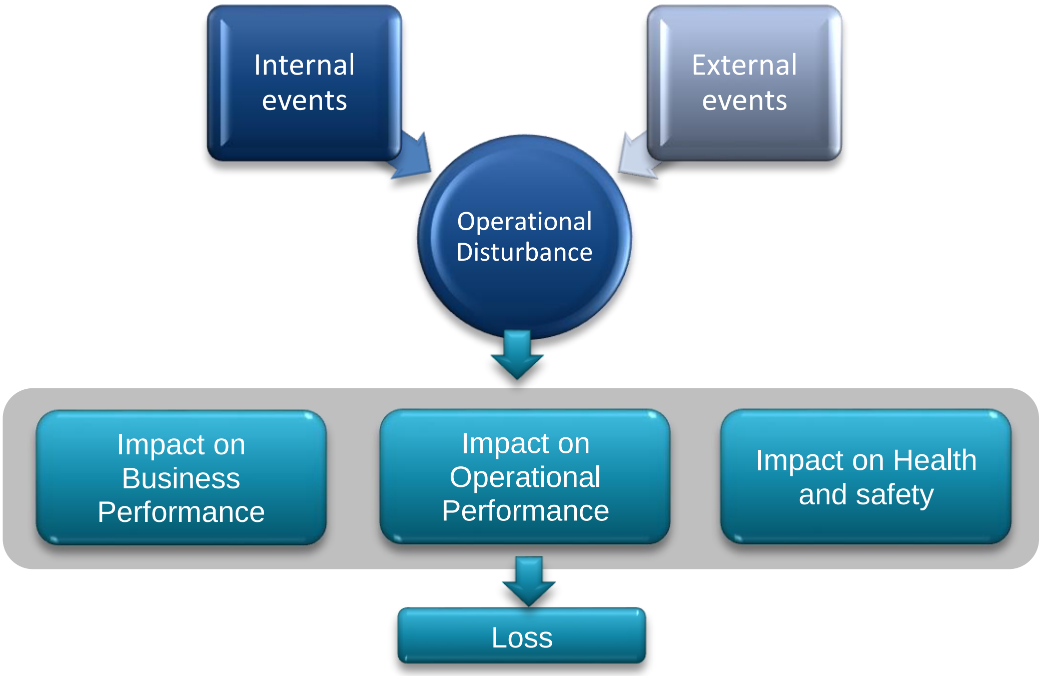

Figure 13: Operational Disturbance mapping diagram (Islam et al., 2008)

2.3.2.3 Classification of operational disturbances

Scholars have used different methods of classifying operational disturbances. According to De Jong (2012), operational disturbances can be resource-related, task-related, supplier-related or job-related. Resource-related setbacks include machine breakdown and worker absenteeism. Cowling and Johansson (2002) further discussed job-related disturbances which include work-in-process increase due to sudden demand changes and rush orders. Supplier-related operational disturbances include shortage of raw materials which can result from the late delivery of a required raw material while task-related disturbances include tool malfunction and equipment damage during an operation.

In other studies, Islam (2012) classified the disturbances as either internal or external where the former are related to the setbacks which are initiated within the production system while the latter disturbances encompass those caused by customers and suppliers. However, Frizelle, McFarlane and Bongaerts (1998) employed a supply chain approach to classify possible causes of operational disturbances according to their position of occurrence. In their analysis, causes were classified as either coming from upstream events, internal events or downstream events (Frizelle et al., 1998). All approaches are related and help describe the dynamics of operational disturbances in terms of their relation to a manufacturing set-up. In this study, De Jong's approach of classifying operational disturbances is used as it relates a disturbance to different parts of the manufacturing system (i.e. customer orders - jobs, suppliers, resources and tasks).

2.3.2.4 Types of operational disturbances

The entire supply chain needs to be monitored and managed well to prepare for the occurrence of disruptions, which can be caused by sudden changes in events within a system. This section outlines different types of operational disturbances other researchers have identified in previous studies. The presented set was then used for further analysis in the identification of the most prevalent setbacks that the TDM sector in South Africa is experiencing. Operational disturbances can be classified as resource, task, and job or supplier-related.

Resource-related disturbances are common in production environments. Bereiter and Miller (1990) and Naruo, Lehto and Salvendy (1990) identified machine breakdown as a major setback that most manufacturing set-ups encounter. Malfunctions may result from inadequate maintenance procedures or the adoption of a wrong operation during manufacturing. Operator absenteeism is another operational disturbance which can be expensive to any production system. When a worker is absent, the shop floor is deprived of certain skills and this may delay production or compromise the quality of outputs produced. Possible causes of worker absenteeism include unsafe working conditions, poor motivation, industrial action or untimely family events. When system resources fail to function well, production is slowed down.

Furthermore, task-related setbacks also emerge during manufacturing. The damage of tools or equipment during production is a common task-related operational disturbance which can temporarily hinder progress. Wear and tear occurs during the use of tools, resulting in them becoming obsolete. Tool damage may also result from poor procedures during fabrication. Naruo et al., (1990) also identified defective raw materials as another task-related setback, which may result from receipt of defective parts from suppliers or the use of poor storage and material handling techniques. In addition, occupational accidents are task-related disturbances which can also result from the resources being used.

Likewise, suppliers can cause some setbacks manufacturers' experience. Upstream problems or changes can lead to shop floor disruptions. Shortage of raw materials, which may result from delayed supply or unavailability of the resources from suppliers, can affect the smooth flowing of operations. In other cases, the firm may be adopting a poor inventory control system, hence resulting in untimely stock outs. An erratic supply of power or water is another supplier-related production setback which has the potential to negatively affect performance. Power cuts render the entire system unavailable since most elements in the production system - machinery, equipment and computers - depend on a supply of electricity.

Downstream changes by customers can result in job-related operational disturbances. These changes include changes in volumes, cancellation of orders, rush orders or changes in due dates. Such events result in work-in-progress increase, which is a major production setback. Table 6 summarises the operational disturbances identified from the literature.

Table 6: Types of Operational disturbances (Dewa et al., 2014b)

Category	Operational Disturbance
Supplier-related	• Erratic power supply • Erratic water supply • Shortage of raw materials
Job-related	• Work-in-progress increase • Defective products
Resource-related	• Worker Absenteeism • Machine breakdown • Software failure • Machine malfunction • Work stalling due to a labour strike
Task-related	• Equipment damage • Tool failure • Material handling disruption • Line blockage

2.4 Global competitiveness through digitalisation

Intense global competition in the business environment is placing significant demand on firms to find better ways of maintaining or increasing their global competitive position. Usually, the cost leadership and differentiation (of products and services) strategies are employed by manufacturing firms to gain an edge over their competitors. However, nowadays it is clear that advancement in information and communications technology as well as growth in integrative systems present a new opportunity for firms to sustain or gain a competitive advantage. Digital technologies are known to streamline business operations while providing timely information to a company's key players. In this knowledge era, technological innovation through digitalisation is visualised as a prime driver to create and maintain a global competitive edge through increased market share (Amable and Verspagen, 1995). Behind the scenes of the world's leading industrial and manufacturing companies, a profound digital transformation is underway. In this context, global competitiveness is defined as the ability of an industry or a nation to provide quality products and services at competitive prices thereby providing adequate returns.

To gain a global competitive advantage, companies utilise digital technologies like mobile devices, intelligent sensors, ERP systems and RFID technology (Fagerberg, 1996). These aid companies to reduce operational costs improve operational efficiency hence increasing a firm's productivity. Furthermore, digital technologies can aid in timeous response to internal and external changes while reducing operational wastes. A number of success stories from leading global manufacturing firms have been written after successful implementation of current digital technologies.

Shanghai General Motors (GM), one of the largest car manufacturing firms in China used ERP systems to enhance the quality of after sales cost services. As a result, the warranty costs were reduced by 34% per vehicle (Shanghai GM, 2007). In another example, the Toro Company, a leader in the lawn and garden market based in the United States, used an ERP system to control the inventory management process of its operations. As a result, the company achieved USD 10 million annual savings due to the elimination of unnecessary inventory (Lollar, Beheshti and Whitlow, 2010). Aggreko, a Scotland-based global company specialising in short-term rental solutions of power, temperature and oil-free compressed air systems, also reaped benefits from utilising current digital technologies. The company combined RFID technology and an ERP system to achieve faster and higher quality service for its customers. The digital solution eliminated the need for workers to conduct manual data entry and significantly reduced the turnaround time for checking equipment in and out from days to minutes (Aggreko Rental firm, 2006). Based on the few accounts revealed above, there is a correlation between technology adoption by a firm and its global competitiveness. However, for a company to digitalise their operations, three factors are important. Firstly, there should be top management buy in and support. Secondly, employees need training on the usage of the digital solution while the firm adopts a culture of change management.

2.5 Benchmarking of the South African TDM industry

The concept of digitalisation can be implemented after fully understanding the industry specific characteristics of a sector. In this section, the benchmarking results from the South African TDM sector are used to derive areas which can be possibly improved by digitalisation. The benchmarking of the South African tooling industry has been an on-going process over the past decade. Benchmarking is the sharing of strategic business knowledge through comparative studies of business processes with the aspiration to generate new and beneficial knowledge through long-term symbiotic participation (Malherbe, 2007). To derive the industry specific characteristics of the South African TDM industry, a SWOT analysis of the current benchmarking results will be conducted (second study objective). The analysis of these results will assist to narrow the scope of the solution to critical areas which need addressing. According to Gretzky (2010), a SWOT analysis is “an examination of an organisation’s internal strengths and weaknesses, its opportunities for growth and improvement, and the threats the external environment presents to its survival”. The tool is a good technique for informed decision-making at the initial stages of a project as exemplified in work by Khalifipour, Soffianaian and Fakheran (2012).

2.5.1 Strengths of South African TDM industry

The South African TDM sector reaps benefits from the environment within which it finds itself. In comparison to other nations, South Africa has a world-class infrastructure, exciting innovation, with research and development capabilities: all which lead to a stable manufacturing base. The South African TDM sector obtains immense support from bodies like the NTIP, which formulate partnership between industry and the government making the sector grow in competitive status.

2.5.2 Weaknesses of the South African TDM industry

Though the South African TDM sector currently finds itself in a good environment, there are many shortcomings which need to be addressed. This section gives a description of the weaknesses noted in the TDM industry in South Africa. More specifically, the South African TDM sector has been constrained in the areas of market share, due date conformance, finances, technological requirements, capacity and business organisation. Firstly, the sector has performed poorly on the global market. Though the South African TDM firms are meant to support the Automotive and Plastics manufacturing sectors, records reveal that a majority of local Overall Equipment Manufacturers (OEMs) import most of their tooling equipment from European and Asian firms. Due to demand increase in the South African Automotive sector, the quantity of tools bought by this sector has increased yearly, as illustrated in Figure 14 (Automotive Export Manual South Africa, 2013). In the year 2013 alone, the South African automotive industry spent approximately 4.09 billion ZAR on purchasing tools. However, 72% of this amount was spent on imports from Europe and Asia with the United Kingdom, Germany and China being the main suppliers, as illustrated in Figure 15 (Automotive Export Manual

South Africa, 2013). Consequently, only 28% left over was used only on local spending of tools by the automotive sector.

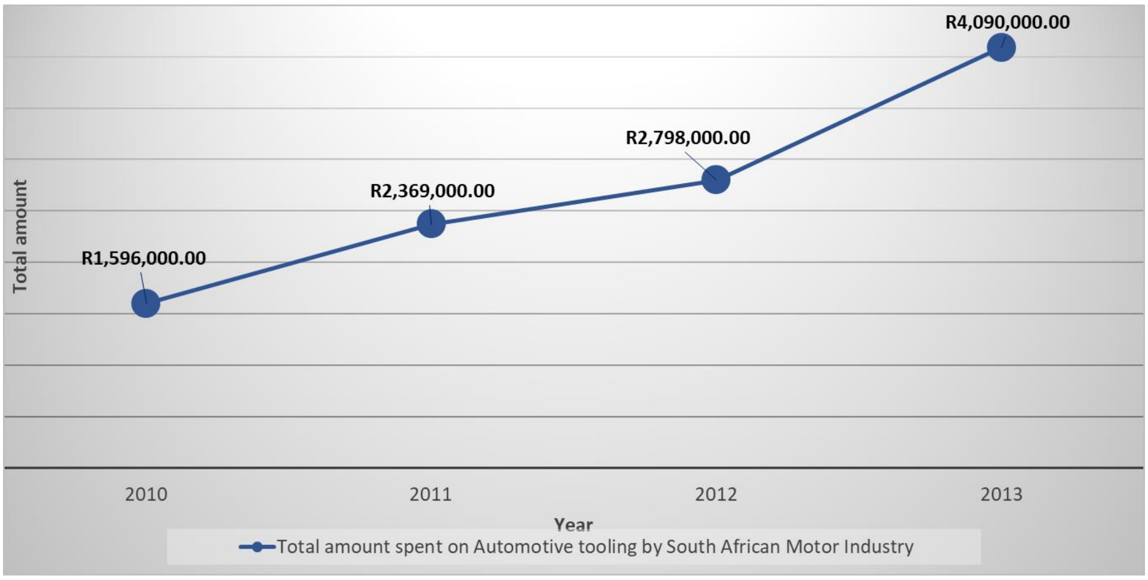

Figure 14: Growth in demand for tooling equipment in South African Automotive Industry (adapted from Automotive Export Manual South Africa, 2013)

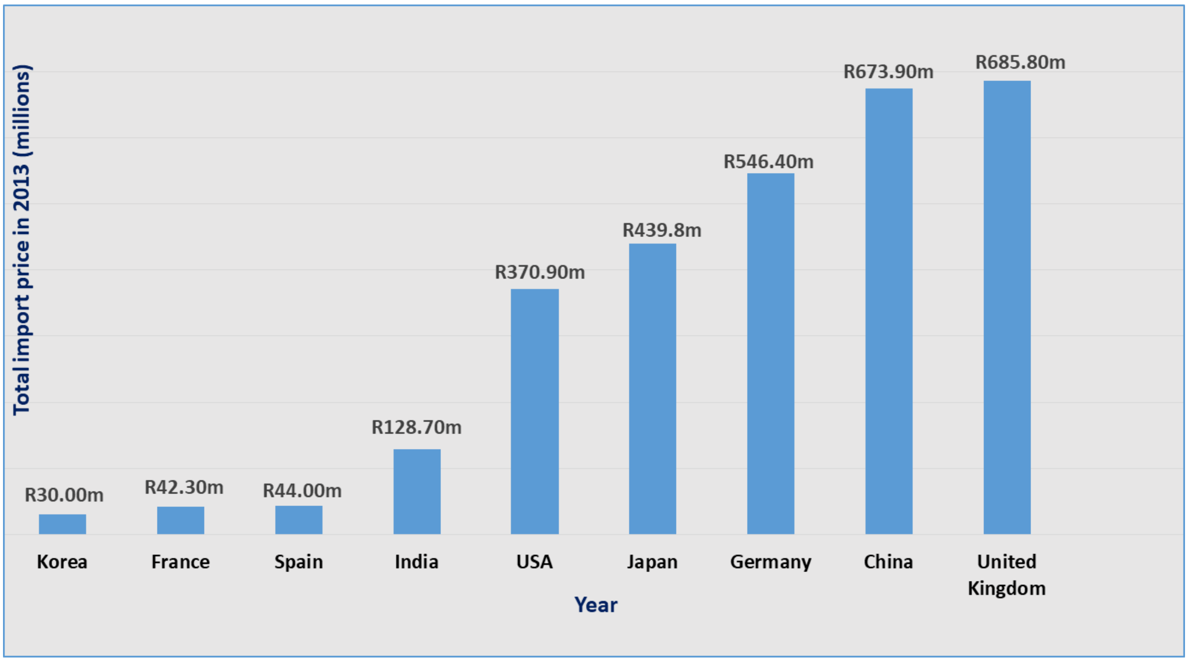

Figure 15: Where the South African Automotive Industry bought tools from in 2013 (adapted from Dewa et al., 2015a)

Secondly, benchmarking results have revealed deficiencies in the areas of due date and budget conformance. With the rapid growth of globalisation and fierce competition from TDM firms in the East, timeous delivery of a quality tool, die or mould within the allowable budget is a non-negotiable characteristic. Unfortunately, results from the benchmarking survey have revealed that a majority of tool-making firms in South Africa suffer in the area of delivery lead times, as shown in Figure 16 below (Malherbe, 2007).

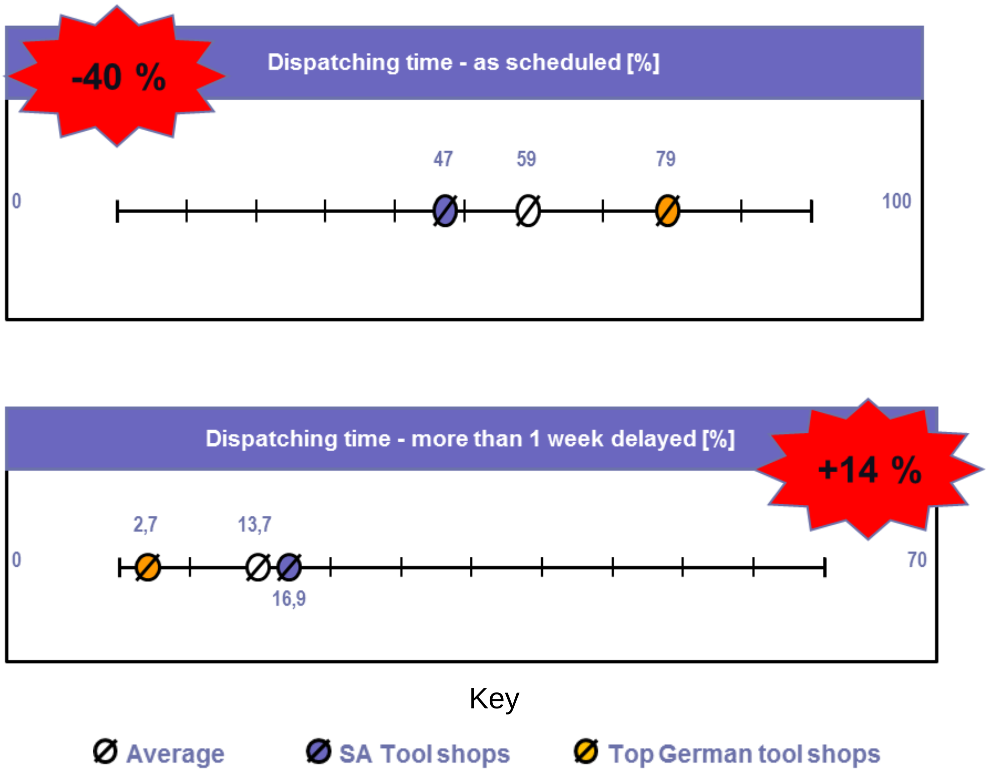

Figure 16: Due date conformance trends (Rittstieg and Garms, 2011)

Furthermore, it was noted that most companies were failing to complete order processing within the prepared budget, resulting in significant losses, as illustrated in Figure 17.

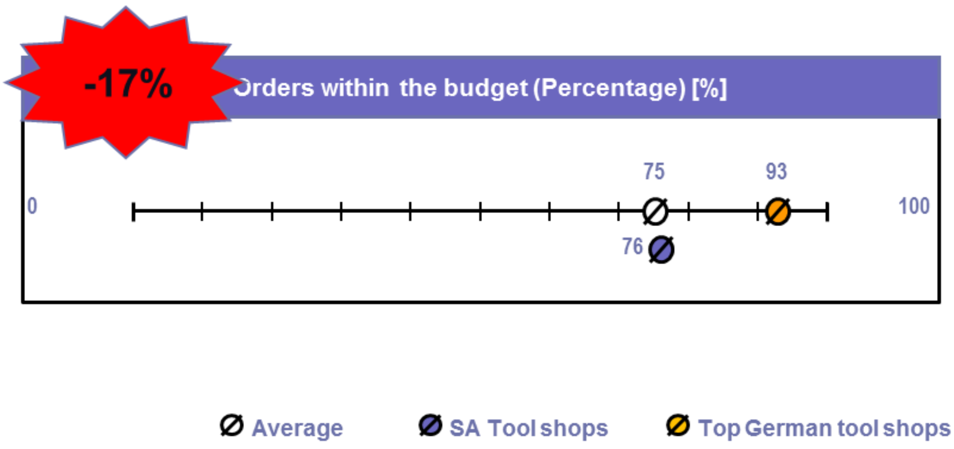

Figure 17: Orders completed within budget (Rittstieg and Garms, 2011)

As a result, the benchmarking exercise conducted revealed that most of the firms in the South African tooling industry were struggling in the area of production lead times, hence not meeting agreed due dates. Further analysis of this observation showed that the main constraints leading to this trend were identified as financial, technological, capacity and human resource related.

Thirdly, some South African TDM firms experience financial challenges. The majority of firms in the South African tooling industry are small, with an average of 10 to 15 employees per firm. According to Geyer and Bruwer (2006) approximately 90% of the firms in the South African TDM industry are in SMMEs. Current statistics on SMME firms reveal that their annual income is less the 10 million ZAR (Mahembe, 2011). As a result, the firms lack enough financial muscle, to invest in the necessary technology required for efficient production, as well as the required design software. As a result, clients perceive the companies as financially unstable entities which cannot work on big projects.

Fourthly, due to the financial constraints discussed earlier, some South African TDM firms still trail behind their international counterparts when it comes to the required technology. Most South African tooling companies are specialists who focus on their key competences, thus delivering a narrow range of products due to their limited and outdated technology. The required technology for processes in the tooling sector can be classified at four levels of production: Design, machining, testing and mould bases. Unfortunately, some South African TDM firms are still lagging behind on possessing the best technology in all these stages.

The main cause of delayed lead times in the observed tool rooms can be attributed to the long order processing times. These delays are a result of a lack of a proper design depository for speedy quoting of jobs. Tool-making firms in nations like Germany and Taiwan possess design software which allows them to quote jobs in 24 hours or less and make any changes as required by clients. A majority of South African tool and die manufacturers still lack the required software for simulation, design analysis, failure mode analysis and stress analysis. However, possession of such software has become a prerequisite for OEMs before a contract can be awarded.

In addition, the majority of South African TDM firms are yet to adopt the latest state-of-the-art machining technology to aid them in producing the best finish in their products. Most firms still use old equipment which significantly compromises delivery lead time as illustrated in Figure 18, thus lagging behind most of their European, American and Asian counterparts. In this context (Figure 18), a percentage point (pp) is the unit for the arithmetic difference between two percentages.

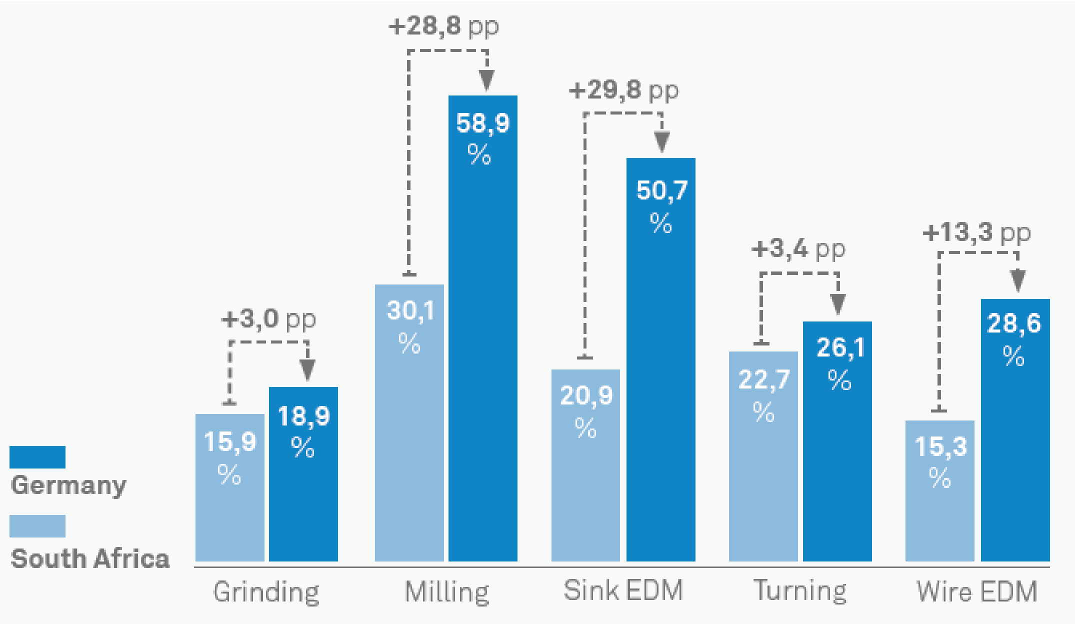

Figure 18: Machines – levels of Automation (Boos e al., 2014)

Furthermore, the majority of international TDM firms on the global scale have adopted the strategy of purchasing standard mould bases as a way of reducing production lead times. When clients approach such firms, parts can be processed quickly using this approach. However, most South African TDM firms still machine their own mould cavities. Though this strategy has cost benefits, it significantly compromises the delivery lead times.

Likewise, it was also observed that the majority of local toolmakers lack the appropriate metrological and measurement equipment for conducting conformance tests on finished tools, moulds and dies. This post-production exercise has become critical in winning contracts within the sector.

Fifthly, the South African TDM sector still lacks access to the global market due to their limited resource capacity base. Since the majority of local tool-making firms are small in size, they lack sufficient resources and capacity for voluminous work. In most cases, order contracts from the automotive sector are big with quotes ranging from 10 to 50 million ZAR per order, leaving the local individual toolmakers incapable of meeting such demands due to their limited number of machinery. If a firm is small (with limited resources), a large project will absorb that firm's entire capacity for several months, rendering it incapable of bidding for more work.

Finally, the majority of South African tooling firms take long periods of time to quote a job. The process of quoting orders was identified as a major bottleneck, with the majority of firms taking long lead times to estimate prices. The majority of South African tooling companies do not have a production planning and scheduling system in place and disturbances disrupt the flow of work on a daily basis, resulting in daily rescheduling (Mkhize, 2014). As a result there is great room for improving the operational procedures within most TDM firms in South Africa.

2.5.3 Opportunities for the South African TDM industry

Despite the above-mentioned challenges observed in some South African TDM firms, there is potential for growth and development of the sector. This section outlines the opportunities the South African TDM sector can take advantage of. The South African TDM sector can take advantage of the on-going benchmarking, skills development and clustering initiatives available to them.

The on-going benchmarking programme of the South African tooling industry has the potential to greatly improve the competitive status of the TDM industry. During the benchmarking exercise, companies are visited and their processes analysed. In the process, expert feedback on best practices in tooling is given and intervention projects are identified. The NTIP has also launched a massive skills development programme which sees many students being trained and injected into the industry so as to bridge the technical expertise gap. Tooling centres of excellence have been established in different provinces and continue to grow (Williamson, 2015). Growth in talent innovation is a key factor to manufacturing competitiveness.

Networking of firms with similar core competencies or collaborative projects is also on-going within the South African TDM (see Figure 2; last stage of the Enterprise Development Programme value chain). There are many benefits which can be derived from the collaboration of tool-making firms. These include ability to embark on larger projects, improved efficiency (Von Leipzig and Dimitrov, 2015) and increased production speed, (Geyer and Bruwer, 2006). Globally, creation of value networks has been known to boost the competitive position significantly.

2.5.4 Threats to the South African TDM industry

There are various threats to the development of the South African TDM industry. This section outlines these factors which threaten the sustainable performance of the industry. The South

African TDM sector is mainly threatened by constraints due to a lack of human capital, global pricing policies, shop-floor disturbances and global competition.

Firstly, due to a lack of sufficient funds and working capital, South African tool-making firms cannot afford the necessary expertise required to manage big projects. As a result, there is currently a massive skills shortage problem in the sector (Williamson, 2015). To deal with this challenge, the Department of Trade and Industry (DTI) initiated a National Skills Fund. In the year 2013, 650 students across 12 learning institutions were trained to address this skills shortage challenge (Williamson and McEwan, 2013). However, the problem remains overwhelming, with a number of vacant posts in the local TDM industry. As a result, most firms may have to make do with semi-skilled or few workers, resulting in project delays or projects finishing over budget. Furthermore, skilled and experienced toolmakers or experts continue to retire, leaving a huge gap in the industry.

Secondly, the size of South African tool-making firms prohibits them from attaining the necessary purchasing power they need, resulting in paying double the international price for material. This affects the firm’s abilities to compete on price with their international counterparts, as illustrated in Figure 19. Small local firms pay double the international standard for material and components, which makes up 32% of the average tooling project. Furthermore, with the globalisation of the tooling industry, local industry advantages related to shipping costs and proximity to market have been degraded by the ability of international companies to generate economies of scale and adopt modern management, manufacturing technology and techniques. This is further exacerbated by the typically small tools produced by local firms not providing a barrier in terms of shipping costs as well as a lack of import duties on tools.

Thirdly, shop-floor disturbances experienced by most South African TDM firms affect the sector. According to Mkhize (2014), the majority of benchmarked companies in the South African tooling industry struggle in the area of production planning and scheduling. Approximately 50% of the firms benchmarked had a production planning system in place. However, most firms indicated the difficulty of adhering to prepared schedules due to operational disturbances, such as rush orders (Dewa, Van der Merwe and Matope, 2016a), which disrupted production work (Van Zyl, 2012).

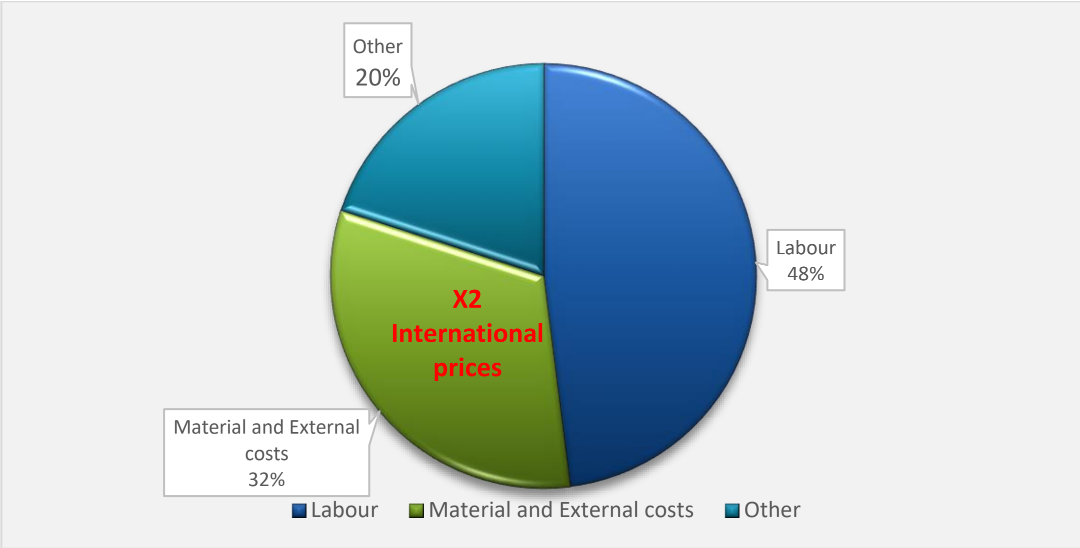

Figure 19: Cost breakdown for South African Toolmakers (adapted from Rittstieg and Garms, 2011)

Fourthly, tooling companies from Europe and Asia continue to challenge the local South African TDM industry due to their ability to deliver quality, cheap tools at a greater speed with unprecedented flexibility. This has resulted in South African OEMs importing most of their tooling equipment from abroad as illustrated in Figure 15 in section 2.5.2 above. A summary for the SWOT analysis of the benchmarking survey is illustrated in Figure 20.

Figure 20: SWOT Analysis summary of results

2.6. Literature synthesis

This section outlines the synthesis of the literature outlined in this chapter. Firstly, the research gaps from the state-of-the-art presented in the chapter (see section 2.2.7) are identified. This is done with the purpose of describing an appropriate design approach for the digitalisation of business processes in the TDM industry. Secondly, the analysis of the SA TDM sector benchmarking results is discussed. The gaps which the paradigm of digitalisation can fill are outlined in this analysis. Thirdly, the implications of digitalisation in the South African TDM sector are identified before the chosen research approach is outlined.

Assistance systems (both digital and technical) in manufacturing have been mainly developed and implemented to support manual tasks. As discussed in the state-of-the-art, methodologies for developing assistance systems have been developed to support manual assembly systems in different contexts (see Table 3). As a result, little work highlighting approaches applicable in scenarios with more operations in manufacturing (for example downstream operations like packaging), remain lacking in the available literature. The task-centric and the user-centric approaches to developing DAS are the most common methodologies implemented in the models discussed earlier (see Table 3). The developer of the DAS can either compare tasks and use them as a basis for deriving requirements in the digitalisation process or use system users to inform their needs on the tasks, interaction options and possibly the environmental requirements the DAS should address.

According to Lusic et al. (2016), the implementation and configuration of Worker Information Systems or Digital Assistance Systems depends on company specific boundary conditions. As a result, to define the application of digitalisation in the context of the tool-making industry, it is imperative that it gets adapted to industry specific characteristics (Schuh et al., 2016a). Due to the customer specific products demanded in the TDM sector, the number of product variants and complexity of assembly operations increase. As a result, employing a task-based approach for the digitalisation of processes becomes difficult. Furthermore, as illustrated in Figure 1, manual assembly operations only make up less than 7% of the entire TDM value chain operations. Consequently, the user-based approach is selected as a more appropriate strategy to digitising tool-making operations. The methodology should entail analysis of the current state of a specific TDM sector, participative derivation of the toolmakers' requirements, design and configuration of the required technical instruments and implementation of the final solution. This is important because only when the tool-room workforce view the assistance system as an asset, can they actively engage in using it, hence a bottom-up approach will improve the acceptability and implementation levels.

Furthermore, due to the wide product range the TDM sector produces, the company specific conditions within the tooling industry differ vastly from company to company. As a result, there is a lack of complete or standard solutions on the market for all tool-making firms, which are eventually forced to develop their own. Due to this factor, researchers have advocated for tool-making firms to develop their own solutions (Schuh et al., 2015). Through the developed individual systems, the sovereignty of the data is owned in the tooling company and the systems will be addressing specific identified problems effectively. TDM companies have to own their own digital solutions and cease from depending on Information Technologies (IT) agencies. Observing the industry specific characteristics of a specific TDM group of companies (possibly in one geographical setting) becomes an imperative as these may differ from place to place. Hence, the SWOT analysis of the South African TDM sector benchmarking results presented in section 2.5, can be used to give an indication of possible areas digitalisation efforts can significantly improve the sector's competitive position.

Due to the decline in skilled toolmakers in the South African TDM industry (see section 2.5.4), there is a growing need to preserve expert knowledge of tooling. This knowledge can be used by the future generation of toolmakers for their daily decision-making. Since digitalisation focuses on data collection for knowledge creation, a digital solution can help to create a knowledge repository to bridge this gap. Furthermore, with operational disturbances like rush orders slowing down production (see section 2.5.4), there is an increased need to improve the agility of tool-making operations. Agility refers to the flexibility a firm possesses in responding to internal and external disturbances. For this important characteristic to be realised, the most prevalent operational disturbances affecting the tooling industry in South Africa need to be further explored. This will ensure that the digital solutions developed will address or keep track of the identified operational risks.

The organisational shortfalls of the South African TDM sector (see section 2.5.2) are a sign of poor business or operational practices. Von Leipzig and Dimitrov (2015) emphasised that the results from the on-going benchmarking surveys clearly show that the initial and later stages of the tool production value stream are being neglected in the South African TDM firms. As a result, the upstream and downstream activities in the tooling value chain (Figure 1, section 1.1) can be a possible indication of the scope to focus on. Von Leipzig and Dimitrov (2015) went on to specify that the South African TDM sector is characterised by difficulties in data collection and manipulation. This factor creates a need for the data collection methodologies to be improved so as to enhance all other operational functions. A study of how data is collected on the shop floor is also imperative to establish gaps which can be solved by digitalisation. It is therefore possible for the operational excellence of shop-floor practices to be improved by introducing current digital technologies. Schuh et al. (2014) described the TDM industry as a knowledge-intensive and data-driven sector. During the fabrication of tools, dies and moulds, many transactions which involve information exchange occur between toolmakers, their downstream customers and their upstream suppliers, as illustrated in Figure 21.

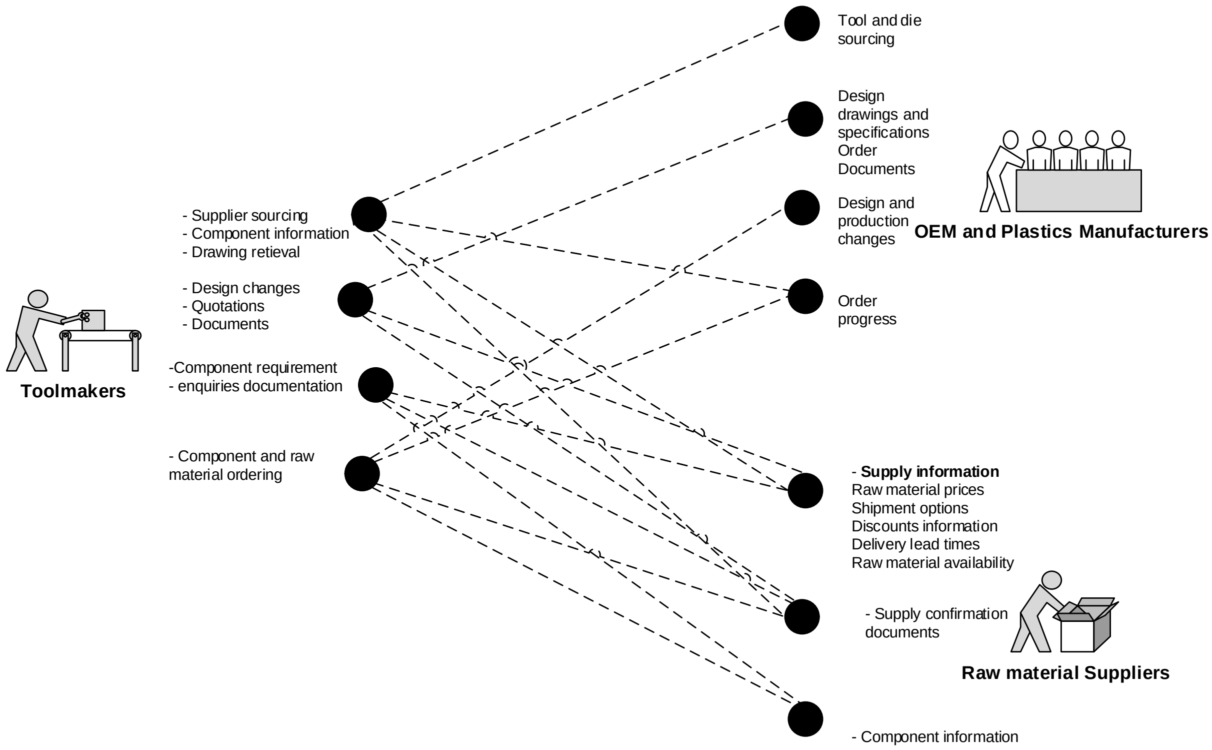

Figure 21: Transactions during order processing in TDM operations (Dewa et al., 2014a)

Furthermore, with the plan of match-making and networking of in-house operations and different tool-making firms by the NTIP in place (Figure 2, section 1.1), digital solutions would adequately facilitate this process. Collaborative ventures are easily enhanced by digitalisation (Schuh et al., 2013).

Due to the wide range of products it produces, the TDM industry is characterised by a huge variability of requirements and specifications in each final product. Figure 21 represents the nature of communication involved in order processing in the TDM sector. A lot of production data is exchanged between toolmakers, their raw material suppliers and their clients (usually Overall Equipment Manufacturers (OEM)). To arrive at an optimal decision, numerous enquiries and computations need to be established, making the process time-consuming and cumbersome. This creates a need for highly agile productive structures with respect to the production technology which facilitate process planning, project management, management of raw materials, information flow and optimal decision-making.

The ‘Industry 4.0 train’ is leaving the station and manufacturing companies must decide when the best moment for them to hop on is. Due to the perceived benefits, there is an urgency for production organisations to embrace the phenomenon; that is Industry 4.0. However, due to the limited financial muscle SMMEs like TDM firms’ experience (as explained in section 2.5.2), these small firms tend to struggle adopting IoT or Industry 4.0 technologies (Erol and Sihn, 2016). In addition, many small firms (like tooling companies), lag behind in terms of basic computer technology usage. In light of this trend, Pye (2016) suggested that small firms (like TDM companies) need to take small steps in Industry 4.0 implementation. Hence, digital technology adoption and use has received little attention or documentation, in the tooling environment of developing economies such as South Africa.

The fourth industrial revolution also poses a disruptive transition on the technological landscape. Christensen (1997) argues that during such seasons (of disruptive transition in technologies), organisations which succeed are the ones who deliberately ignore the disruptive features of new technologies and find ways to embrace them. Sticking with a known technology or methodology is a cause of failure during times of disruptive transition. However, the adoption on digital technologies on the shop-floor in TDM firms will place a demand for the companies to change their business models, strategies and require management to train workers. It is therefore paramount for the potentials these technologies offer to be fully explored and utilised. A good starting point will be to understand the nature of the TDM sector as recorded in this chapter.

An action research approach will be employed in the study for analysis of the current state of the South African TDM firms and selection of the appropriate technologies. In this approach, companies will be visited (case study approach) and the value co-creation approach (Richter, Trier and Richter, 2017) used to derive the user requirements. This approach allows for shop-floor workers (who will use the digital solutions) to be a part of the design process. Interaction with users in deriving requirements is always an iterative process which works well when employing different strategies (mixed methods). In the study, triangulation, knowledge engineering and systems engineering techniques will be used for the value co-creation process of designing and developing the solution to digitalise operations in the South African tooling sector. A detailed account of these methods is discussed in the next chapter.

2.7. Conclusion

This chapter gave an overview of literature on the field of digitalisation and current results from the benchmarking of the South African TDM industry. Based on the analysis of the benchmarking results, digitalisation can aid in facilitating preservation of knowledge in tooling, data collection, agility and collaboration within the South African TDM sector. However, according to the available literature on the challenges the South African TDM sector experiences, the area of data collection and manipulation was identified as a major possible deficiency which can be addressed by digitalisation. The next chapter will give a detailed account on the research design and methodology used in the study.

Chapter 3: Research design and methodology

3.1 Research design

This chapter outlines the research design and methods used in the study. According to Krishnan et al. (2015), a systematic approach, which involves analysis, design, development and testing, is required to achieve digital transformation of a business's operations. This design strategy entails analysis of the current state of an industry, identification of processes requiring improvement and careful selection of appropriate technologies to bring about the digital transformation.

The study employed the methodologies of triangulation, knowledge engineering, and systems engineering. As such, content analysis of available literature; site visits with observational note-taking; semi-structured, one-on-one interviews with field experts; and questionnaire surveys were used as means for data collection. Moreover, this chapter only focuses on the methodology used to achieve objectives three to seven (as presented in section 1.6) as the first two objectives of the study were addressed through a literature study of the available work on digitalisation and published benchmarking results of the South African TDM industry (see Chapter 2).

3.2 Triangulation methodology

To achieve the third study objective, an empirical study was conducted. Francis and Tharakan (1989) and Quezada, Córdova, Widmer and O'Brien (1999) agreed on the fact that empirical studies place special emphasis on affiliated research leading to framework establishment for the improvement of an entity's strategies. Based on the problem areas identified during the SWOT analysis (objective two, section 2.5), the specific processes which can benefit from digitalisation need to be identified and selected. To achieve this, the operational procedures within a field domain should be observed and careful selection of processes which can benefit from digitalisation identified. According to Bogner, Voelklein, Schroedel and Franke, 2016, to define the *status quo* in any company, the current situation needs to be analysed for the identification of deficits, starting points and any unexploited potentials.

The methodology of triangulation was utilised to determine the current operational practices employed in the South African TDM sector. The purpose was to finalise establishing the industry specific characteristics of the South African TDM industry by analysing current operational procedures. As such, a questionnaire survey of TDM firms in the Western Cape

Province and semi-structured, one-on-one interviews with five TDM firm owners with observational note-taking were used as a means of data collection.

3.2.1 Rationale for the triangulation methodology

The methodology of triangulation was employed utilising questionnaires; semi-structured, one-on-one interviews; and site tour observational note-taking as a means of data collection. The triangulation methodology was selected so as to gain the benefits of conducting both a quantitative and qualitative analysis for this purpose (Bryman, 2006). In this way, the findings from the qualitative research can be used to validate the findings from the quantitative research conducted. The questionnaire was used to determine the current operational practices conducted and disturbances the sector experiences. The semi-structured one-on-one interviews were employed to validate the survey questionnaire findings and obtain more opinions on the reasons for the results obtained from the questionnaire.

According to Wright (2006), survey questionnaires can help in quickly collecting data from a larger sample size making the results more credible and accurate since a more representative population would have been used. The research tool of questionnaires was specifically selected so as to establish quantitative data on the number of companies who were following certain business practices, and the frequency of occurrence of specific operational disturbances. Furthermore, statistical analysis can easily be conducted on the obtained results from a questionnaire survey. However, the limitations of the questionnaire survey tool are that crucial qualitative information on reasons for identified trends cannot be obtained (Wright, 2006). Furthermore, there is a possibility for respondents to misunderstand questions, thus wrongly answering them or being biased in completing the questionnaire if questions are not well constructed.

To address the above-mentioned limitations of a questionnaire survey, semi-structured, one-on-one interviews were conducted with five TDM company owners. Within the Western Cape Province of South Africa, only five firms consented to be benchmarked in the year the visits were conducted. As such, these five companies were used for the analysis. Interviews reap benefits in that they allow for qualitative opinion-based reasons to be derived from respondents (Brown and Danaher, 2017). A semi-structured approach was utilised so that the flexibility of the interview sessions was improved and to allow for more information to be collected during discussions. However, interviews have limitations in that they cannot give quantitative results. The results from interviews are purely subjective and opinion-based. Furthermore, interviews take a large amount of time to conduct. As a result, only a small sample size can be used.

The purpose of the interviews was to establish the procedures and current practices in the South African TDM industry. Furthermore, the interviews would help shed more light on the operational disturbances the sector experiences. The analysis of the opinions derived could then be used to gain understanding of the trends observed from the quantitative analysis. The appropriate respondents during the interviews were primarily operations management personnel in the South African tooling sector. However, opinions from shop-floor workers were also considered during the site tours.

During the visits, the interview respondents also facilitated a site tour of the facility after the interview session. This helped the researcher to understand the processes and systems employed in a tool-room environment. The research tool of observational note-taking was used at this stage, with the researcher constructing process flow diagrams for all critical functions observed. This would then help validate the interview responses and give more understanding to the processes employed in a TDM firm. Since the researcher is not an expert in tooling operations, this could then be used to improve the understanding of a tooling environment for more informed decision-making in the study.

3.2.2 Research instruments employed

This section explains the design of the research tools used in the triangulation methodology. A questionnaire survey and semi-structured interviews were conducted at this stage of the study. A questionnaire was prepared and sent to a number of companies (see Appendix 3-1). The questionnaire , which was adapted from the one used by Islam, Rashed and Bagum (2012), was developed in two stages: a pilot study to test and refine the data collection instrument and a formal study to collect the required information. The pilot study would improve the quality of the questions by eliminating bias and errors in each question asked. In the questionnaire survey, a targeted population size of 150 TDM companies forming an industrial cluster in the Western Cape region of South Africa were selected for investigation. Contact details of these companies were obtained through the Western Cape Tooling Initiative (WCTI) offices, and emails were then sent to the potential research participants. The purpose of the questionnaire was to determine the operational practices on the shop-floor within the South African TDM sector. Other variables in the questionnaire study were the identified operational disturbances (see section 2.5.2), a set of events that might have caused them and a set of consequences which would result from them. Furthermore, other questions included tool room specific data like product range, order qualifying and order winning factors. Each operational disturbance and possible consequence was questioned as a closed-ended question requiring responses on a five-point Likert scale, proposed by Dawes (2012). This was done so as to determine the frequency of occurrence for the variables in question. A ranking scale of never = 1, rarely = 2, sometimes = 3, often = 4 and always = 5 was employed. An open ended question was included at the end of each section for respondents to include additional information they deemed relevant to the study. When completing the questionnaires, respondents were asked not to disclose company names or names of individuals so as to abide by the Stellenbosch University's research ethics code of conduct.

Interviews with the managers from the five different firms were used to validate the findings of the questionnaire survey. Interview and observation guides were prepared prior to the visits (see Appendix 3-2). To ensure consistency in the results obtained, the same guide and procedure was employed during the visits at the five companies. The protocol for each visit was as follows: upon arrival, an interview was conducted with the factory owners for approximately 45 minutes. Thereafter, a company tour was conducted with the respondent explaining the entire process chain from the first stage (customer enquiry) to the last (packaging and delivery) using one example of a product. Thereafter, further interviews with shop-floor workers were conducted to further understand the operational procedures. Respondents were also given the opportunity to comment on benefits or limitations of their current operational procedures at different stages. During the interview session, notes on the responses obtained were recorded on the interview and observation guide prepared. No audio recording of responses were done during the benchmarking visits. The researcher kept the names of respondents or companies private on the pages with responses to stay within the ethics guidelines.

3.2.3 Data collection strategy

All potential respondents were contacted via email or phone to obtain their consent to participate in the study. The research participants who gave their consented response received the designed questionnaire and were given approximately two weeks to complete and return it.

During the benchmarking visits, an interview guide targeting specific areas of the tooling business was used to gain the required answers from respondents (see Appendix 3-2). Visits to the firms were conducted by the researcher, accompanied by NTIP experts and German tooling experts. During the visit, an interview was conducted first, followed by the site visit to observe practices.

The obtained questionnaires were always kept in a locked private place to ensure good storage of the results. Computer files containing the results were stored as password protected documents as well to increase the information security.

3.2.4 Data analysis strategy

The Statistical Package for Social Sciences (SPSS – version 21.0) was employed as an engineering tool for the data analysis of the collected questionnaires. Descriptive and inferential statistical analysis of the data was conducted to establish frequencies, means and rank parameters observed. To establish the relationship between the identified operational disturbances and their consequences, a correlation analysis, based on the Pearson correlation analysis, was also conducted in SPSS.

The opinions derived from the interviews were used as a means to explain reasons for the trends identified during the questionnaire survey. Microsoft Visio was employed in the computerised drawing of process flow diagrams, identified during the site tours.

3.3 Knowledge engineering methodology

To achieve the fourth objective of deriving the system requirements through analysis (see section 1.6), the method of knowledge engineering was employed. Knowledge engineering involves the derivation of expert knowledge within a specific domain or area through a consistent interaction with field experts in that area (Lucas and van der Gaag, 1991). During this stage, specific selected experts in the Western Cape Province TDM industry were frequently visited. During the visits, semi-structured, one-on-one interviews were used as a means of data collection.

The Delphi or expert-opinion method was used in the careful selection of the field experts in the TDM industry. Authorities in the Western Cape tooling industry assisted in recommending specific experienced tool-making personnel. The experts' knowledge on processes which require digitalisation and the key parameters to consider, were derived from these interviews. These findings would be used for the development of a digital blueprint of the system functionality for the envisaged solution. In other words, the responses from the interviewed experts aided in the establishment of required system features.

3.3.1 Rationale for knowledge engineering methodology

The knowledge engineering methodology was chosen since opinion-based qualitative data on field knowledge in tooling was required. According to Hall (2012), the methodology is effective in acquiring expert knowledge in a domain or field for the purposes of building an expert system. As such, semi-structured interviews were conducted with five different experts in the tooling industry. Interviews are an appropriate tool for obtaining opinion-based data as discussed in section 3.2.1. To keep the responses flexible and obtain more information, a semi-structured approach was utilised. In some instances, the expert would demonstrate some concepts using examples for better understanding to be obtained.

3.3.2 Data collection strategy

The fourth objective initiated the design phase for the digital solution. Firstly, the shop-floor processes which can benefit immensely from digitalisation were identified. Thereafter, the system functions, input parameters and users were derived. Results from the previous analysis coupled with expert opinions guided the decision-making process at this stage. Hence, during the visits, some of the following questions used to derive the information included processes which can benefit immensely from digitalisation and parameters associated with each process.

Due to the wealth of information obtained at a quick pace during the interview sessions, the researcher would conduct an audio recording of some interview sessions (only after obtaining the respondent's consent). This would help in capturing all responses without missing anything as the researcher would listen to the sessions after the interview and record all missed points. Both the interview responses and audio recordings were stored on storage devices which remained locked away during the course of the study. This was done to ensure security of the data obtained.

3.3.3 Data analysis: Analytical Hierarchical Process (AHP)

The process of parameter derivation was three-fold. Firstly, using importance in the tooling business as criteria, the key system functions were established. Secondly, for each business function identified, the main parameters to reckon were derived. Finally, based on the scenario analysis, the desired system features or characteristics were defined.

The engineering tool known as the Analytical Hierarchical Process (AHP) approach was employed to rank identified key parameters for the envisaged model. The AHP is a multi-criteria, decision-making methodology, which was proposed by Saaty (1980, 1990). It uses a well-defined mathematical structure of consistent matrices and their Eigen vector to generate weights on the selection criteria (Saaty, 1990). To make decisions with AHP, the following steps should be followed (Saaty, 2008):

1. The problem should be defined.
2. A decision hierarchy, with the goal of the decision at the top followed by objectives from broader perspective, should be developed. Then intermediate-level criteria are developed from the top level down to the alternatives.
3. A set of pairwise comparison matrices is developed with each element on an upper level used to compare the elements in the level immediately below it.
4. The priorities of the comparison of the criteria of the upper level are used to weigh the criteria in the level immediately under it.

In the first stage, the facilitator interviews the decision-makers to structure the problem and develop a hierarchical structure of the criteria which enables users to focus on specific criteria and sub-criteria when allocating the weights. Brugha (2004) also proposed a complete guideline to structure a problem hierarchically and compiled hierarchies in different applications. To avoid large differences when decision-making involves a large number of elements, the elements should be clustered (Ishizaka, 2004).

Secondly, a pairwise comparison matrix is developed using a scale of numbers that indicates how many times more important or dominant one element is over another element, with respect to the criterion or property by which they are compared as shown in Table 7. The development of the matrix is discussed in section 3.3.3.

In the third stage, the parameters investigated are then ranked by determining their priorities during the interview process. The priority rating of each parameter is obtained by finding the Eigen vector of the pairwise comparison matrix. This is achieved by raising the matrix to large powers and summing each row and dividing each by the total sum of all the rows (Saaty, 2008). Once the priorities have been determined, the principal Eigen value can be obtained from the summation of products between each element and the sum of the columns of the reciprocal matrix.

Table 7: Fundamental scale of absolute numbers (Saaty, 1980)

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another, its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then activity j has the reciprocal value when compared to i.	
1.1 – 1.9	If activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

The final step in the process involves checking for consistency in judgement. This is done by measuring a Consistency Ratio (CR), as shown in equations 1 and 2.

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad \text{(Equation 1)}$$

where λ_{max} is the Principal Eigen value of the pairwise comparison matrix and n is the dimension of the matrix. The CR is given by:

$$CR = \frac{CI}{RI} \qquad \text{(Equation 2)}$$

where CI is the Consistency Index and RI is the Random Consistency Index, given in Table 8. If the determined CR is smaller or equal to 10%, the inconsistency will be acceptable. However if the CR is greater than 10%, the subjective judgement will need to be revised.

Table 8: Random indices (Saaty, 1977)

n	3	4	5	6	7	8	9	10
RI	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

3.4 Systems engineering methodology

The systems engineering methodology was employed for the development of the digital solution. The purpose of this method is to attain the fifth, sixth and seventh objectives (see section 1.6) which involved selection of the appropriate digital technologies, design, development, testing and validation of the final solution.

3.4.1 Rationale for Systems Engineering methodology and research tools

The Systems engineering methodology was chosen because, according to Hoefler and Mar (1992), the approach allows for a systematic problem definition to solution realisation which results in a prototype being developed and tested. Decision matrices derived from the literature were employed as the research tools for the selection of the appropriate software and hardware platforms (fifth objective). The system requirements derived from the fourth objective were used as input at this stage. The main advantage of this tool is that a decision matrix uses expert knowledge from other researcher recommendations to come up with the best informed decisions. However, the selection process is subjected to the bias of the recommendations given in the available work (Haddad and Morgado, 2008).

The agile approach of software development was used for the design and creation of the digital solution (sixth objective). According to Spataru (2010), the agile approach simplifies the development process. This is because development is conducted in an incremental manner for each module, unlike in the waterfall approach which follows a hierarchy of long steps (Spataru, 2010). A case study for a selected TDM company was used to test and validate the solution (seventh objective). At this stage, real-world scenarios and data were used to test the robustness of the system.

3.4.2 Data collection strategy

The steps involved in attaining the fifth objective were two-fold: firstly the system features derived in the second and third objectives were used for the selection of the appropriate digital technology classes needed. At this stage, all the technologies stated in the study hypotheses (See section 1.2) were evaluated in terms of their relevance in meeting the derived system requirements. After the selection, a follow-up analysis to justify the chosen technologies was conducted to validate the selection. Secondly, the available development platforms (software and hardware) were compared using set criteria for the purposes of selecting the best platform. Theoretical frameworks provided for in the literature were used during this stage. A questionnaire was designed to verify the selected technology (see Appendix 3-3) and decision matrices developed, according to Satterlee et al. (2015) for the software and hardware selection (see Appendix 3-4). The phases followed in this case are summarised in Figure 22 as adapted from Satterlee et al. (2015).

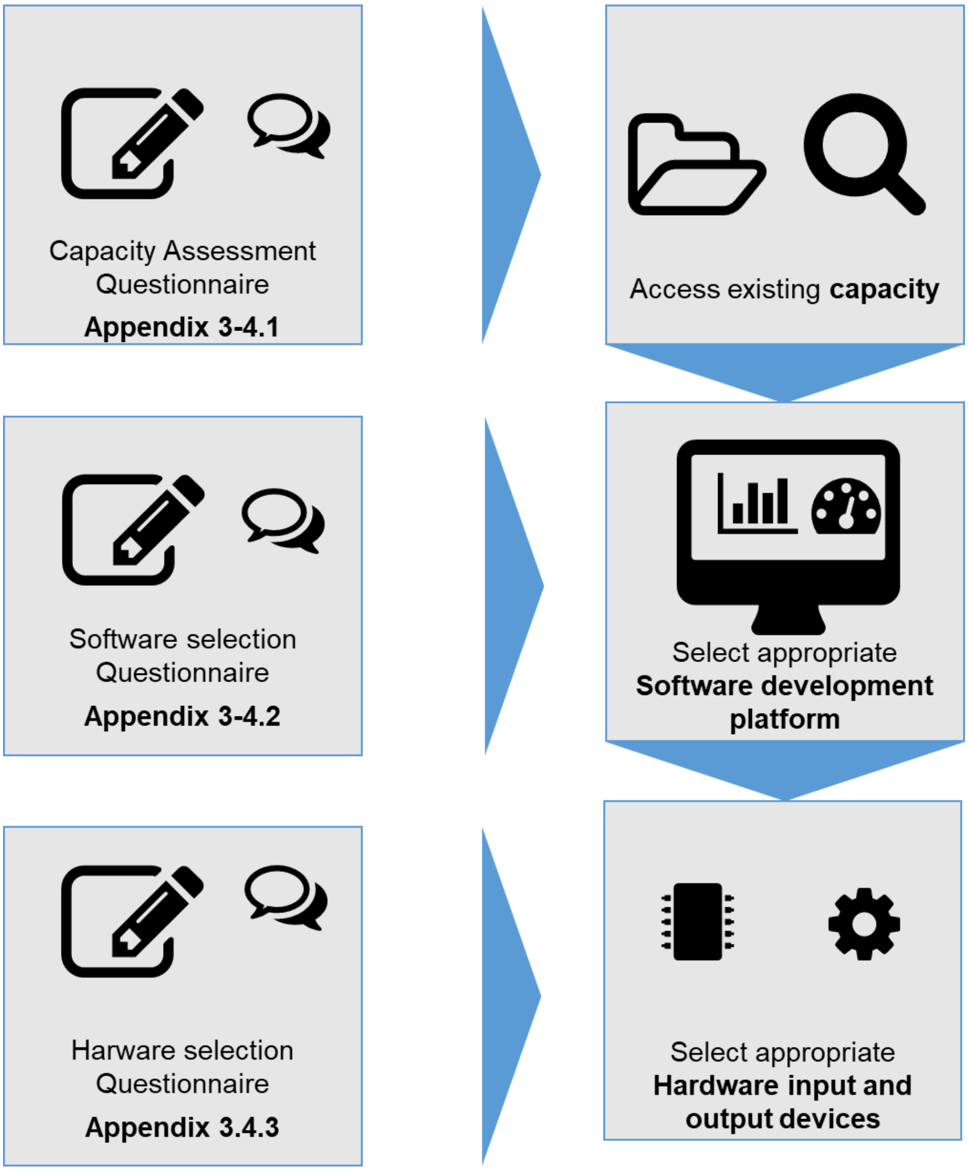

Figure 22: Software and hardware selection phases (adapted from Satterlee et al., 2015)

The remaining two objectives, which involve design, development and testing of the system, were implemented in one chosen company as different tooling firms produce a wide range of products and services. As a result, the industry specific characteristics vary from one company to another (Schuh et al., 2016a). One of the five companies visited during the benchmarking phase (objective three) consented to participate in the solution design and development phase. The method of concurrent engineering was employed at this stage. As a result, case study specific data related to this selected firm was used. Moreover, the phases illustrated in Appendix 3-5 were used during this stage. In some cases, observational note-taking was employed to establish the practices involved in the data collection.

After the development and testing of a complete digital solution, the same company chosen during the design phase was utilised for the validation process (seventh objective). The validation process follows three distinct phases:

- System preparation;
- System deployment; and
- Product selection and testing.

3.4.3 Data analysis

The analysis at this stage involved the experimental tests of the developed solution. Specific products were selected and used in real-world case studies to test the robustness of the system. User feedback was used as a means to improve and refine the final solution.

3.5 Study Limitations

The major limitation in this study is that the derived processes and parameters are based on the judgement of the experts consulted. Hence, the results obtained were purely dependant on the opinions of the respondents consulted, with the researcher making decisions based on the information obtained. Furthermore, the study was solely done for firms in the Western Cape Province tooling industry. Thus, the results are limited to perceptions in this province alone. If the study was conducted at a national level i.e. in all provinces, it is possible that a different set of parameters might have been derived. The study was also conducted mainly for injection Mould Making firms. A further limitation is that the researcher is not an expert in the field of tool making.

3.6 Ethics

As most of the data obtained during the visits is company-sensitive, ethical clearance was sought before the survey or visits were conducted to ensure the study was conducted in accordance with the institution's ethics policy. To ensure company specific data was kept secret, the anonymity of research participants and their firms was kept private during all data collection processes. The data collection instruments were sent for approval by the Stellenbosch University Research Ethics committee. The instruments were successfully approved and an approval letter was obtained (see Appendix 1-2). This letter assisted in engaging the NTIP and WCTI who accepted the study to be conducted within the companies.

3.7 Conclusion

This chapter gives detail on the research methodology employed in the accomplishment of all the set objectives. A literature study was employed for the achievement of the first two objectives (see Chapter 2). The triangulation methodology was employed for the attainment of the third objective while knowledge engineering was employed to achieve the fourth objective. Systems engineering methodology was employed in the design, development and validation of the final digital solution in the final three objectives.

Chapter 4: Findings and analysis - Current operational practices and major shop-floor disturbances

4.1 Introduction

This chapter outlines the major research findings for the third objective, which involved determination of the current operational practices employed by firms in the South African TDM industry (see Section 1.6). The purpose of the objective was to finalise the context definition or industry specific characteristics of the South African tooling environment. The findings are presented as follows:

- Firm demographics;
- Key performance indicators;
- Information systems employed;
- The major operational disturbances affecting the sector;
- Causes and consequences of operational disturbances identified;
- Work flow analysis;
- Key roles identification;
- Key decisions made per role; and
- Process-mapping for key procedures.

4.2 Questionnaire survey findings

This section gives an account of the results obtained during the questionnaire survey on the operational procedures employed by the South African TDM sector. Of the 150 companies consulted, 102 firms agreed to take part in the study, making them the sample size for analysis. A total number of 102 questionnaires were sent out to the organisations participating. A follow up on receipt of the questionnaires was done via telephone calls and emails. Of the 102 questionnaires, 71 were returned; hence the response rate was 70%, which is acceptable. Among the 71 returned for analysis, only 58 were in an acceptable format (13 were spoiled or inadequately filled).

4.2.1 Sample characteristics or firm demographics

The majority of firms observed offered more than one service. Some of the firms observed have injection moulding and general machining facilities (52% and 44% of the firms respectively), as shown in Figure 23. The mean number of employees for the observed population of companies was 17, with a mean annual income of less than 10 million ZAR. Hence the majority of the firms are SMMEs, according to the classifications defined in South African National Credit Regulator by Mahembe (2011).

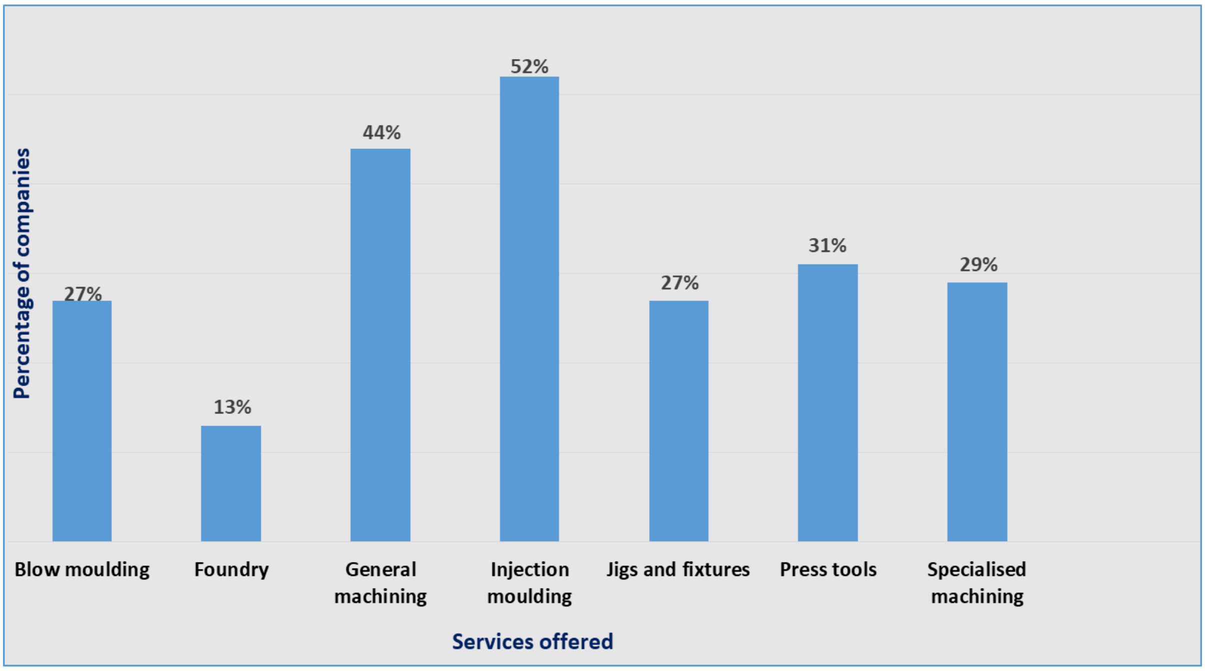

Figure 23: Services rendered by observed firms

4.2.2 Key competitive performance objectives

The respondents were asked on the key Competitive Performance Objectives (CPOs) they deemed crucial in the TDM sector. According to the results illustrated in Figure 24, 42% of respondents, who were industrial captains in the TDM sector, believed that product quality was the most important CPO that TDM products should possess for the firms to win market share. Due date conformance (17%), product cost (13%) and product time-to-market (11%) were also deemed as critical success factors for firms doing well in the sector.

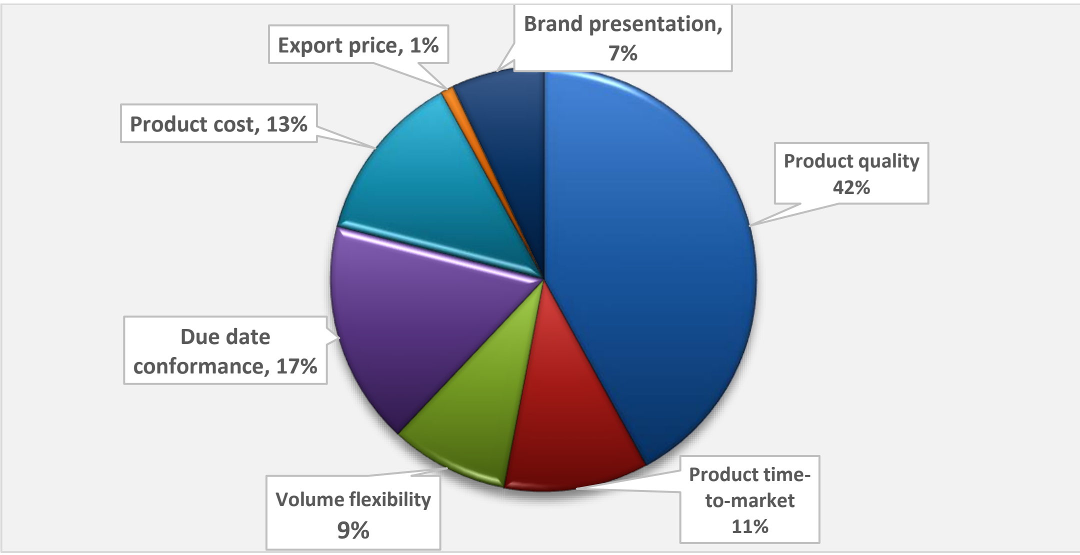

Figure 24: Key Competitive Performance measures in TDM sector (Dewa et al., 2014b)

4.2.3 Information systems employed

Since the area of data collection and manipulation was identified as an area to focus on in the previous objective (see section 2.6, chapter 2), all the operational procedures with regard to data collection were analysed. The data collection and manipulation strategies utilised on the shop-floor was another enquiry during the questionnaire survey. In some cases, firms used more than one methodology for data capture. 77% of the firms indicated that they recorded their transactions manually, while 23% of the firms used computers. Microsoft Excel was the major computer software utilised by firms using computers (76%), while 14% used web-based tools and 10% of firms confirmed the use of customised stand-alone Enterprise Resource Planning (ERP) systems (Figure 25).

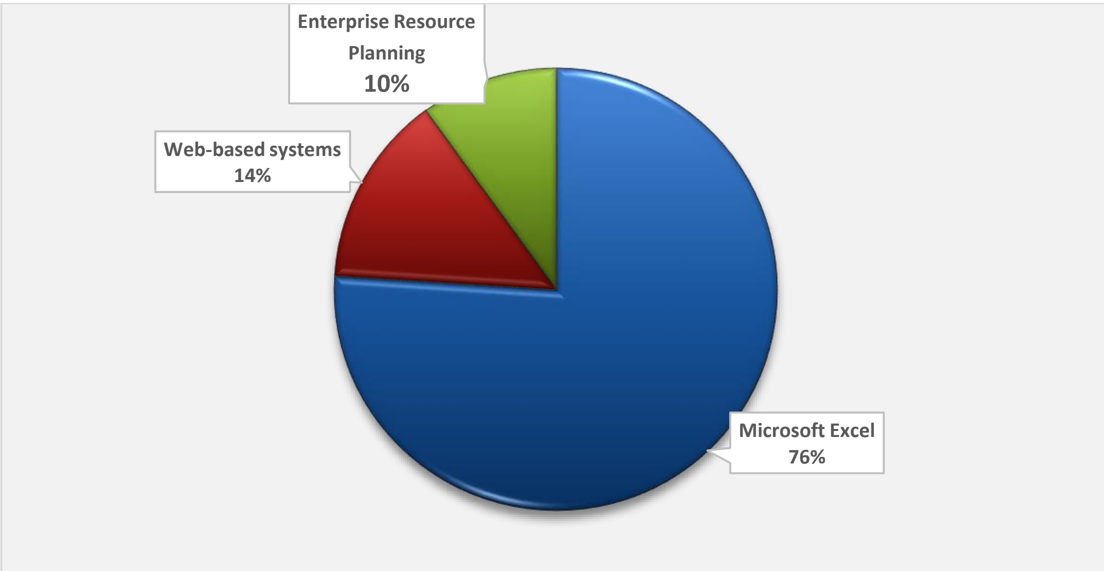

Figure 25: Computerised systems employed

4.2.4 Most prevalent operational disturbances

The seven types of operational disturbances discussed in the literature review (chapter 2) were also questioned in terms of their frequency of occurrence in the studied TDM workshops. All organisations were found to encounter one major disturbance, namely machine breakdown, with 91% of the firms having reported experiencing equipment damage and raw material shortage. The possible causes of the identified operational disturbances and their consequences on business performance were also outlined. Table 9 summarises the operational disturbances identified.

Table 9: Summary of identified operational disturbances (Dewa et al., 2014b)

Operational Disturbance	Category
Work-In-Process increase	Job-related/Task Related
Shortage of raw materials	Supplier-related
Defective raw materials	Supplier and Task-related
Equipment damage	Task-related
Machine break down	Resource-related
Worker absenteeism	Resource-related
Accidents	Resource/Task-related

The percentage of investigated firms experiencing each operational disturbance class (shown in Table 9) is presented in Figure 26.

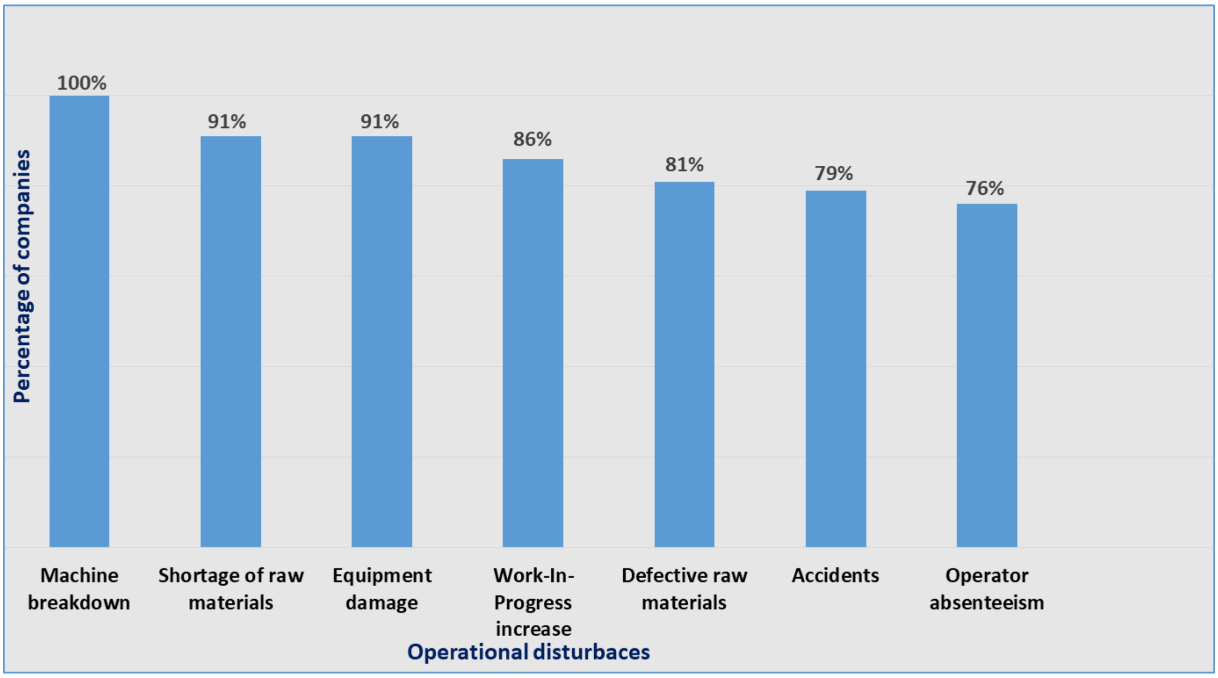

Figure 26: Prevalent operational disturbances (Dewa et al., 2014b)

To establish the most prevalent operational disturbances experienced by the TDM sector in South Africa, mean values for each disturbance based on descriptive statistics in SPSS were used to rank the operational disturbances. The disturbance with the highest mean was ranked first.

Table 10: Descriptive Statistics for Operational Disturbances (Dewa et al., 2014b)

	Raw Material Shortage	Defective Raw Materials	Work In Process Increase	Machine Breakdown	Equipment Damage	Accident Occurrence	Operator Absenteeism
Sample Size	58	58	58	58	58	58	58
Mean	2.93	2.33	2.61	3.33	2.53	1.96	2.20
Std. Deviation	0.953	0.893	1.013	0.632	0.847	0.660	0.840
Rank	2	5	3	1	4	7	6

Results of these calculated means for each operational disturbance class, based on the frequency levels gathered during the analysis, are displayed in Table 10. The disturbances were ranked according to these means with the highest rank (1) assigned to the setback with the highest mean value and the lowest rank (7) assigned to the lowest mean value. According to the information shown in Figure 26 and Table 10, the most significant operational disturbances experienced by firms in the TDM sector are:

- Machine breakdown;
- Shortage of raw materials;
- Work-In-Process (WIP) increase; and
- Equipment damage.

Of the four identified operational disturbances, machine breakdown was the most common in terms of frequency.

4.2.5 Possible causes of operational disturbances

Seventeen identified possible root causes of the operational disturbances were examined in terms of their frequency of occurrence in the studied firms. The results presented in Figure 27 show that 63% of the firms investigated attributed late delivery of raw materials from suppliers as the major cause of some of the disturbances experienced. Lack of worker motivation, poor machine maintenance and supplier production, quality, and transportation challenges were also cited as key causative factors to the experienced setbacks by the participating respondents.

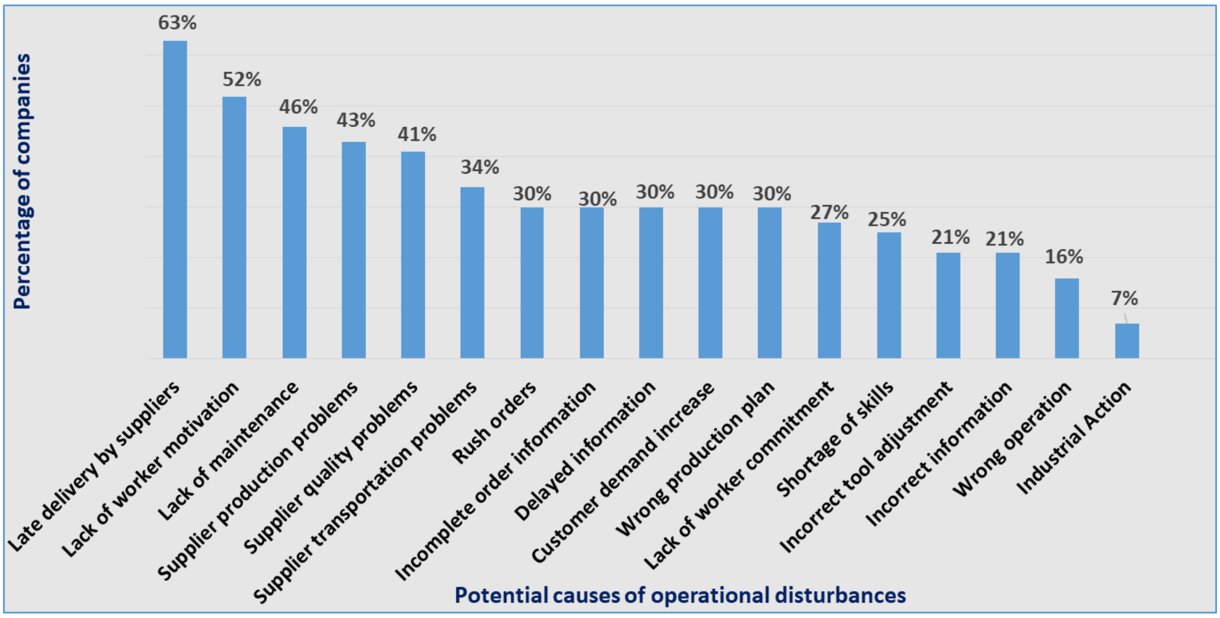

Figure 27: Root causes of operational disturbances (Dewa et al., 2014b)

The relationships existing between the operational disturbances and the causes were also established. Results of the correlation analysis illustrate these relationships and are displayed in the table below (Table 11).

Table 11: Operational Disturbances and causes correlation (Dewa et al., 2014b)

Causes / Disturbance	Late delivery by suppliers	Supplier production problems	Supplier quality problems	Supplier transportation problem	Shortage of skills	Industrial action	Lack of worker commitment	Lack of worker motivation	Wrong operation	Incorrect tool adjustment	Lack of maintenance	Rush orders	Customer demand Increase	Incorrect Information	Incomplete information	Delayed information	Wrong production plan
Shortage of raw materials	.380**	-.047	-.002	-.116	.030	.084	-.128	-.184	-.072	.005	-.217	.376**	.063	.157	.067	-.072	.063
Defective raw materials	.147	.139	.212	.150	.067	.132	.085	-.044	-.276*	.139	-.006	.118	.215	-.079	-.070	-.075	.022
WIP increase	.187	.336**	.120	.066**	.226	.109	.122	.200	.036	.204	.059	.148**	-.072	.081	.153	.148	.038
Machine breakdown	.b	.b	.b	.b	.b	.b	.b	.b	.b	.b	.380**	.b	.b	.b	.b	.b	.b
Equipment damage	-.123	-.116	-.128	-.047	.030	-.159	.041	.184	-.069	.005	.153**	.063	-.207	.157	-.069	-.072	.063
Accidents	-.240	.170	.240	-.369**	.089	-.029	.204	.085	.090	.054	.118	-.232	-.045	.051	.027	-.045	-.045
Operator absenteeism	-.045	.228	.128	.136	.318*	.154	-.035	.242	.121	.010	.184	.186	.009	.288*	.105	.098	.363**

**correlation is significant at the 0.01 level (2 tailed). *correlation is significant at the 0.05 level (2 tailed)

4.2.6 Impact of disturbances on business performance

Sixteen experienced consequences, due to the operational disturbances, were identified and examined in terms of their frequency of occurrence in the surveyed companies. The results presented in Figure 28 show that 91% of the firms investigated experienced long downtime periods as the major result of some of the disturbances experienced.

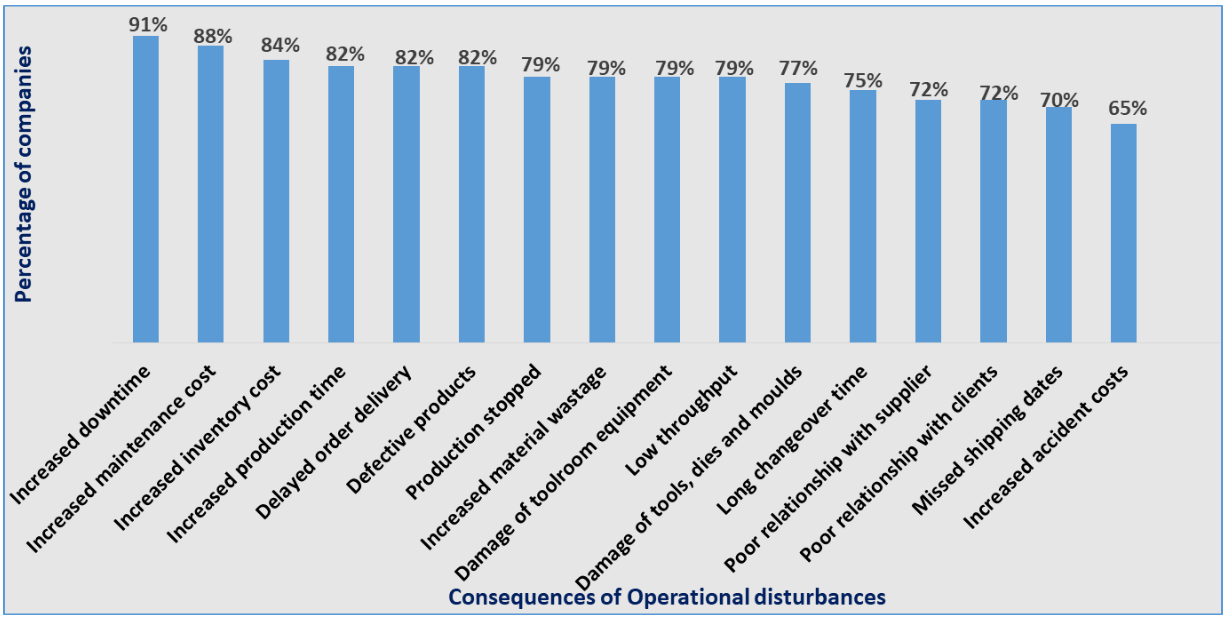

Figure 28: Consequences of operational disturbances (Dewa et al., 2014b)

The mean values of each operational consequence were also determined and the results of the ranks are presented in Table 12. Increased downtime, increased inventory cost, increased production cost, late delivery of orders, increased maintenance cost and increased production cost were identified as the main consequences experienced in the sector. However, the other results of the operational set-backs discovered were low throughput, delayed deliveries in orders and the production of defective products. In some instances long changeover times between orders requiring set-up are experienced. These consequences compromise the image of the company and put the business at a high risk. Cases of high accident rates can easily make workers insecure and cause absenteeism from duty for long periods of time thus stopping production and slowing down the delivery of the orders. The consequences have a domino effect on each other as one consequence may result in another

Table 12 : Descriptive Statistics for Consequences (Dewa et al., 2014b)

Consequences	Sample Size	Mean	Std. Deviation	Rank
Defective products	58	2.43	0.920	7
Low throughput	58	2.52	0.978	5
Delayed order delivery	58	2.50	0.996	6
Long changeover time	58	2.36	1.038	8
Increased downtime	58	2.90	1.038	1
Missed shipment date	58	2.12	0.900	13
Production stopped	58	2.10	0.912	14
Increased production cost	58	2.59	0.992	3
Increased material wastage	58	2.21	0.932	11
Increased accident cost	58	1.84	0.745	16
Increased maintenance cost	58	2.77	1.000	2
Increased inventory cost	58	2.53	1.037	4
Operator absenteeism	58	0.83	0.566	17
Poor relationship with clients	58	2.00	0.926	15
Poor relationship with suppliers	58	2.14	1.043	12
Damage of tools, dies and moulds	58	2.23	0.945	10
Damage of tool-room equipment	58	2.35	0.973	9

The identified relationships existing between the operational disturbances and the consequences were also established. Results of the correlation analysis illustrate these relationships and are displayed in Table 13.

Table 13: Correlation between disturbances and Consequences (Dewa et al., 2014b)

Consequences / Disturbance	Defective products	Low throughput	Delayed order delivery	Long changeover time	Increased downtime	Missed shipment date	Production stopped	Increased production costs	Increased material wastage	Increased accident cost	Increased maintenance cost	Increased inventory costs	Poor relationship with clients	Poor relationship with suppliers	Damage of tools, dies and moulds	Damage of tool room equipment
Raw material shortage	.014	-.066	-.067	-.168	-.185	-.032	.015	-.011	-.018	-.147	-.166	-.062	.049	-.068	-.110	-.229
Defective Raw materials	.416**	.196	.324*	.161	.220	.164	.254	.133	.201	-.096	.173	.236	.302*	.286*	.211	.072
Work-In-Progress Increase	-.208	.066	.067	-.047	-.115	-.166	-.162	-.214	-.173	.028	-.104	-.198	-.146	-.147	-.175	.090
Equipment breakdown	-.052	.130	.042	.110	-.049	-.129	-.037	-.077	-.072	-.074	-.188	-.235	.000	.006	-.036	.062
Accidents	-.120	.128	.118	.051	.141	-.154	.053	.119	.188	.374**	.247	.012	.170	.139	.239	.333*
Operator absenteeism	.179	.417**	.156	-.041	.089	-.027	.273*	.121	.135	-.023	-.009	.068	.135	.162	.109	.145
Machine breakdown	1	.177	.354**	.367**	.562**	-.043	.239	.295*	.488**	-.080	.313*	.310*	.510**	.535**	.522**	.341**

**correlation is significant at the 0.01 level (2 tailed). *correlation is significant at the 0.05 level (2 tailed).

4.3 Interview and site tours findings

All five of the companies visited used manual data collection methods, a finding which correlates with the survey findings (see section 4.2.3). The main reason given by respondents for this was the concern of the need for huge amounts of money to invest in digital data collection methodologies. Furthermore, the visited TDM firms were tool rooms which operated on a product-based basis within a job-shop environment. All respondents indicated that due date conformance was a major challenge with setbacks disturbing the daily operations.

Machine breakdown was also cited as a major operational disturbance by four out of five companies. However, another setback of power cuts was communicated by all respondents. This disturbance had become prevalent at the time the interviews were conducted. During the site visits, thirteen different roles found in a tool-room environment were identified (see Appendix 4-1 for the role definitions). A majority of the firms are SMMEs. As a result, the majority of the roles defined in Appendix 4-1 were assumed by more than one person; for instance, the Tool Room Manager would in most cases be responsible for the cost estimation and purchasing functions as well.

Furthermore, during the benchmarking visits, the procedures involved in tool production were observed with the aim of depicting current practices in the sector. The specific steps involved in producing press tools and injection moulds were also investigated. The generic production flow, adapted from Henriques and Pecas (2013), was used as a guide of the stages involved in tool production (Figure 29). Based on the illustrated process flow (Figure 29), tool making can be defined as following five broad procedures: quotation and invoicing; design; planning, purchasing and production; packaging; and despatch. The discrete steps followed for each stage were established and links were made with the roles responsible for each stage. The different procedures are illustrated in flow diagrams shown in Appendix 4-2 to Appendix 4-8. The role process mapping is shown in Table 14 below.

The purpose of observing the different tasks involved in a tooling environment was for establishing the task model (see section 2.2.7). Breaking down the tasks into smaller discrete steps helps in the clear identification of processes requiring digital assistance. Possible selected tasks may include complex processes, tasks which have strain implications on the workers or repetitive processes which are error prone. The method of observational note taking can help validate the interview responses on the identification of tasks. Observing workers while carrying out routine tasks can aid in quickly identifying areas digital assistance can greatly improve.

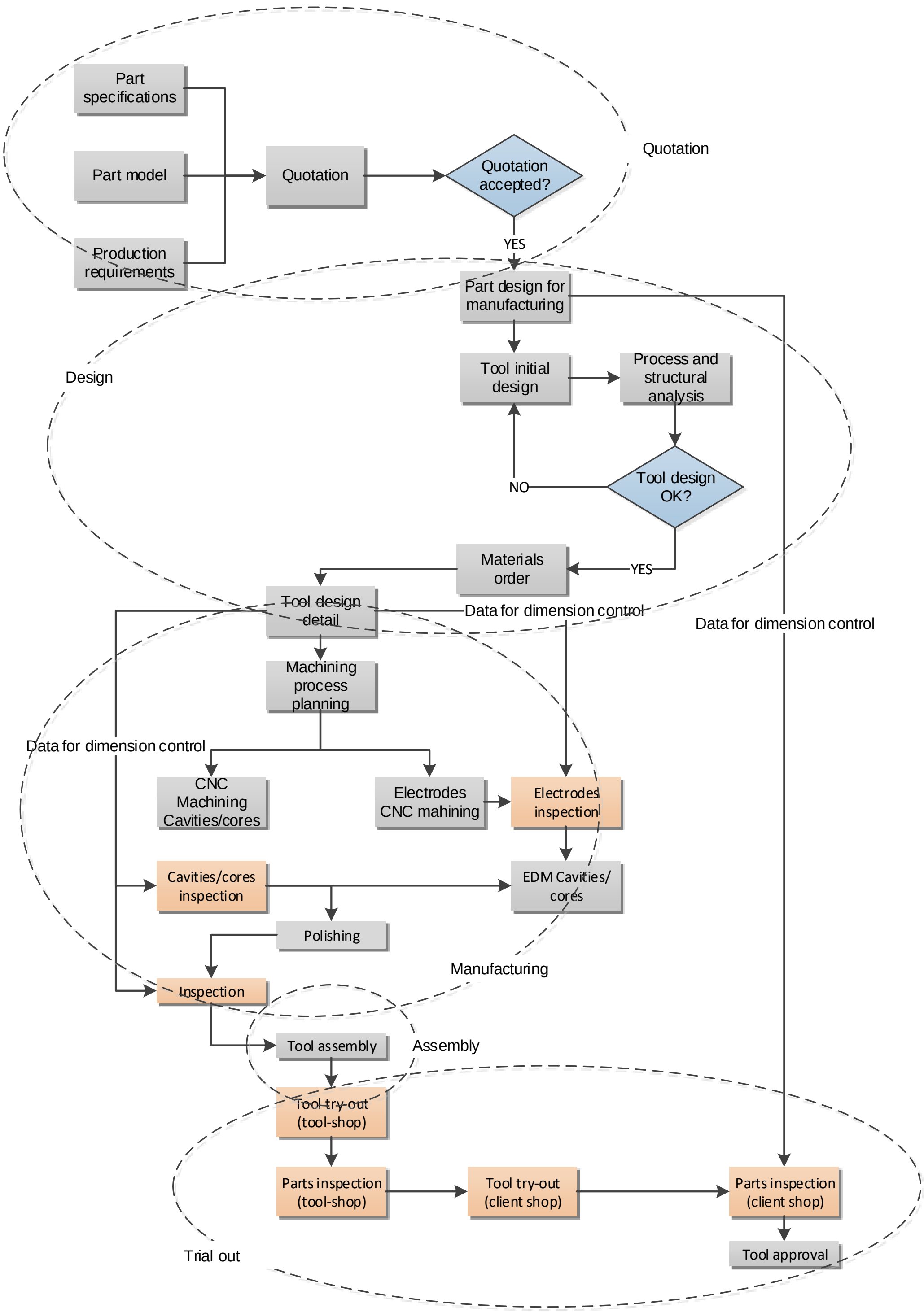

Figure 29: Tool manufacturing processes (adapted from Henriques and Pecas, 2013)

The process flow diagram is a detailed representation of the value chain shown earlier in chapter one (see Figure 1). The production of tools involves many complex and knowledge intensive stages. These tasks are conducted by highly skilled workers who make decisions at each stage of the value chain. Table 14 summarises the roles found in a tooling environment and the key decisions each role makes.

Table 14: Role process data mapping

Role(s) responsible	Process(es)	Key operational decisions	Input data	Output information/ documents
• Tool Room Manager	Enquiry	• Accept or reject an order based on available resources and competencies	• Job specifications and production requirements • Engineering drawings • Sample of part	• Quotation • Invoice
• Cost Estimator	Quotation	• Decide on the price of a tool based on customer requirements		
• Tool designer	Design drawings	• The dimension details and tolerances of the part to be produced	• Customer approved job specifications and production requirements • Sample of part	• Engineering drawings of the tool to be produced
• Project Manager	• Material purchasing • Goods receiving • Tool production planning and scheduling	• The materials required for a tool • Machine and operator process planning	• Drawings and Job specifications	• Purchase orders • Job Card or Time sheets • Production schedule
• Toolmaker • Heat Treatment Operators • Metallurgists • Metrologist • Milling and Turning Operators • EDM operators • Polishers	• Tool production • Packaging	• Machine and operator process planning	• Job card or time sheets • Production schedule	• Injection mould or press tool • Packaged product

4.4 Analysis and discussion of Results

The results showed that increased downtime was a major consequence due to the setbacks experienced in all firms surveyed. This is possibly due to machine breakdown experiences (major disruption established) which stop production and slow down operations. Eventually, orders are delivered late to customers while maintenance, inventory and production cost are increased. Upstream quality-related problems result in the production of defective products, thus resulting in waste of time and materials.

As illustrated in Table 11, it was noted that the production of defective products is strongly correlated to defective raw materials. Machine breakdowns are strongly correlated to delayed order delivery, increased downtime, wastage of raw materials, and damage of equipment, resulting in poor relationships with clients. Figure 30 summarises the relationships established from the correlation analysis.

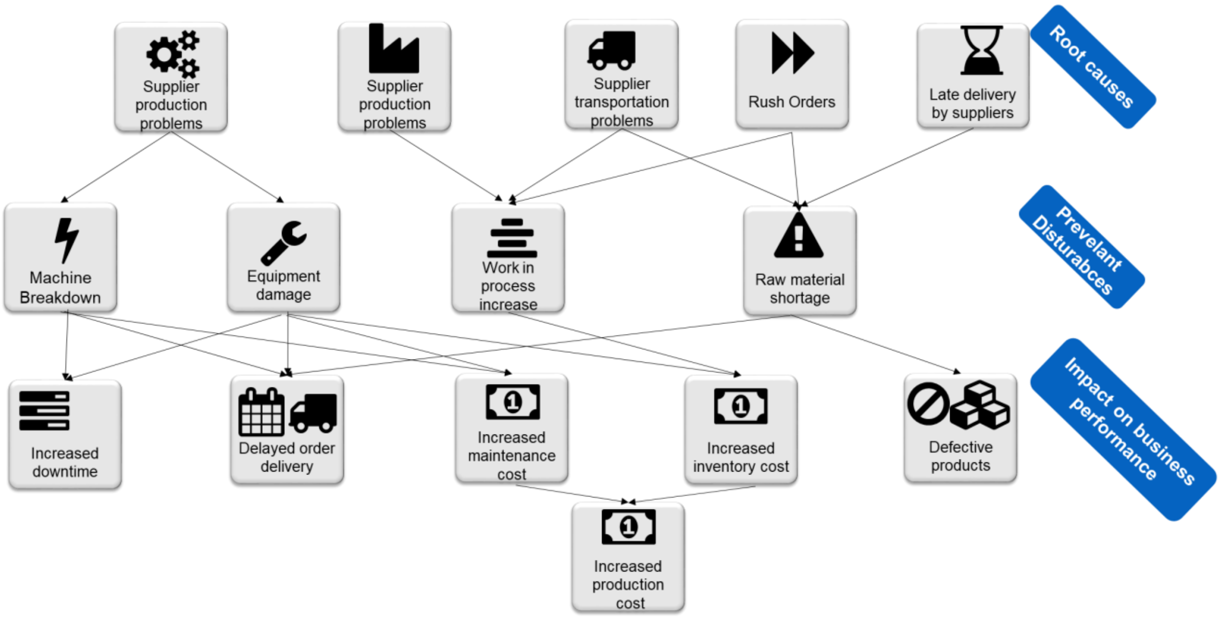

Figure 30: Cause disturbance consequence mapping (Dewa et al., 2014b)

Furthermore, due date reliability was deemed the second most important feature by the respondents for competitiveness. This result correlates with the literature with due date reliability becoming a crucial factor in the TDM industry. Likewise, the majority of firms observed used manual data collection methods, an observation which may be the reason why the sector struggles in data collection and manipulation, as cited by Von Leipzig and Dimitrov (2015).

Though the results show machine breakdown to be the major shop-floor disturbance, frequent power cuts due to load shedding were added to the list of disturbances a few months after, based on the semi-structured interview findings. Due to maintenance backlogs, skill shortages and challenges in securing coal, the power generated by Eskom (South Africa's major electricity supplier) has declined over the past few years (as shown in Figure 31). This has resulted in the national electricity demand surpassing the current supply. To avoid power system failure on the national grid, Eskom then resorted to frequent load-shedding schedules as the last resort, leaving many local businesses in a power crisis. According to Van der Nest (2015), load shedding involves planned rolling blackouts on a rotating schedule throughout the country to avoid a situation of total system failure.

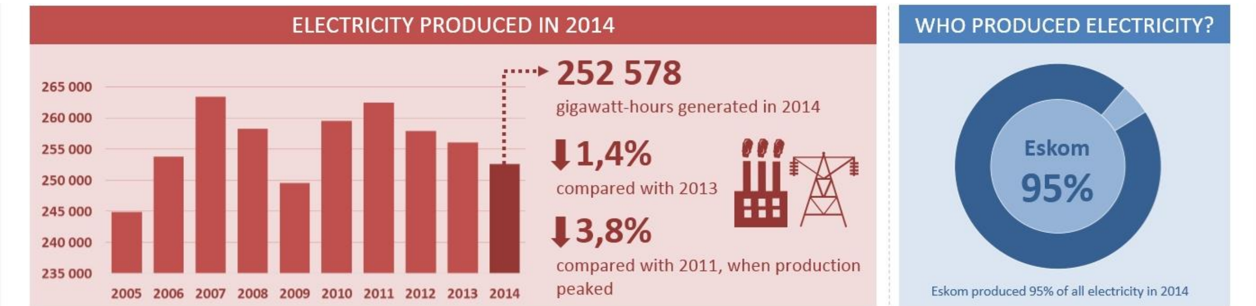

Figure 31: Trends in electricity generated and consumed in past years (Statistics SA, 2014)

When load shedding occurs, manufacturing operations are shut down resulting in increased downtime, decreased productivity and, at times equipment damage. The majority of manufacturers still lack enough working capital for them to purchase or hire back-up generators. As a result, when power cuts occur, orders may be delayed due to interruptions on scheduled tasks requiring electrical power. With the increased frequency of load shedding since the autumn of 2014, some South African companies were left with no choice but to plan their operations with the consideration of the power-cut interruptions as another constraint. Though the setback of power cuts was added, it was not explored in terms of its frequency of occurrence as conducted in section 4.2.4. Furthermore, the manual data collection methods used in the majority of TDM firms also present, a lot of operational challenges, as discussed below.

Manual shop-floor data collection presents a lot of challenges which negatively affect business operations in SMMEs. Firstly, since the data is manually captured into an Enterprise Resource Planning (ERP) system or software package, at predetermined time intervals (e.g. the end of a shift or job), the time value of the data is severely compromised. Generation of reports and information analysis only occurs after the data entry is completed. However, this can be detrimental to productivity as knowing information about what transpired on the shop floor after the fact may be too late to address the issue, especially in a dynamic manufacturing environment.

The tool room is a highly dynamic production environment. Dewa, Van der Merwe, Matope and Nyanga (2014c) cited that during tool-room operations, events rarely flow as scheduled. Scheduled orders may get cancelled while new jobs are inserted. In addition, certain machinery for production may become unavailable due to breakdowns or scheduled maintenance, while newly purchased resources can be introduced. In some cases, scheduled tasks may take longer than anticipated. Other uncertainties like operator absence, unavailability of tools and depletion of raw materials are possibilities. These unforeseen dynamic events on the shop floor can render an optimal process plan and schedule generated earlier after considerable effort, unacceptable. If this happens, a new schedule must be generated to restore system performance and maintain achievement of business goals competitively. This factor makes timely capturing of shop-floor data imperative. Late data collection restricts decision-makers from the ability to make timely interventions in cases of disturbances.

Secondly, due to the rigorous amount of labour involved in manual data collection, the task is often deemed tedious and demanding. Often workers concentrate on their tasks at hand and deem the data collection procedure to be a disturbance to their value-adding activities. As a result, workers can possibly postpone data entry for prolonged periods of time and in most cases record incomplete data. This leads to inaccurate or inconsistent reports being generated. Furthermore, in most cases the data capture is conducted by a different operator from the one who initially records the data. This can lead to challenges in the form of wrong entry or data duplication and time wasting. Since human error is an inevitable possibility, accuracy of the data captured is therefore compromised and, in some cases the flawed entries make the information generated confusing to decision makers. This can occur if, for example, different data sets for the same information are located in different domains or departments (i.e. data inconsistency). Reports with missing data cannot be used for decision-making as this may lead to poor choices being made. In addition, any wrongly entered data can be difficult to detect or eradicate.

Thirdly, manual data collection is a costly methodology in terms of the resources consumed in the form of printed paper and pens. The method is expensive when it comes to resource usage and time spent on it. Finally, the quality of the data gathered by manual means is usually dependent on the worker's perceptions of the purpose of the recorded data. If workers perceive the recording as a way of monitoring their performance, flawed information is usually omitted or wrongly recorded, as some operators may fear the punishment associated with failing to conduct some tasks.

The availability of real-time information is critical to the success of any production environment (Dewa, Mhlanga, Masiyazi and Museka, 2013). Having current manufacturing data at your fingertips is the first step for any organisation to realise a high-tech competitive enterprise in a highly global world. The future in manufacturing lies in the development of information solutions that allow manufacturers to be more proactive, intelligent and informed while supporting the execution of timely decisions (Dewa, Matope, Van der Merwe, Nyanga and Masiyazi, 2014d).

The availability of real-time production information results in improved productivity, delivery responsiveness and increased profitability (Satyavolu et al., 2015). According to Cowling and Johansson (2002), real-time information can greatly aid in dynamic scheduling within a manufacturing set up. As a result, a more realistic schedule can be generated based on the availability of resources and orders in-progress on the shop floor. The streamed data from real-time information can be used to observe events which may lead to operational disturbances and create alerts before the disturbances negatively affect business operations. Hence, the real-time data supports the prognostics for predicting manufacturing maintenance issues with regard to machinery (Snatkin, Karjust and Majak, 2013). Workers, line managers and top management will be able to make informed decisions based on the available information presented. Business functions like process planning, costing, and scheduling are therefore supported effectively.

Accurate and timely production information forms the basis of all optimal manufacturing decision-making. Manufacturing firms usually employ ERP or Manufacturing Execution Systems (MES) to generate reports used for decision-making. However, these systems depend on shop-floor data as an input for them to process and generate these reports. This eventually makes the shop-floor data collection process a crucial stage in the production value chain as any problems with the initial data collection can initiate a ripple effect on the reports generated by ERP systems, thus negatively impacting business operations ("Mobility in Manufacturing", 2012).

However, due to the financial constraints South African toolmakers face identified in section 2.5.2 (Dewa et al., 2015a), most firms lack the financial muscle to invest in sophisticated ERP software to enhance their daily business transactions. As a result manual methods such as pen and paper continue to be employed for shop-floor data collection by the majority of firms. Consequently, these firms struggle due to many shortfalls.

4.5 Conclusion

The third objective of determining the current operational practices and prevalent operational disturbances in firms in the South African TDM sector was successfully conducted. The findings from the analysis clearly validate earlier findings that the sector has had challenges in the area of data collection and manipulation. Therefore, the organisational practices in data collection and manipulation can be improved by introducing digital solutions. The operational disturbances affecting the sector were also established with analysis of possible causes and resulting consequences.

Chapter 5: Findings and analysis - System requirements analysis and design

5.1 Introduction

This chapter focuses on the results obtained for the fourth objective (see section 1.6). Based on the analysis conducted from the prior objectives, the fourth objective involved development of the digital solution blue print through a system requirements analysis. To achieve this end, the method of knowledge engineering was employed, with field experts from five different tool-making firms who were interviewed to obtain results on:

- Identification of processes which can experience significant improvement through digitalisation;
- Parameters for the identified processes; and
- User needs and specifications derivation.

Semi-structured interviews and observational note taking were utilised as the data collection strategies, as discussed in section 3.3.1.

5.2 Expert and company background

The five experts visited were mainly from injection mould design and press metal tool production specialist firms within the Western Cape Province Tool, Die and Mould Making (TDM) and Plastics manufacturing industry. The mean number of employees for the observed population of companies was 10.4. The specific number of toolmakers in each of the visited firms is shown in Figure 32. The names of the firms are not outlined so as to abide by the academic ethics code of conduct. The tooling expert from company D had the greatest experience, as depicted in Table 15 (with 40 years' experience in the tooling industry). The average experience was determined as 28.6 years.

Table 15: Experts' experience in years (Dewa et al., 2016b)

Expert from company	A	B	C	D	E
Experience of the expert (years)	19	28	23	40	33

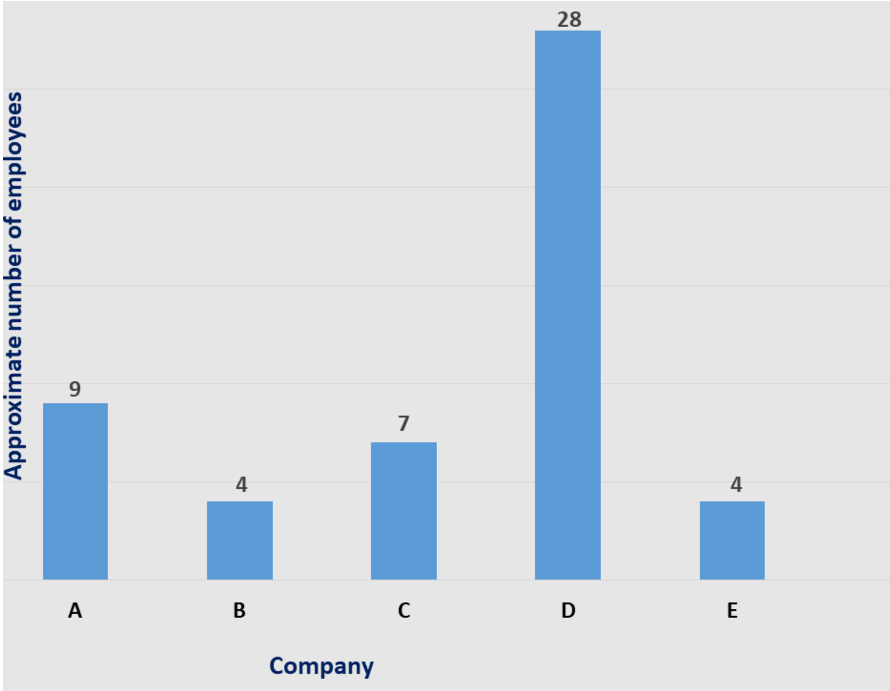

Figure 32: Number of employees in the tool rooms visited (Dewa et al., 2016b)

Companies A, B, C and E are stand-alone TDM firms, while company D is a tool-room serving in-house operations of a larger manufacturing organisation.

5.3 Data collection strategies

During the process analysis, the methods used to collect data were also observed. This was done as a way of validating the findings in the third objective (see section 4.2.3). A majority of companies were also employing manual data collection methods, as shown in Table 16. Three of the firms using computers only, use Microsoft Excel for any parametric entry. However, these computerised entries are made after the data is manually recorded.

Table 16: Data collection strategies during cost estimation (Dewa et al., 2016b)

Cost estimator from Company	A	B	C	D	E
Software system	Excel	None	None	Excel	Excel
Manual or computerised	Computerised	Manual (file system)	Manual (no system)	Computerised	Computerised with back-up filing system
Number of quoting experts	1	1	2	2	1

5.4 Selected business processes

It is almost impossible for any digital solution to address all the requirements in a domain. As a result, there is a need to narrow the scope to the most important business functions. The experts' opinions on the processes which can significantly benefit from digitalisation were asked for during the interviews. The selection of the processes was based on the ones which greatly impacted the major key performance indicators of quality and due date reliability, highlighted in section 4.2.2. There was also a general consensus in the experts' responses that due date reliability and time-to-market are now emerging as critical success factors in the domain. As such, the visited experts were questioned on the tooling functions which greatly impacted the due date reliability or speed of a project. The experts all alluded to the following critical functions:

- Cost estimation
- Project management – planning, scheduling and control
- Production

It was therefore concluded that improving the data collection in the domains of cost estimation, process planning and production functions would significantly improve business operations in a tooling environment.

5.5 System parameters

The next stage in the analysis involved derivation of the parameters recorded during the identified functions of cost estimation (quoting), production planning and manufacturing (production) stages. More interviews with field experts were conducted to obtain this data. At this stage, job quoting, project and production experts were visited at different times. Five different firms (which were mostly injection mould specialists) were consulted during this exercise. Furthermore, the method of observational note-taking was employed to validate the responses given during the interviews. In this case, the respondents would use a selected example to demonstrate the procedures followed in preparing a quote, generating a production schedule or recording production-related data.

5.5.1 Cost estimation parameters

An interview guide was prepared for the interaction process. The guide involved both open-ended and closed-ended questions which required the expert to give information on:

- Cost estimation approach employed;
- Job costing system used;
- Average time it took an expert to quote a new and an old job;

- Average due date and budget conformance; and
- Key parameters used in quoting.

According to Duverlie and Castelain (1999), there are four different approaches estimators use when determining the price of a job. These are the intuitive, analogical, parametric and analytical methods. The intuitive method is employed when the estimator heavily relies on his or her knowledge, based on experience, to make decisions. In most cases, gut feeling or rule of thumb are employed to make a decision using this approach. On the other hand, the analogical method uses information from similar jobs based on historical records to approximate the cost of a new job. The parametric method seeks to evaluate the costs of a product based on specific parameters characterising the product. However, the product does not necessarily have to be fully described to follow this method. The analytical method allows for evaluation of the cost of a product from a decomposition of the work required into elementary tasks. This makes the analytical method the most suitable for firms using a machine hourly rate costing system. In addition, the estimation process is complex in that so many different decisions are made at the same time. Hence, job estimation is a multi-criteria decision-making problem.

5.5.1.1 Cost estimation approaches and systems employed

Each of the visited firms was questioned on the job estimation processes and policies they adopted. Table 17 summarises the job quoting approaches used by the visited firms.

Table 17: Job quoting approaches (Dewa et al., 2016b)

Expert from company	A	B	C	D	E
Job quoting approach	Geometric-parametric	Intuitive; Analytical	Intuitive; Analytical	Geometric-Parametric	Geometric-Parametric
Software system	Excel	None	None	Excel	Excel
Number of quoting experts	1	1	2	2	1

Three out of the five firms visited utilised Microsoft Excel for quoting, based on the parametric and geometric approach, with the remaining two using the intuitive approach. It was interesting to note that the firms using the intuitive approach (companies B and C) did not have any historical records of jobs done or a record keeping system.

5.5.1.2 Cost Estimation lead times, due date and budget conformance

Since prompt quoting of jobs is of paramount importance, the survey also sought to investigate the average time the interviewed experts spent quoting both old and new jobs. Furthermore, the respondents were given the opportunity to cite reasons for delays and failures to end the project within budget. Cost estimators from companies A and E had the lowest lead times in quoting a job while estimators from company C admitted to struggling to send a customer invoice early, as shown in Table 18.

Table 18: Job quoting lead times (Dewa et al., 2016b)

Company	A	B	C	D	E
Approximate number of days (New jobs)	2 days	3 – 5 days	7 – 14 days	3 – 5 days	2 days
Approximate number of days (Old jobs)	Less than 24 hours	2 days	3 – 5 days	1 day	Less than 24 hours

All firms visited confirmed that the quote generated would never be accurate. In some cases, the firms experienced a profit or a loss per job. When queried on the major reasons for huge deviations between the quoted price and the actual cost of the job, the reasons shown in Table 19 were stated.

Table 19: Reasons for budget non-conformance (Dewa et al., 2016b)

Expert from company	A	B	C	D	E
Reason for failure to conform to budget	Excessive labour hours	Inaccuracy in operation times estimation (labour hours)	Longer operation times	Wrong quote; Customer specification changes; Planning inefficiencies; Labour costs	Overtime

The main reason stated for budget non-conformance and delays was a failure to control labour time so that it is within the plan. However, the respondent from company D highlighted that sometimes non-conformance meant the quote was wrongly prepared in the first place.

5.5.1.3 Derivation and classification of parameters

The greater part of the time spent during the visits was on identification of the key parameters used when quoting a job. Each expert was presented with an open-ended question to specify what the parameters were. To validate the responses given, each expert demonstrated with an example of a previously quoted job. The main cost elements identified were material, labour and machining costs, as shown in Table 20. However, in most cases the experts broke down the cost elements to the smallest elements possible. The expert from company E had a more elaborate system which specified the parameters in the strictest detail possible. This eventually makes the cost estimation process of injection moulds a multi-criteria decision-making process, hence justifying the need to use the AHP procedure to rank each of the cost elements according to their contribution to the total cost of an injection mould job. Based on the data collected and presented in Table 20, the costs incurred during injection mould manufacture can be broadly classified as:

- Material costs;
- Labour and machining costs; and
- Services (outsourcing).

5.5.1.4 Ranking of parameters – AHP problem definition

In the costing of an injection mould, the key parameters to be considered are the material, labour, machining and service cost elements as depicted in Figure 33 below. These elements are further decomposed into the common constituent elements, as shown in Figures 34, 35 and 36.

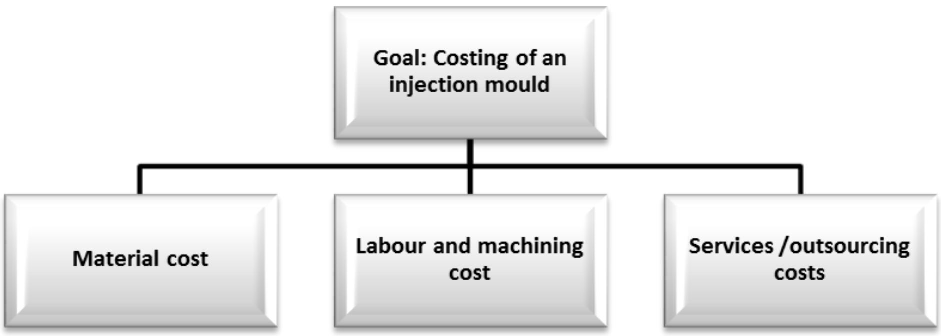

Figure 33: Injection mould cost top hierarchy (Dewa et al., 2016b)

The material cost can be further broken down into the costs incurred in securing the mould base, copper electrodes, cavity steel core, hot runner system and tooling components, as illustrated in Figure 35.

Table 20: Derived costing parameters (Dewa et al., 2016b)

Expert(s) from company	Cost parameters derived
A	• Material • Cooling system • Machining • Labour • Tooling cutters • Outsourcing
B	• Material • Labour • Heat treatment • Design • Subcontracting • Outsourcing
C	• Material • Labour • Consumables • Heat treatment
D	• Material • Labour • Heat treatment • Machining
E	• Material and services - Mould base - Copper (electrodes) - Cavity core steel - Heat treating and plating - Manifold hot-runner system - Components - Texture - Tooling (cutters and inserts) - Sample material - Tooling delivery • Labour - Data management - Mould design - Computer simulations - Advanced engineering - CNC machining - General shop labour - CMM parts

Similarly, the labour and service cost components can be further broken down as illustrated in Figures 35 and 36 respectively.

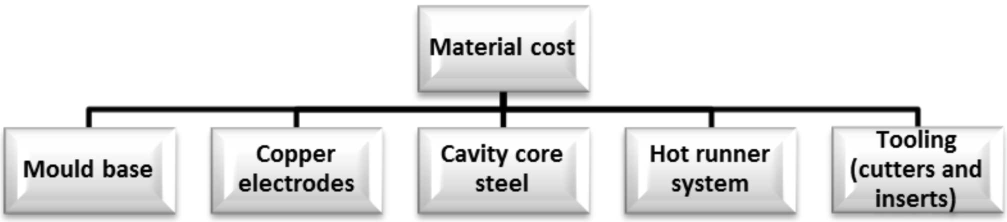

Figure 34: Material cost sub hierarchy (Dewa et al., 2016b)

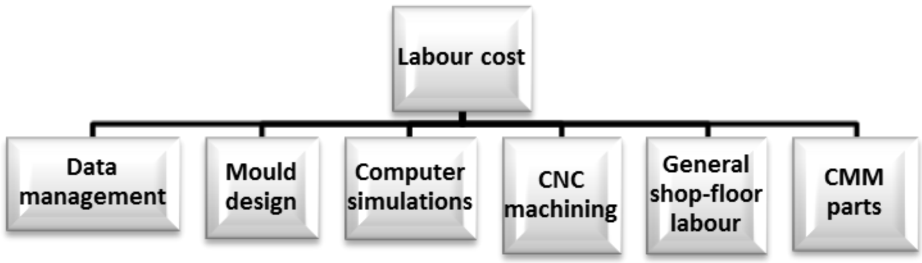

Figure 35: Labour cost sub hierarchy (Dewa et al., 2016b)

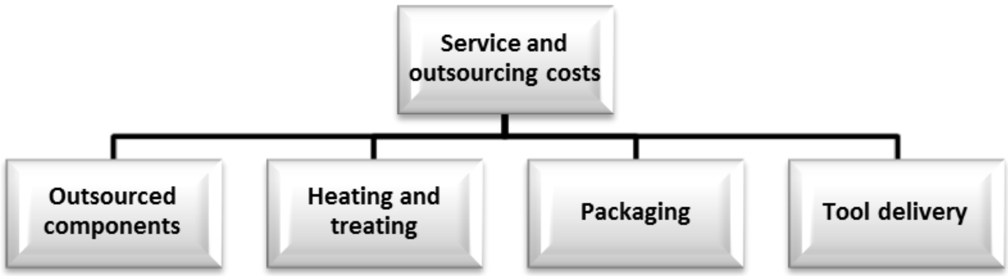

Figure 36: Service and outsourcing cost sub hierarchy (Dewa et al., 2016b)

5.5.1.5 Cost estimation parameter ranking

The methodology employed also included ranking of the parameters determined in terms of their contribution to the overall cost of a job. The purpose of the exercise was to identify the cost elements requiring careful estimation and stricter monitoring during the production phase, since deviations carry such huge consequences. To achieve this, three stages were followed:

A. Pair-wise comparisons

The cost estimator (decision-maker) evaluates the relationships between the first level criteria (i.e. the material, labour and service cost components). Questions were asked in the following format: “How important are labour costs for a product to the material costs when it comes to contribution to the overall cost of the job?” Based on the framework given in Table 7, on a scale of 1 – 9, a pairwise comparison value is assigned, where that L represents the labour costs, M the material costs and S the service costs, the pairwise comparisons derived are shown in Table 21.

Table 21: Pairwise comparisons (Dewa et al., 2016b)

	L	**M**	**S**
L	1	6	9
M		1	4
S			1

All the interviewed experts identified labour costs as the most critical cost component requiring stricter reckoning, monitoring and control. One of the interviewees specifically stated that labour costs would always account for approximately 55 – 60% of the total tool or mould cost. Hence, based on this analysis, labour-related costs were deemed to have extreme importance compared to service-related costs. Labour-related costs have a strong plus importance as compared to material-related costs, while the cost of material has a moderate plus importance with respect to service-related costs (see Table 7, section 3.3.3 for pairwise parameters). The cost of the hot runner system and the mould base makes the material-related costs relatively high in comparison to the service-related costs.

B. Development of a pairwise matrix

The pairwise comparison matrix is completed by putting the inverse of the scales for the inverse relationships, as shown in the Tables 22 and 23 respectively.

Table 22: Pairwise comparison matrix (Dewa et al., 2016b)

	L	**M**	**S**
L	1	6	9
M	1/6	1	4
S	1/9	¼	1

Table 23: Column totals (Dewa et al., 2016b)

	L	**M**	**S**
L	1	6	9
M	0.1667	1	4
S	0.1111	0.2500	1
Column totals	1.2778	7.2500	14

C. Priority determination and ranking

The pairwise comparison matrix is normalised by dividing the values in each column by the column sum, as shown in Table 24. To determine the priorities of each criterion, the normalised principal Eigen vector is obtained by averaging across the rows.

Table 24: Normalised table (Dewa et al., 2016b)

	L	**M**	**S**	**Priority**	**Rank**
L	0.7826	0.8276	0.6429	0.7510	1
M	0.1305	0.1379	0.2857	0.1847	2
S	0.0870	0.0345	0.0714	0.0643	3

Row averages = $\begin{pmatrix} 0.7510 \\ 0.1847 \\ 0.0643 \end{pmatrix}$

Hence, based on the results, labour costs are ranked first with material and service costs ranked second and third respectively.

D. Checking for consistency

The final step involves checking for the consistency of the solution by determining the Consistency Index as shown below:

Weighted sums = $\begin{pmatrix} (0.7510 \times 1) + (0.1847 \times 6) + (0.0643 \times 9) \\ (0.7510 \times 0.1667) + (0.1847 \times 1) + (0.0643 \times 4) \\ (0.7510 \times 0.111) + (0.1847 \times 0.25) + (0.0643 \times 1) \end{pmatrix} = \begin{pmatrix} 2.4379 \\ 0.5671 \\ 0.193911 \end{pmatrix}$

Consistency vector = $\begin{pmatrix} 2.4379/0.7510 \\ 0.5671/0.1847 \\ 0.193911/0.0643 \end{pmatrix} = \begin{pmatrix} 3.2462 \\ 3.0704 \\ 3.0157 \end{pmatrix}$

$\lambda_{max} = \frac{(3.2462+3.0704+3.0157)}{3} = 3.111$

Using Equation 1 (see section 3.3.3), CI = $\frac{\lambda_{max} - n}{n-1} = \frac{(3.1111-3)}{(3-1)} = 0.055$

Hence, using Equation *2 (see section 3.3.3)* the consistency ratio;

$CR = \frac{CI}{RI} = \frac{0.055}{0.58} = 0.096 = 9.6\ \% < 10\%.$

Since the CR < 10%, the judgement can be accepted.

5.5.2 Process planning parameters

Project managers were also consulted on the procedures and parameters reckoned during the process planning phases of a project. All respondents were using manual and visual tools for process planning, such as white boards with orders and task assignments to resources. There was a general correlation of responses on the information required, as shown in Table 25 below.

Table 25: Process planning in tool making

Order	Parts required	Procedure per part	Machine required	Worker assigned	Estimated time	Schedule (weekly)					
						M	**T**	**W**	**T**	**F**	**S**
Job A	Part A	Task 1	Machine 1	Worker 1							
		Task 2	Machine 2	Worker 2							
		Task 3	Machine 3	Worker 3							
		Task 4	Machine 4	Worker 4							
	Part B	Task 1	Machine 1	Worker 1							
		Task 2	Machine 2	Worker 2							
		Task 3	Machine 3	Worker 3							
		Task 4	Machine 4	Worker 4							
	Part C	Task 1	Machine 1	Worker 1							
		Task 2	Machine 2	Worker 2							
		Task 3	Machine 3	Worker 3							
		Task 4	Machine 4	Worker 4							
		Task 5	Machine 5	Worker 5							

Each job is assigned a number and may usually have a number of parts. During the planning, the procedures or tasks followed for the fabrication of each part are outlined in detail. Resources, usually the artisans and machines required to complete a task, are then allocated for each task. Furthermore, an important stage in the planning involves estimation of the task completion times in line with the budget (according to the cost estimated rates). Finally, the schedule for the tasks is prepared. Another exercise in the planning process involves determination of the Bill of Materials (BOM) for each part to be produced and purchased. This process involves derivation of the weight of material required based on the dimensions of length, width and height.

5.5.3 Manufacturing parameters reckoned

Information collected on the shop floor during production is crucial in the monitoring of progress made for control and interventions. Feedback from the experts revealed that different companies use different methods to collect information from the shop floor, as represented in Table 26 below.

Table 26: Shop-floor data collection instruments (Dewa et al., 2016b)

Company	A	B	C	D	E
Shop-floor data collection instrument	Time sheets and material usage sheets	Job card	Job card	Time sheets and stock sheets	Job card
Data required	• Actual times per task • Actual material consumed	• Actual times per task • Actual material consumed	• Actual times per task • Actual material used	• Actual times per task • Actual material used	• Actual times per task • Actual material used

In most cases, firms use a job card for collection of data on the shop floor (company B, C and E). Companies A and D used time sheets and material usage sheets for the same purpose. The data is manually collected and then entered into a computer for analysis at a later stage. The main limitations of this method are that:

i. The times recorded by workers usually only account for the total time spent without specifying the value-added and non-value added time. Usually disturbances may emerge and need to be reckoned so that the true time spent making a part is known for future use.

ii. Analysis of collected data at discrete interval times will cause emerging problems to occur unnoticed. The availability of real-time data always improves the agility and flexibility of a production system.

The downtime experienced due to disturbances, as discussed earlier, was not recorded in all companies.

5.6 System requirements derived

The interaction with experts also included derivation of system requirements for a digital solution. The five features described in this section were highlighted by the respondents (experts).

5.6.1 Collaborative manufacturing

Due to globalisation, the manufacturing of products is no longer a local activity done by a single company, but rather a distributed venture as more firms are realising the need to improve their flexibility and agility. All respondents indicated that the different roles (identified in section 4.3, see Appendix 4-1) participating in any project may possibly be situated in different locations. Hence the first system requirement derived is the capability to facilitate distributed sharing of information over long distances between different role players in the tooling industry (Dewa, Van der Merwe and Matope, 2015b). Furthermore, tooling firms need to be continually linked to their suppliers and customers for seamless information transfer. As such, collaborative manufacturing has been proposed as a key strategy for improving the competitive position of a tool-making firm.

5.6.2 Flexibility

Another feature advocated for by respondents was that of flexibility: the ability to respond to internal and external changes. This is mainly because during a tooling project events rarely go as expected (Dewa et al., 2014b). The respondents all indicated the possibility of production plans being disrupted due to disturbances in the production environment. As a result, digitalisation should enable the ability to trigger alerts for events which lead to shop-floor risks before they disturb operations and negatively impact customer experiences.

5.6.3 Ease in data collection

The developed solution should also facilitate ease in data collection. Manual data collection requires highly intense administrative work which can be taxing to a toolmaker who will be having other responsibilities. As a result, the duty can be postponed to later stages. Hence, the digital solution should simplify the data collection process.

5.6.4 Creation and preservation of expert knowledge

Tool-making firms need to abide by an established quality management system standard which requires compliance with regards to preserving historical records of orders done. Due to the rigour involved in manual data collection methods, the majority of firms have been failing to keep records of their work. As a result, the solution developed should enable the preservation of orders done. This will help preserve expert knowledge. With the decline of skilled toolmakers in the country, preserving expert knowledge will serve to ensure that young tool-makers make better decisions in generations to come. The above features suggest that toolmakers need a digital solution which has holonic characteristics (Dewa, Matope, Van der Merwe and Nyanga, 2014c). According to Wyns (1999) applications like these promise the benefits that a holonic organisation provides to living organisms and societies; stability in the face of disturbances, adaptability and flexibility in the face of change, and the efficient use of available resources in a distributed environment.

5.6.5 Real-time tracking of orders

Nowadays, the ability for Overall Equipment Manufacturers (OEMs) to monitor the progress of their jobs (processed in a TDM firm) has become imperative to win orders. As a result, an emerging requirement is the ability to monitor the progress of tasks for on-going projects and obtain real-time feedback on their current status.

5.7 Discussion on results

The cost estimation, project management, and production processes were selected by experts, due to their importance in the tooling value chain. The section below explains why the processes are deemed crucial.

Firstly, the successful calculation of costs is an important requirement for the performance of TDM companies. However, cost estimation of products in the tooling industry is a complex task requiring immense expert knowledge and sound judgement. Higher estimates may lead to loss of orders or customer goodwill, while lower estimation will affect business profitability. According to Jones (2009), the estimation decision requires sound judgement and knowledge in:

- Injection moulding specifications and functions;
- Reading and understanding of engineering drawings in both printed and Computer-Aided Design (CAD);
- Mould tool design;
- Tool-making procedures;
- Mechanical engineering;

- Basic physics;
- Plastic material properties;
- Behaviour of polymer flow;
- Basic electronics; and
- Robotics.

A delay in quoting is bad practice. This is because research has shown that, in the Mould Making industry usually less than 10% of all offers turn into orders (Dewa, Van der Merwe, Matope and Nyanga, 2016b; Fonseca, Henriques, Ferreira and Jorge, 2007; Duverlie and Castelain, 1999 and Denkena, Lorenzen and Schürmeyer, 2009). Hence, accurate and timely cost estimation before tool, die and mould production is a key attribute for sustaining global competitiveness. Due to the skill shortages the South African TDM industry has experienced, the majority of tool-making firms take a long time to quote a job. Furthermore, results from benchmarking exercises of these firms have shown that the majority of quotes generated lack accuracy due to the methods employed (Figure 17). For effective and timely cost estimation, the parameters to be considered must be known together with the decision heuristics followed.

Secondly, project management of orders in a tooling environment is another complex task requiring great skill and expertise. This is mainly because operational disturbances like rush orders or breakdowns can complicate the life of project managers. Initially prepared process plans and schedules can easily become invalid, thus being continually revised (Dewa, Van der Merwe and Matope, 2016a). For a project to finish within the budgeted time, efficient project management techniques should be employed.

Finally, all value adding activities in a tool room need careful procedure conformance and great skill. As a result, administrative work on the shop floor can be a nightmare if not well designed and managed. The time taken to do each operation is a critical parameter as it will help in giving order progress feedback. Furthermore, knowledge of manufacturing task times serves as a valuable future input during the cost estimation of the same job in the future. After establishing these system functions, the key parameters for each function were derived. Since labour-related costs are the greatest contributor to the overall tool cost, monitoring and control of production time is crucial. One of the consulted experts indicated that over 60% of the tool's costs are labour-related.

5.8. Conclusion

The system functions and parameters were derived. Cost estimation, project planning and production functions were deemed to be crucial in the contribution to shop-floor management and meeting delivery due dates. As a result, the main system users will be cost estimators, project managers and artisans in a tool-making environment. The use case model generated in Figure 37 and the information in Table 27 summarises the key findings in the chapter.

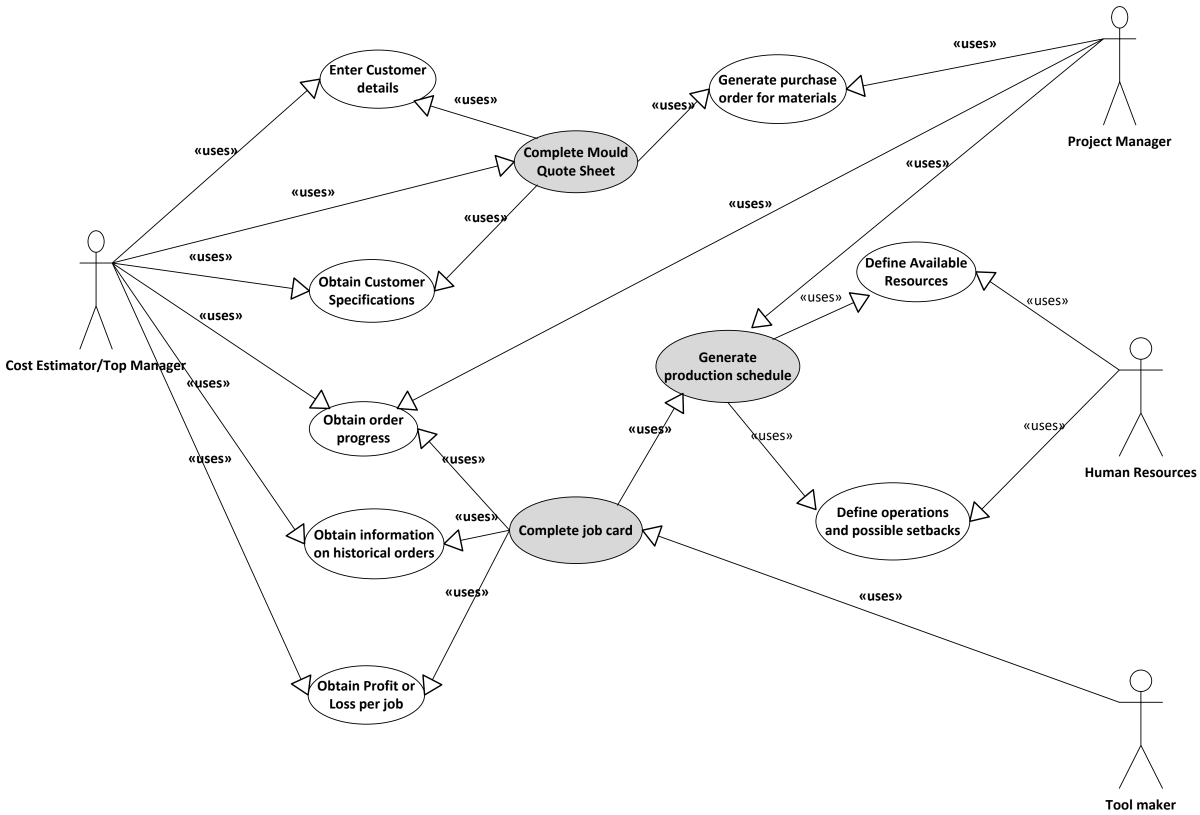

Figure 37: System Use Case model

The major system functions derived are highlighted in grey. Though the cost estimation, process planning and production cases are the major functions, the Human resources function play a crucial role in defining the required operations and resources.

Table 27: System users, functions and parameters

<table>
<tr><th>Users</th><th>Functions</th><th>Parameters</th><th>Data for each parameter</th></tr>
<tr><td rowspan="3">Cost Estimator</td><td rowspan="3">• Cost Estimation
• Quoting</td><td>• Labour costs</td><td>Number of hours for:
• Data management
• Mould design
• Computer simulations
• Advanced engineering
• CNC machining
• General shop labour
• CMM parts</td></tr>
<tr><td>• Material Costs</td><td>Material type and weight required for:
• Mould base
• Copper (electrodes)
• Cavity core steel
• Components
• Texture
• Tooling (cutters and inserts)
• Sample material</td></tr>
<tr><td>• Service costs</td><td>Number of hours required for:
• Heat treating and plating
• Manifold hot-runner system</td></tr>
<tr><td rowspan="3">Project Manager</td><td>• Planning</td><td>• Material types and dimensions</td><td>• Material types
• Length, width and height of material
• Mass required</td></tr>
<tr><td>• Purchasing</td><td>• Supplier lists
• Supplier costs
• Contractors list
• Contractor costs</td><td>• Price of all materials
• Prices of all services</td></tr>
<tr><td>• Scheduling</td><td></td><td>• Available resources – man and machines
• Available dates and times</td></tr>
<tr><td rowspan="2">Production workers</td><td rowspan="2">• Manufacturing</td><td>Value-added time</td><td>• Setup time
• Operation time</td></tr>
<tr><td>Non-value added time</td><td>• Setup downtime
• Operation downtime
• Operational disturbance reason</td></tr>
</table>

Chapter 6: Findings and analysis - System development and validation

6.1 Introduction

In this chapter, the selection of the digital technologies relevant for shop-floor management in the South African tooling industry (fifth objective) is conducted. Furthermore, the chapter also outlines the sixth and seventh objectives' results (see section 1.6), which involved the design, development, testing, deployment and validation of the digital solution. A case study based on one selected company was conducted and results from this study are outlined.

6.2 Digital technology selection

The framework of Industry 4.0 technologies, illustrated in Figure 6 (and cited in the study hypotheses), was used in the selection of the relevant technologies which will address the needs outlined in the previous objectives (see section 5.6). As illustrated in Table 28, cloud computing platforms and mobile devices are possible solutions for the digital solution required.

Table 28: Digital technology selection framework

Derived System Requirements / **Digital Technologies**	Application Domain Digitalisation	Ease in data-collection	Distributed data-collection	Preservation of knowledge	Generation of reports and real-time alerts	Flexibility in the face of changes	Real-time tracking of orders
IoT platforms	Process-level	○	✓	○	○	✓	✓
Location detection technologies	Supply-chain	○	○	○	○	○	✓
Advanced human machine interfaces	Supply-chain	○	○	○	○	○	○
Authentication and fraud detection technologies	Process-level	○	○	○	○	○	○
3D printing technologies	Product-level	○	○	○	○	○	○
Smart sensors	Product level	○	○	○	○	○	
Mobile devices	Process-level	✓	✓	○	✓	✓	✓
Big data analytics and advanced algorithms	Process-level and Product Level	○	○	○	○	○	○
Multilevel customer interaction and customer profiling technologies	Supply-chain	○	○	○	○	○	○
Cloud computing platforms	Process-level	○	✓	✓	✓	✓	✓
Augmented reality wearables	Process-level	○	○	○	○	○	✓

As evidenced in Table 28, a web-based mobile digital solution can help address the derived system requirements. To validate the chosen mobile technology, the decision matrix guide (shown in Appendix 3-3) was employed. The first step involved verification of the number of data types collected at each phase in terms of them being quantitative or qualitative in nature. This was done mainly because mobile data collection is best suited for cases where the majority of the data collected is quantitative in nature (Satterlee et al., 2015). As a result, the derived parameters shown in Table 27 (see section 5.8) were further explored for the purposes of classifying the data types as either quantitative or qualitative, as illustrated in Table 29. Table 30 summarises the results shown in Table 29. It can be seen that 62.2% of the data is purely quantitative in nature on average.

Table 29: Data type classification

Functions	Parameters	Data for each parameter	Data type class (Quantitative/Qualitative)
• Cost Estimation • Quoting	• Labour costs	• Labour function	Qualitative
		• Number of hours for processes.	Quantitative
	• Material Costs	• Material type	Qualitative
		• Dimensions (length, width and height)	Quantitative
		• Weight required for:	Quantitative
	• Service costs	• Service type	Qualitative
		• Number of hours required services:	Quantitative
• Planning • Purchasing • Scheduling	• Material types and dimensions	• Material types	Qualitative
		• Length, width and height of material	Quantitative
		• Mass required	Quantitative
	• Supplier costs • Contractor costs	• Price of all materials	Quantitative
		• Prices of all services	Quantitative
	• Supplier lists • Contractors list	• Service providers and suppliers	Qualitative
	• Available resources • Task start times and end times	• Available resources – man and machines	Qualitative
		• Available dates and times	Quantitative
• Manufacturing	Value-added time	• Task	Qualitative
		• Setup time	Quantitative
		• Operation time	Quantitative
	Non-value added time	• Operational disturbance reason	Qualitative
		• Setup downtime	Quantitative
		• Operation downtime	Quantitative

Data collected on the production shop floor is mainly quantitative (67% - see Table 30). The second step in the analysis involved checking: the annual frequency of data collection per function; the time sensitivity of the data collected and the logic complexity during the data capture for each function (see guide in Appendix 3-3). It was also observed that data collection during the all above-mentioned selected functions was always repeated, with an average of over 300 instances per annum for the cost estimation process (due to customer enquiries). For each of the identified functions, the data collected is time-sensitive, with the logic complexity during the cost estimation phase being the most complicated.

Table 30: Summary of data types results

Business function	Quantitative data collected (%)	Qualitative data collected (%)
1. Cost estimation	4/7 = **57.0%**	3/7 = **43.0%**
2. Production planning, purchasing and scheduling	5/8 = **62.5%**	3/8 = **37.5%**
3. Manufacturing	4/6 = **67.0%**	2/6 = **33.0%**
Overall average	**62.2%**	**37.8%**

6.3 Software and hardware selection

The development platform was chosen using set criteria prescribed in the questionnaire shown in Appendix 3-4 (3-4.1 and 3-4.2). Responses from experts on the questions shown in Appendix 3-4 are summarised in Tables 31 and 32 below.

Table 31: Existing capacity analysis

Question	**Summary of responses by experts**	**Implications**
Availability of mobile devices (Smart Phones or Tablets etc.)	**No.** However, most workers are in possession of these devices at a personal level.	If workers possess the mobile devices, there may be no need to invest in buying the devices.
Availability of workers skilled in the use of mobile devices and ICT expertise	**Yes.** Few workers in a tooling environment are skilled in ICT. Usually the Tool Designers are good at using computer technology (due to their daily use of computers)	There may be a need to train workers on how to use digital technologies if there are introduced.

Table 32: Software and hardware requirements

Question	Summary of responses by experts	Software implications	Hardware implications
Integration with existing data management platforms	**Yes.** Some firms already use Excel and Pastel for data management.	The selected software platform should be compatible with many platforms, especially Microsoft Excel.	The selected device must be compatible with the software platform chosen.
Ability to take photos, graphics or video	**Yes.** During the order definition stage, there may be needed to take a photo of the sample product or part. In some cases toolmakers may need to take a video of the process on a machine.	The selected software platform should support capturing and storage of pictures and video in the dataset.	The selected devices should have built-in cameras for taking photos and video. They should also have the capability and sufficiently large screen to display graphics and video.
Need to record GPS data	**No**	None	None
Need to collect data from the field	**Yes.** The engineering drawing is also supposed to be captured during the production process.	The selected software platform should support the capturing of pdf. Files for the engineering drawings.	The selected devices should be able to connect to either a cellular or wireless network (Wi-Fi).
Complex filter logic in data collection	**Yes** The logic for the cost estimation and production data collection processes is complex.	The selected software platform should support skip logic during the development phase.	The selected devices must have a decent amount of processing power.
Need for external support during development	**Yes.** The researcher and respondents conducting or participating in the study are not a software developers, so will need help during the development phase.	The selected software platform should have a dedicated support service (or community) who will assist in the development phase.	None (software related question)
Need for merging with external data sets	**Yes.** There is need to integrate the data collected with financial systems in the future	The selected software platform should be compatible with existing data sets.	None (software related question)

6.3.1 Selected development platform

Based on the responses obtained as illustrated in Tables 31 and 32, five mobile development platforms which possess the properties identified were chosen and compared. Table 33 below summarises the criteria which was used in the selection of the software development platform for the digital solution.

Table 33: Mobile platform selection

	Platform property	Price by number of surveys	Ease of coding	Ease of export into a database	Support by service provider	Compatibility with existing capacities	Potential for development	**Total score (%)**
	Property weight factor	*0.25*	*0.20*	*0.15*	*0.15*	*0.15*	*0.10*	100
Development platform								
Team Desk		7	6	5	4	4	4	57.5
Meta task		6	8	5	4	4	3	55.0
AppSheet		10	10	9	10	10	5	**93.5**
Zoho Inventory		4	5	3	7	8	9	56.0
App see mobile analytics		8	6	5	7	9	8	71.5

The assigned weights for the different options were conducted based on the expert opinions presented in work by Heitkötter, Hanschke and Majchrzak (2013). The factor of cost for using the platform was ranked the highest. This is mainly because tool-making firms are SMMEs and may not be keen on investing in something before knowing its benefit to their operations. As such, the highest weight of 25% was assigned to the price incurred for using a particular platform per number of surveys. The second factor, which relates to ease of coding, is a development-related feature. This feature is critical since it determines the development time and so was assigned a weight of 20%. A similar weight of 15% was assigned to each of the system integration-related features which include; ease of export into a database, technical support by the service provider and compatibility with existing capacities. The potential for platform development was the lowest ranked criteria, with a weight of 10%. These critical factors are all concerned with the ease of development and integration of the solution. Based on the assessment, the AppSheet development platform was selected as the best environment (see highlighted section in Table 33). The total weight for the AppSheet environment is 9.35 out of 10 (93.5%).

Since compatibility of a hardware device with the selected development platform is a crucial factor (see guide in Appendix 3-4.3, Question 1), all hardware devices compatible with the AppSheet development environment and possessing the characteristics summarised in Table 28 were selected as the appropriate edge devices. According to the creators, AppSheet runs on iOS and Android devices in the majority of mobile and desktop environments (AppSheet, 2017). Table 34 summarises the recommended versions for each operating system.

Table 34: Recommended versions for the operating systems (AppSheet, 2017)

Operating system	**Acceptable range**	**Recommended version and space**
Android	Version 9.0 or higher	Version 10
iOS	Version 4.4.4 or higher	Version 6.0 or higher, with memory space 2G RAM or more

According to the AppSheet team (2017), versions of iOS earlier than version 9.0 can cause subtle bugs or performance problems. Likewise, earlier versions of Android 4.4.4 can cause subtle bugs or performance problems.

While the primary focus is for mobile devices, AppSheet apps also run in a web browser, often within an iframe. In fact, on unsupported mobile platforms such as Windows Phone, it is recommended to run it within a browser.

Most functionality is supported in a browser except for:

- Bar code scanning;
- Offline image and document caching;
- Offline app launch; and
- Some upcoming functionality (like push notifications).

It is usually recommended to use a modern browser. AppSheet works best on Chrome (AppSheet, 2017).

6.3.2 Selected hardware (input device)

Based on the recommendations given in section 6.3.1, the Samsung J2 mini tablet or phone was selected as an appropriate input device for the mobile system. The phone comes with Google store, which allows users to easily install the AppSheet runtime environment. Thereafter, AppSheet applications can be easily installed and used in the phone. The device, which costs 1700 ZAR on the market, also carries numerous built-in sensors such as accelerometers, gyroscopes, microphones and a QR-code scanner. The phone is illustrated in Figure 38.

Figure 38: Samsung J2 Mini

The device memory required depends on the application context features such as:

- The amount of data downloaded to the device. This depends on the number of tables and the number of rows and columns in each table.
- The complexity of the app. This depends on the number of tables, views, expressions, etc.
- The device features used by the app. The camera and scanner add significantly to the RAM required. The higher the camera image resolution, the more memory required.

If an Android device is purchased for use with AppSheet, it is recommended by the AppSheet (2017) team to choose Android 6.0 or greater, with at least 2GB of RAM. More memory may be required depending on the number and resolution of photos captured.

6.4 Company-based case study

A concurrent engineering approach was employed to develop the system prototype and a specific selected company consented to participate in the development process. The stages described by the flow chart illustrated in Appendix 3-5 were used to guide the development process. The company, which has been in existence for seventeen years, is a specialist in the design and production of press tools, dies and injection moulds. However, as part of their services the firm also conducts some repair work on tools that fail while with the customer. The company also has a series production section. The firm has a total of twenty-three employees, nine being toolmakers on the shop floor.

6.4.1 Analysis of the current system of operation

During the visits, the company's current operational policy with regard to shop-floor data collection and challenges experienced was assessed. The problems in data collection on the shop floor at the visited company are summarised in Figure 39 below.

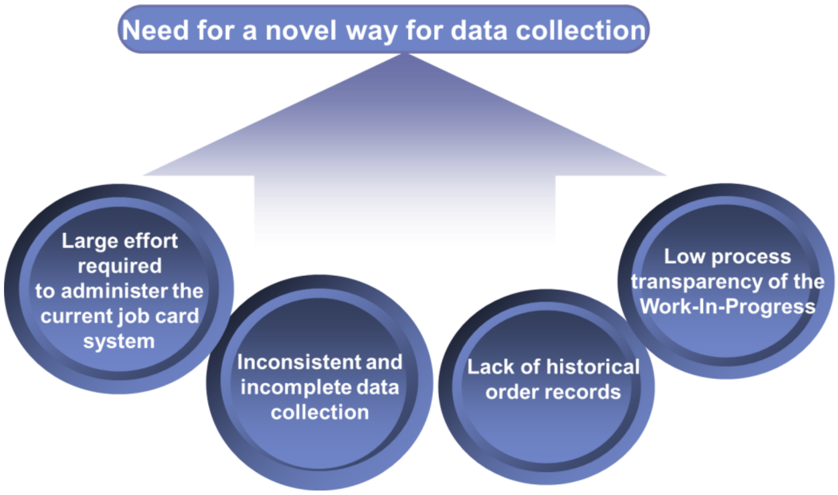

Figure 39: Problems in data collection

The visited company has been experiencing operational problems in the area of data capture. One of the major challenges highlighted by workers was that of the enormous effort required to administer the current job card system. Diaries were utilised for collection of data of operational times for tasks done by employees. Since the method was irregularly used, this resulted in a number of operational shortcomings. Firstly, there was low transparency of the work-in-progress during production, with difficulties in tracking order progress. Secondly, since the recording of the data in diaries was not always done, there were many cases of inconsistency in data collection with null records in most instances. This resulted in limited process planning and poor visualisation of shop-floor status. The personnel responsible for the data capture into existing software systems usually failed to record meaningful data since the records were done irregularly and there were cases of duplicity and redundancy.

6.4.2 System design and development

The proposed digital system blueprint was designed using Microsoft Visio and developed in the selected AppSheet environment. Firstly, the factory manager assisted in the derivation of the overall business logic of the firm. This stage involved observation of the business workflow rules, manual documentation system and all the roles involved at the different stages. The processes involved are summarised in Figure 40. The process is initiated by a customer inquiry on the tools to be produced. Based on the enquiry, the design of the part is conducted concurrently with the quotation. Once complete, the customer approves or rejects the offer. If approved, the planning for the production is conducted and the part or tool is fabricated.

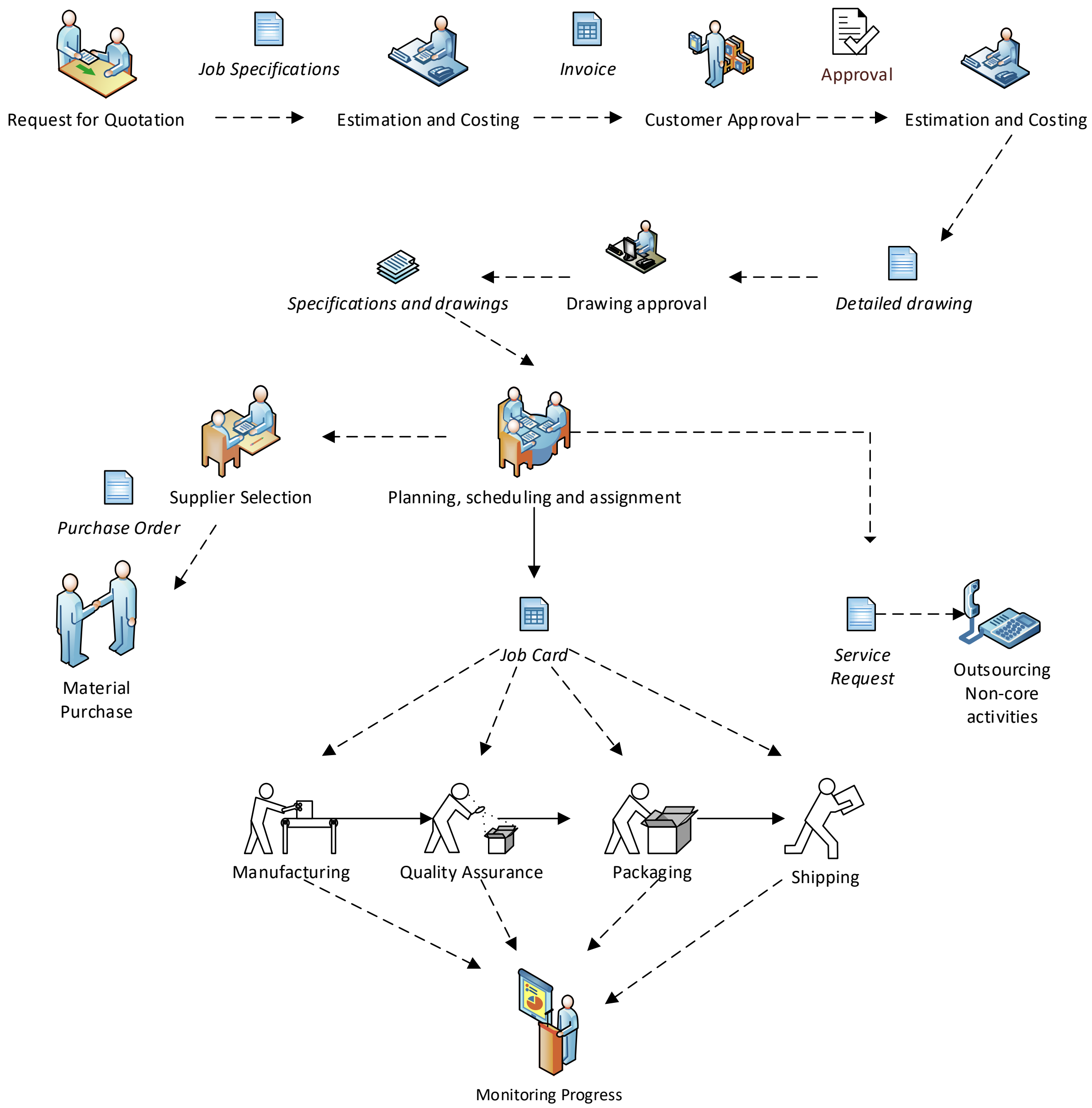

Figure 40: Manual system of operation

The documents employed at each stage were also observed. Based on the prior analysis (see section 5.7), the key documents used during the quotation, planning and production phases were specifically focused on. An illustration of the documentation used during the quoting, planning and production phases is shown in Appendix 6-1, Appendix 6-2, and Appendix 6-3 respectively. Analysis of the data types of the documents and further interviews with management aided in the derivation of the system features and functions as shown in Figure 41. The mobile solution should primarily aid in the data capture of the required information for the purposes of report generation and performance analysis.

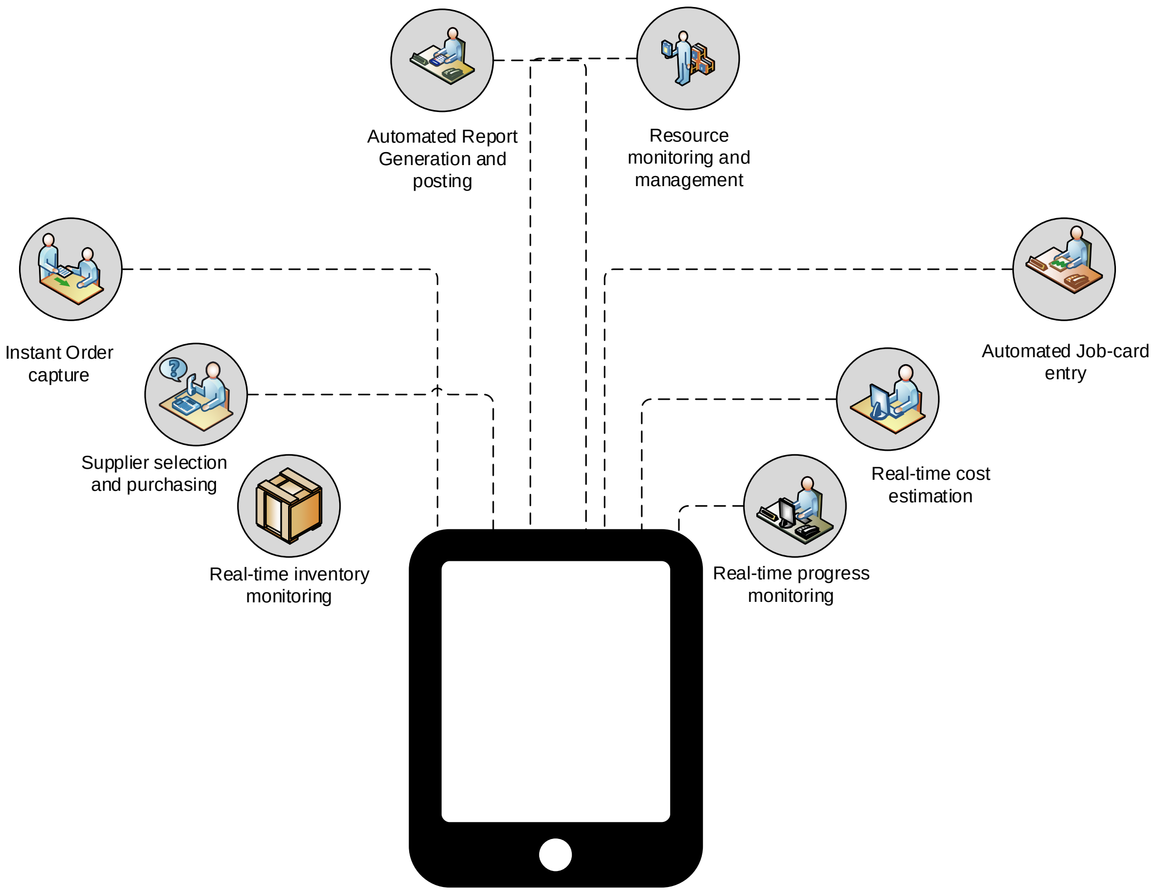

Figure 41: System functions and needs

6.4.2.1. Entity Relationship Diagram

The database design and development was the first stage in setting up the system. The entity identification for each class was derived and an Entity Relationship Diagram (ERD) was developed as shown in Figure 42. The ‘Google docs’ platform was utilised in the development of the backend database for each of the tables.

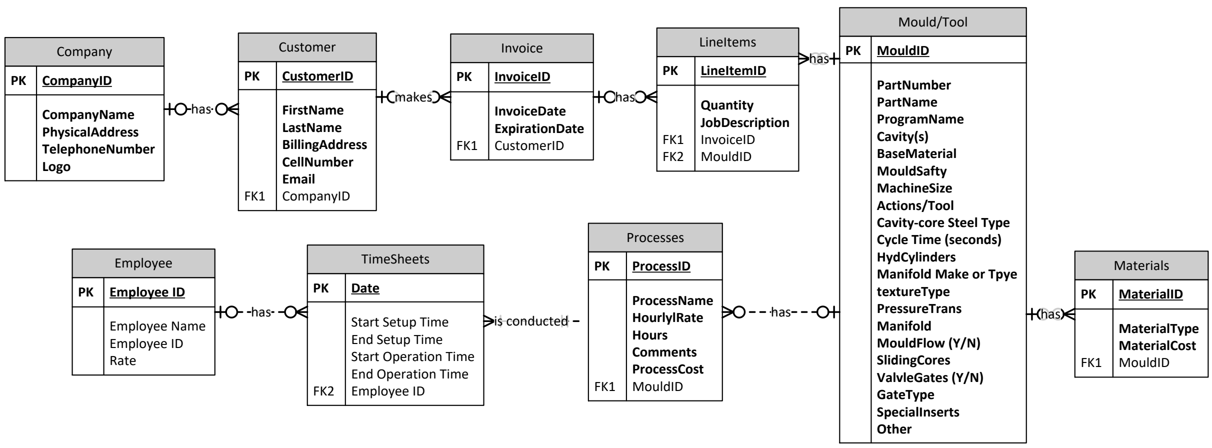

Figure 42: System Entity Relationship Diagram

6.4.2.2. System module development

The researcher developed a web-based, mobile solution according to the design specification in Section 6.4.2.1. The mobile solution has five different sub-modules which were deployed to different parts of the company. Figure 43 illustrates the main switchboard for the system. Each user only obtained a module relevant for their operations.

Figure 43: Shop-floor Management System (SMS) modules

The resources module is used to prepare the system through the recording of all of the company's resources, which include worker details, machines and assets. The users can also define common disturbances experienced and daily operations conducted. These are also used by other modules of the system during the quoting, planning and production phases. This part (resources module) was specifically deployed and made available to the Human Resources department of the business. The navigation flowchart for the resources module is illustrated in Figure 44 below. Some of the user interfaces for the resource module are shown and described in Appendix 6-11.

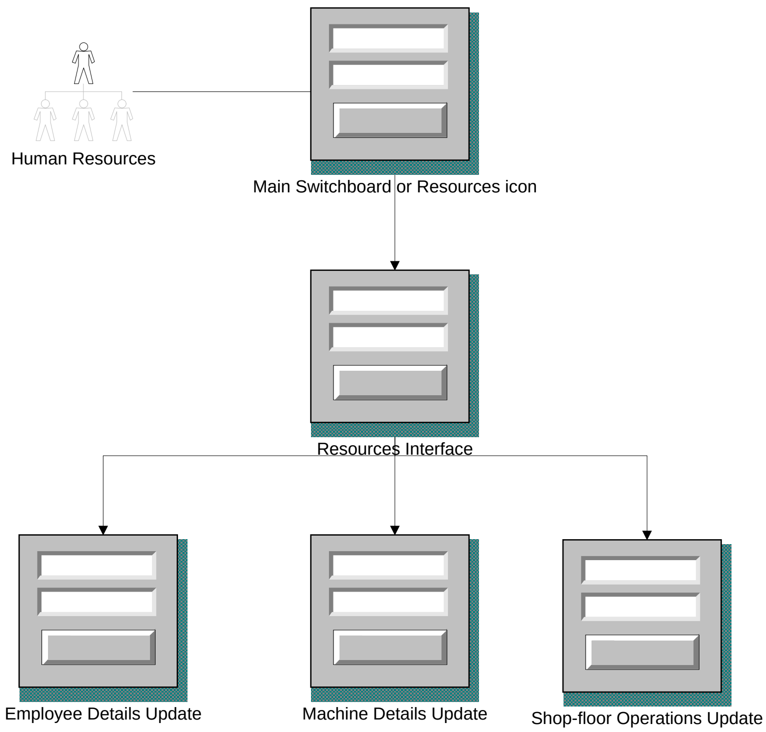

Figure 44: Resources Module navigation flowchart

The sales module was deployed to the Sales and Cost Estimation teams of the business. The module allows for the capture of customer details and job specifications for each order or job after customer enquiry. Upon receipt of an enquiry, the cost estimators determine the price of the job through parametric entry of the operations, materials and services rendered per order. Upon completion of the costing, automated emails are generated and sent to the client with details on the quoted prices and terms. This process significantly reduces the time spent on other administrative duties such as quote and invoice generation.

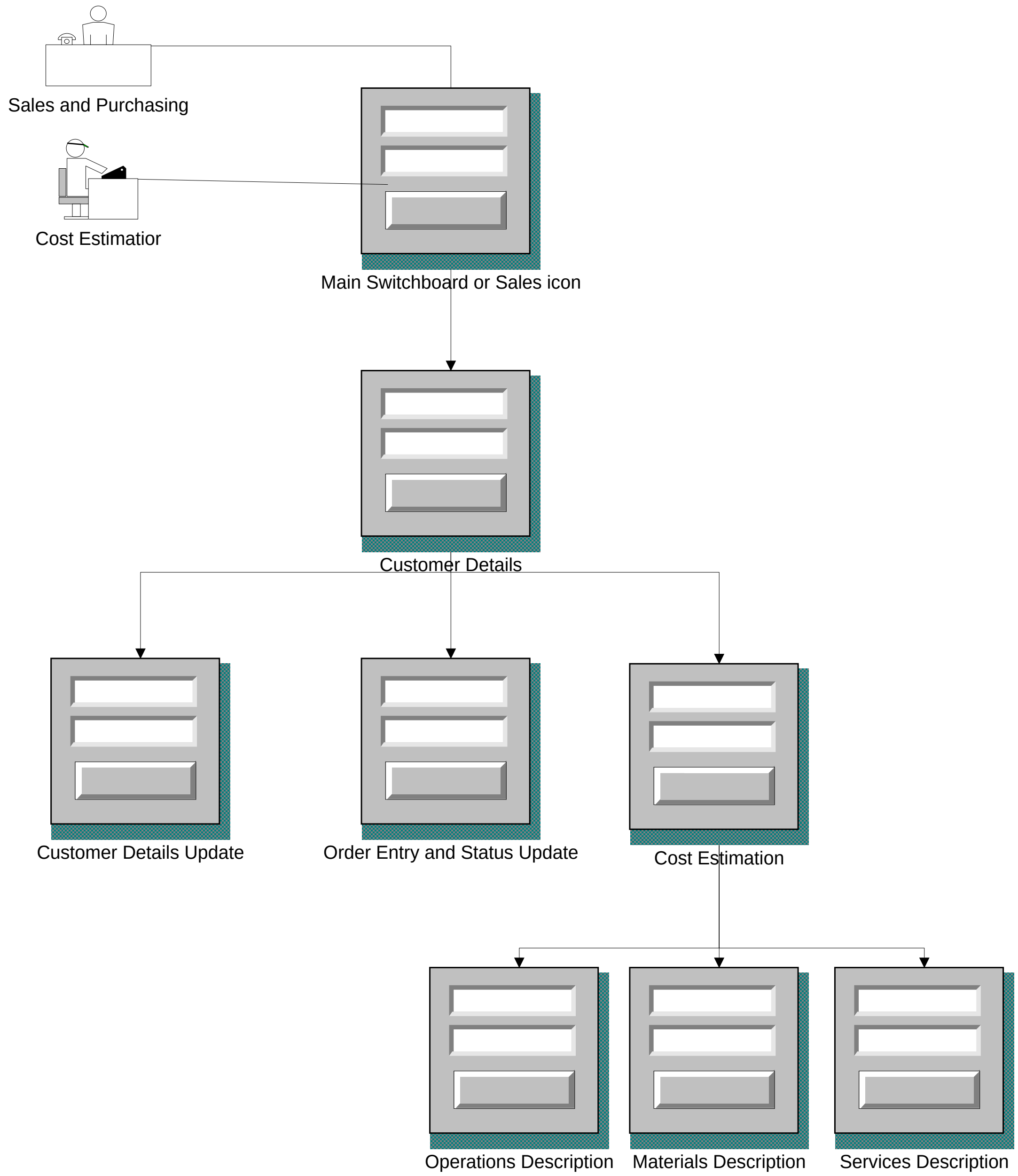

Figure 45: Sales Module navigation flowchart

The navigation flowchart for the Sales module is illustrated in Figure 45 above. Some of the user interfaces for the sales module are illustrated and explained in Appendix 6-12. A common trend in the tooling business derived during the analysis was that of repeat orders occurring in the future. Due to this trend, the system also allows for the duplication of an old order so that the cost estimation process is not repeated (duplication of effort on the same thing). Upon approval by the customer, the order details are made available to the scheduling module of the system. Process planners or Project Managers can access all approved jobs from the scheduling module. In this platform, raw material purchases from suppliers are facilitated. After the materials are received, tasks are assigned to the shop-floor toolmakers. Once deployed, each toolmaker can view tasks assigned to them via the production module. The navigation flowchart for the scheduling module is illustrated in Figure 46 below.

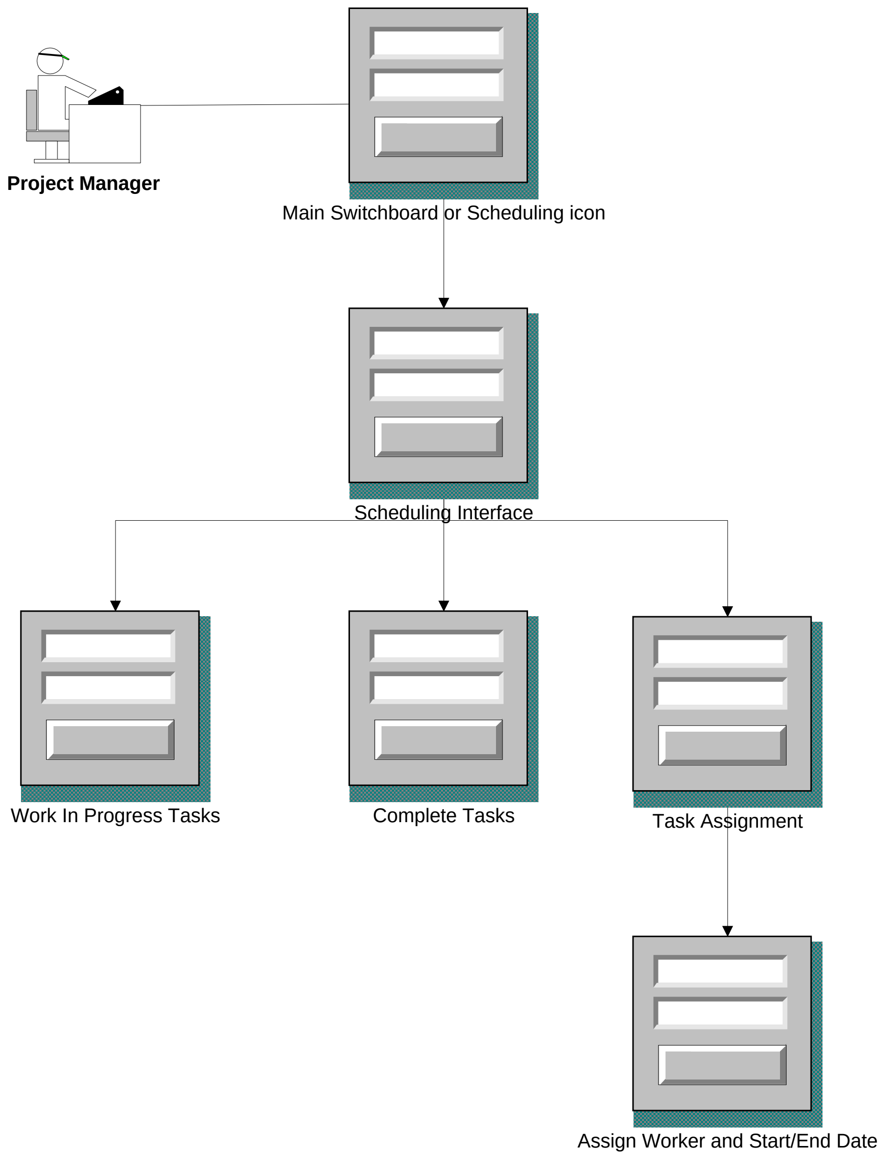

Figure 46: Scheduling Module navigation flowchart

The user interface for assigning workers for the scheduling module is illustrated and described in Appendix 6-13.

The production module is specifically deployed to the workers on the shop floor for the time-based entry and account of tasks done. In real-time, workers can enter the start and stop times for their jobs. Based on the analysis given in Section 4.2.4, workers can also input data on any recurring disturbances occurring during production. Once disturbances are recorded, the managers obtain triggers of the event via email. Figure 47 below illustrates the production module navigation flow chart. Some of the user interfaces for the production module are illustrated and explained in Appendix 6-14.

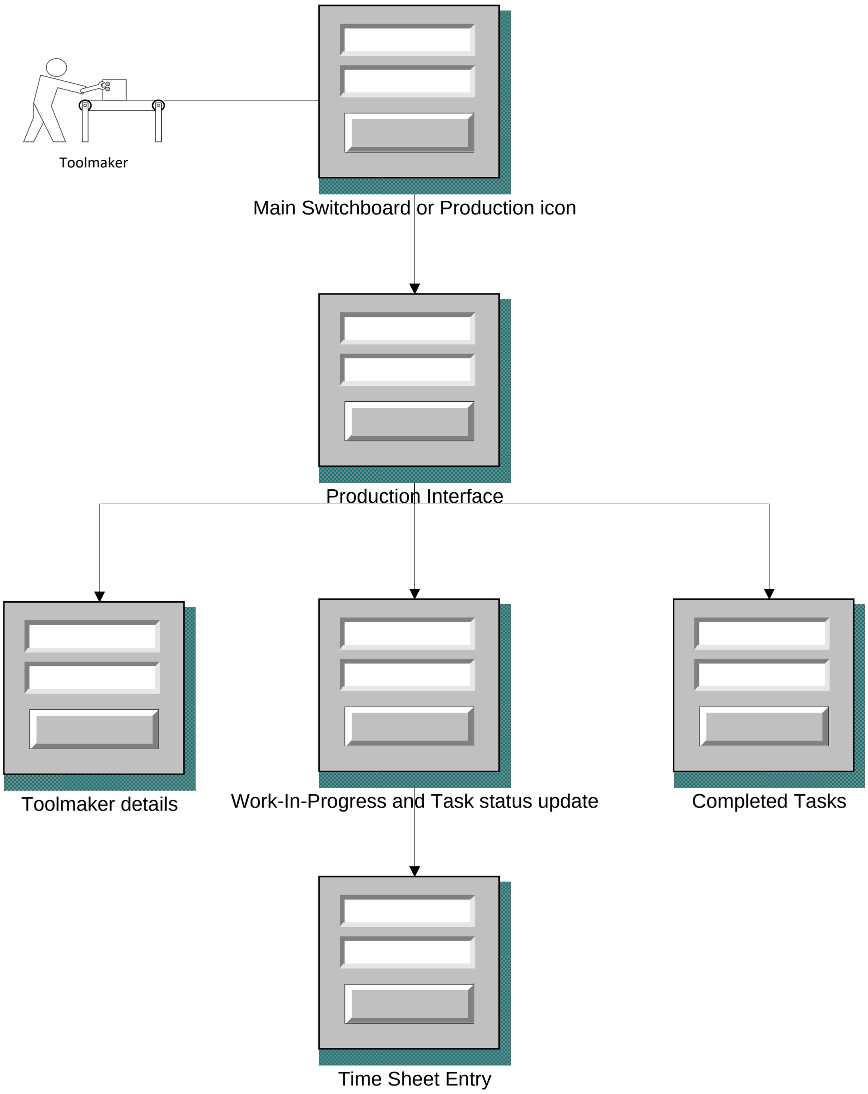

Figure 47: Production Module navigation flowchart

The dashboard module of the system is deployed to the top management only. The platform facilitates the real-time monitoring of shop-floor activities on key performance order-related indicators, which include, due date conformance and order percentage progress. The managers can also view, in real-time, costing analytics such as actual cost incurred versus estimated cost, labour hours per employee and machine run times. The navigation flowchart for the dashboard module is illustrated in Figure 48 below. One of the dashboard screen interfaces is illustrated and explained in Appendix 6-15.

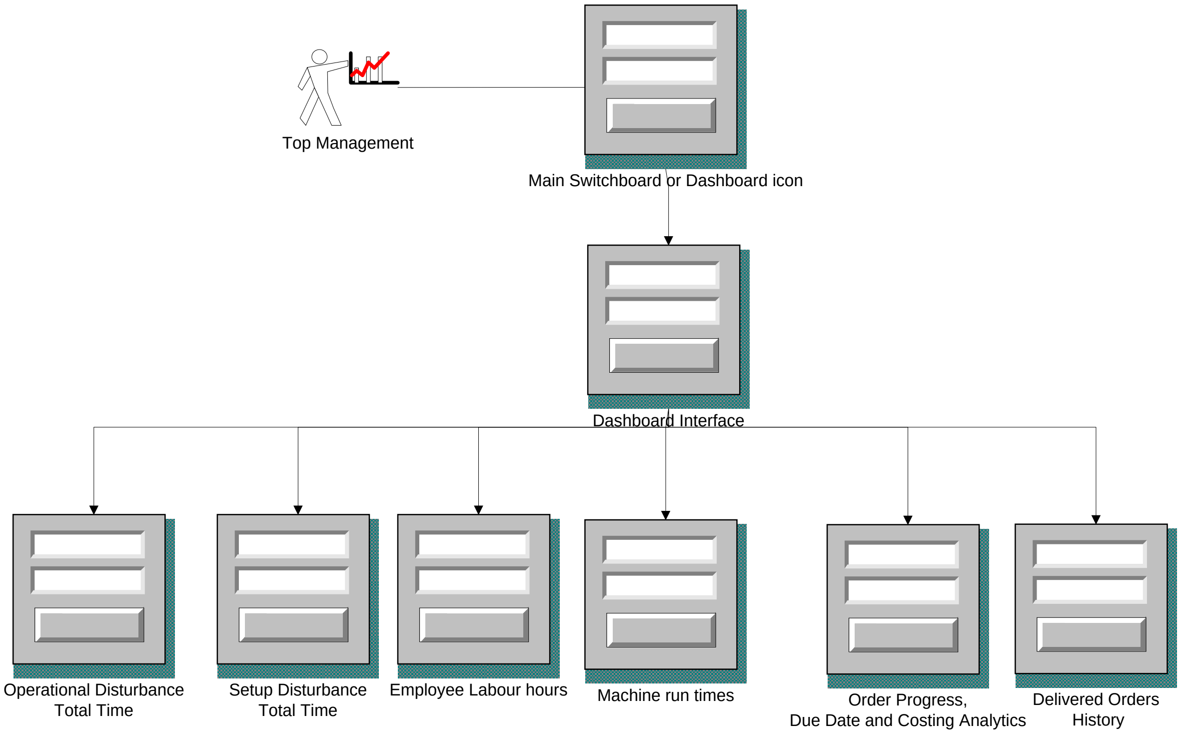

Figure 48: Dashboard navigation flowchart

Though this is the main part top management uses to gain visibility of shop-floor events, they requested to have access to the other four above-mentioned modules.

6.4.2.3. System decision-making algorithms

During the system development phases, the decision makers at different roles were observed. The phases of decisions made determined the interface conditional logic during the data capture. The decision algorithm for the order definition, cost estimation, operational description, materials definition, service definition and production algorithms are all illustrated in Appendices 6-4 to 6-9 respectively.

6.4.3 Overview of Shop-floor Management System

The overall system architecture and functionality is illustrated in Figure 49. With the use of web-based platforms, the captured data can be conducted in a distributed manner. This simplifies the methodology as information can be accessed in real-time at any place. Mobile devices speed up the shop-floor data collection reducing the costs incurred in preparing and printing paper-based documents. Furthermore, the conditional logic set in the mobile devices simplifies the end-user's collection process, thus reducing rigour involved in recording the data manually.

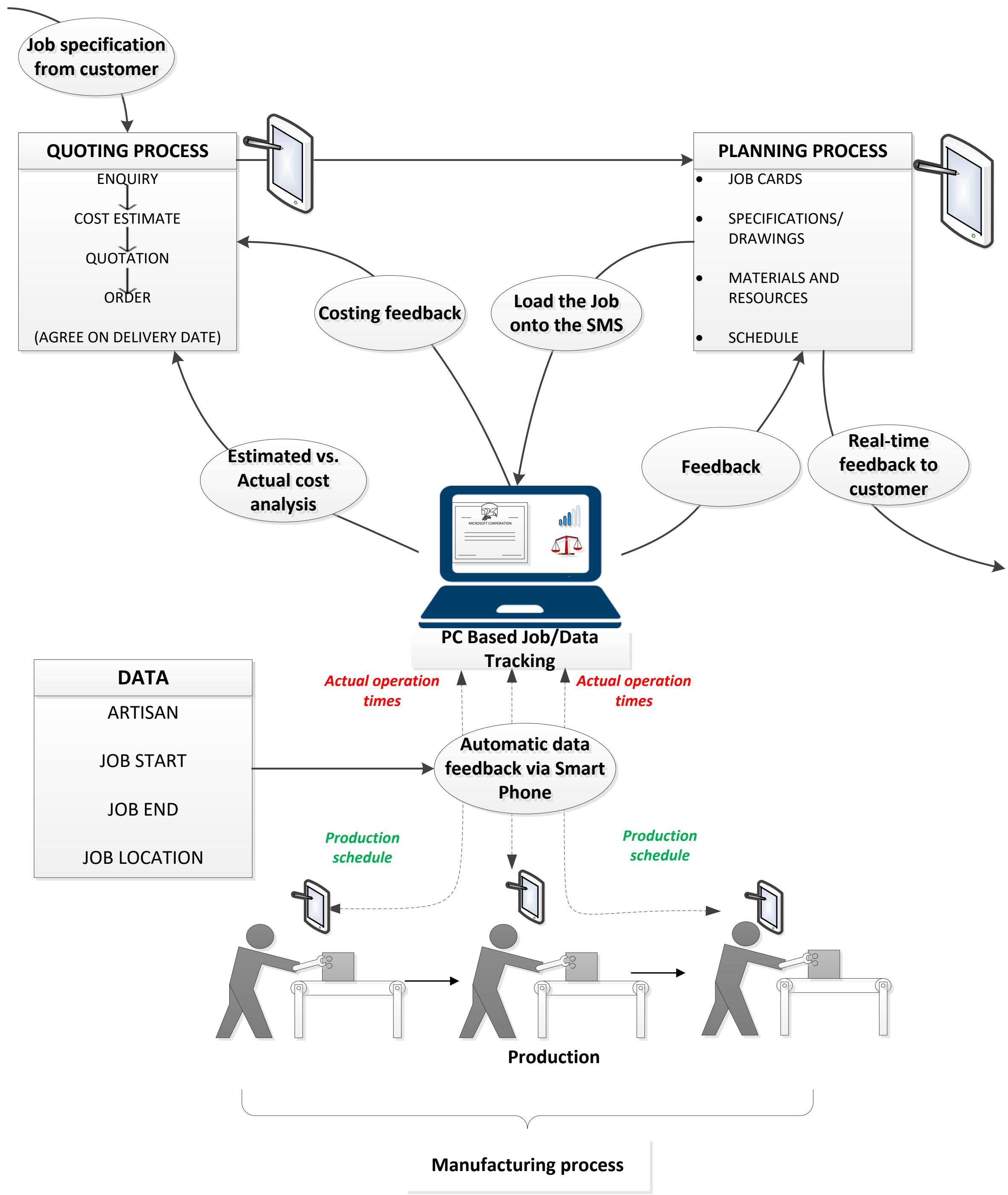

Figure 49: Schematic diagram of SMS overview

Using the morphological box shown in Table 4 (chapter 2, section 2.2.7), the developed Shop-floor Management System (SMS) can be described using certain criteria. Table 35 below gives a summary of the SMS description using a morphology box. The shaded areas describe the SMS features.

Table 35: Morphological description of the SMS (adapted from Hinrichsen et al. 2016)

CHARACTERISTICS	CHARACTERISTIC VALUES						
TYPE OF SYSTEM SUPPORT	Physical				Informational		
TYPE OF DIGITAL ASSISTANCE SYSTEMS	Stationery (fixed installation)		Mobile (mobile installation)		Hand device	Wearable -Head -Upper body -Arms/Hands -Legs/Feet	
DATA TRANSFER	Linked by cable				Wireless		
TYPE OF SUPPORTED OPERATIONS	Customer Enquiry	Cost Estimation and quotation	Design drawing	Materials purchasing	Production planning and control	Production and assembly	Packaging and delivery
SCOPE OF PROCESS SUPPORT	Partial process(es)				Total process		
HUMAN-MACHINE INTERFACE	Unimodal				Multimodal		
TYPE OF INFORMATION OUTPUT	Visual (optical)			Auditory (acoustic)		Tactile-kinesthetic (tactile)	
TYPE OF VISUAL INFORMATION OUTPUT	On-screen display			Representation in the working area		Working area display superimposed over the assembly object	
SCOPE OF VISUAL INFORMATION OUTPUT IN THE WORKING AREA	No output	Selective presentation		Limited display of symbols, images and drawings		Extensive presentation of items such as images, videos and animations	
TYPE OF THE INFORMATION INPUT/SYSTEM CONTROL	Manual (via actuators)		Verbal (voice control)		Gesturing (tracking system)	Automatic (sensory)	
SCOPE OF USER CONFIGURATION	Set configuration of information input and output			Individual configuration of information output		Individual configuration of information input and output	
USER RECOGNITION	None			Registration and uploading of user profiles		Automatic registration and uploading of user profiles	
SITUATION/MOTION DETECTION	None		Via measurement sensors		Via optical sensors	Other	
COMPATIBILITY /INSTALLATION EFFORT	Entire workplace has to be newly configured		Basic adjustments made to the workplace		Minor adjustments made to the workplace	No adjustments made to the workplace	
FLEXIBILITY IN RECONFIGURING THE WORKPLACE	Substantial adjustments to be made to the main hardware		High software reconfiguration effort (done by qualified specialists)		Average software reconfiguration effort (done by specialists on site)	Low software reconfiguration effort (done by user on site)	

The developed SMS is a digital assistance system which aids South African toolmakers with timely production information. The DAS is an informational system which employs hand-held mobile devices. Data is transferred through wireless means. The system covers the cost estimation, production planning and production operations in terms of operational scope, hence only supporting partial processes. The system is multimodal since text, image and time-based data is exchanged between operators in a tooling environment. The output is displayed on mobile devices in a visual manner and all data in manually entered using the text boxes and command buttons. The system also requires users (operators) to register for them to use the system. Environmental parameters are not detected by the system and the system does not cause any adjustments to the workplace layout or existing information systems.

6.5 System testing and validation: Case study

After the system development phase, each module was tested for the removal of any syntax or logical bugs. During this stage, fictitious data was fed into the system for the purpose of observing if the outputs were consistent with the design logic. After removal of all errors, the system was deployed to the end users. Different parts of the business obtained different functionality of the entire application, as summarised in Table 36 below.

Table 36: Deployed modules

Business function	Module deployed
Top management	All modules
Shop-floor manager	Dashboard
Human Resources	Resources
Sales/Marketing team	Sales
Cost estimators	Sales
Process planners or Project Managers	Scheduling
Workers (toolmakers)	Production

After successfully deciding on the deployment strategy of the different parts of the application, the initial data capture was conducted by the Human Resources department. At this stage, all of the company's resources, which include worker details, machinery and required processes, were recorded. Thereafter, the system was deployed to different individuals as per their role using the framework depicted in Table 36. The majority of company personnel were already in possession of smart mobile devices with the operating characteristics which allow installation of AppSheet applications. For testing purposes, a few products were selected and utilised to see the functionality of the system.

6.5.1 Product type one: Single part job

The first experiment was conducted for a single part production to test the robustness of the system. The part selected for testing purposes was a 160mm vented lid, shown in Figure 50 below.

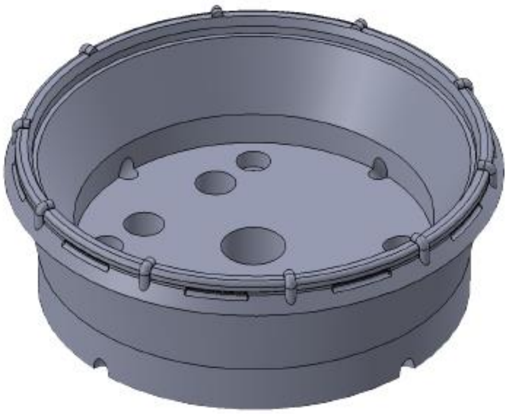

Figure 50: 160mm vented lid

After the cost estimation, the scheduling of the tasks was conducted upon customer approval and receipt of the required materials. The fabrication of the part required a few operations which include surface grinding, milling of the profile and holes, and finishing. The second experiment involved collection of data for the repairs of another 160mm vented lid which had failed to meet design specifications.

6.5.2 Product type two: Injection mould

The third experiment was conducted for a more complex product made up of many parts (see Figure 51). An injection mould for producing brackets was chosen for this purpose. Since the product was made of several parts, the operational descriptions were conducted for each part for the overall costing to be finalised.

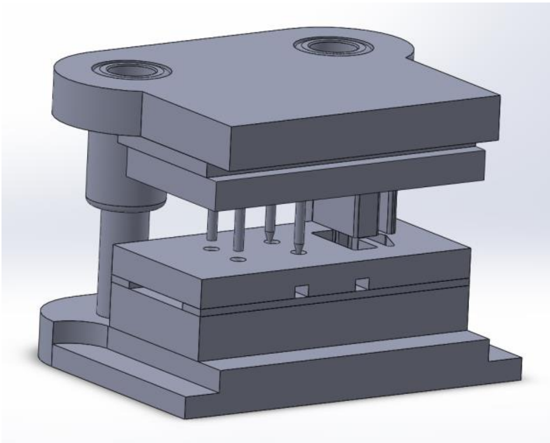

Figure 51: Huhtamaki Injection mould

The injection mould is made up of nine different parts which require different operational procedures. The nine parts are shown in Appendix 6-10. As a result, a total of 10 different parts (for both product one and two) were used as a means to validate the system.

6.5.3 Analysis and results discussion

The AppSheet mobile development was selected as the best platform, as analysed in section 6.3. This is mainly because the platform requires no prior programming experience for one to use it. Furthermore, the AppSheet platform freely allows development and testing of a prototype. Costs of implementation are only incurred during the deployment stages. The user community for the environment is huge making support by experts easier and the platform integrates easily with a number of common database platforms such as Microsoft Excel. This becomes useful since the majority of South African toolmakers already utilise Excel for data computation, as observed in Figure 25.

The experiments were successfully conducted for all the ten parts. The cost estimation time was on average 15 minutes for each part, a significant improvement to the time taken when using manual methods. Top management indicated that cost estimation usually took over an hour for each part using their old manual methodology.

Furthermore, toolmakers on the shop floor indicated that the developed tool simplified the time sheet data entry as opposed to the diary system they were using. This was mainly because one had to only press a button indicating what was happening during the production instead of having to think on how to account for their usage of time. Top management found the system outputs from the dashboard to be critical indicators of how the tool room was performing.

The main concern raised was that toolmakers usually work on many tasks concurrently. This meant one would need more than one device for the data entry for each task. To resolve this problem, it was suggested that a mobile device be situated at each station while each worker also possesses their own mobile device. In this way, an account of what will be happening at each machine can be made easily, as the tasks are conducted per machine.

A testimonial of the work on the development and testing of the Shop-floor Management System (SMS) was published in the Western Cape Tooling Initiative newsletter (May 2017) as shown in Appendix 6-17. This increased the visibility of the developed tool to the entire Western Cape Province TDM industry. The work on the researcher’s involvement in the benchmarking process is also shown in Appendix 6-16.

6.5.4 *Roll out and implementation strategy*

The Shop-floor Management System (SMS) developed in this dissertation facilitates real-time data collection and information sharing which is crucial for decision-making. The SMS can be implemented in a South African tool-room environment. The AppSheet platform (which was used during the development phase) allows access to ordinary Excel files and can be integrated with other dataset types easily. A majority tool making firms use Microsoft Excel for their information systems, as shown by the results in Section 4.2.3. This makes implementation of the system easy as firms need only to integrate their files with the Excel platforms and reinvent their data collection.

To roll out and implement the system, TDM firms must be willing to take a few steps. Firstly, management must be supportive when it comes to adoption and implementation of the system. They should ensure that the required devices are purchased and workers are trained in the use of the system. This is a crucial stage as it brings all workers to the same level of technology literacy and understanding. Secondly, an administrator responsible for the system must be identified and selected within a company. This will ensure the day-to-day maintenance of the system. Eventually, the firm will cease from depending in external ICT vendors since they will be empowered to resolve any system problems on their own. Finally, the firm should continually meet to discuss any emerging requirements for the purposes of upgrading the system's functionality.

6.6 Conclusion

This chapter summarises the development and the validation phases of the study. All stages followed in the selection of the software and hardware devices, development, testing and validation of the system are given. Due to the misconception of cost of implementation, and a low technology maturity level, the majority of the TDM firms usually continue using manual methods in their day-to-day running of business on the shop floor. However, the rapid growth in ICT devices in the 21^{st} century makes most technologies available at reasonably low costs, making digitalisation something easy to implement. The SMS presented in this chapter is an example of this fact.

Chapter 7: Conclusion

7.1 Summary of findings

The research explored the concept of digitalisation in the context of the South African TDM industry. A framework for the implementation of current digital technologies on the shop floor within a tooling environment was developed and tested. Based on the analysis of the on-going benchmarking results of the South African TDM industry, it was concluded that the majority of firms struggle in the area of data collection and manipulation. Other internal shortcomings observed were the operational disturbances the firms experience on a day-to-day basis. These operational risks included machine breakdowns, sudden shortage of raw materials, power cuts, accidents, rush orders and equipment damage.

Five firms in the Western Cape Province TDM sector were visited during benchmarking schedules. The shop-floor operations of cost estimation, process planning and scheduling, and time sheet entry were selected as critical areas which can be improved by the implementation of digital technologies. Furthermore, the methodology of knowledge engineering was used to determine the parameters which need to be recorded for the three identified processes. After parameter derivation, a decision matrix for technology selection was employed and web-based mobile technologies were recommended as potential solutions for the digitalisation of the identified operations.

The AppSheet mobile application development platform was utilised to develop the mobile web-based solution, with hardware devices compatible with AppSheet selected as well. A Shop-floor Management System (SMS) was developed for one specific company and tested for three different scenarios of part production, injection moulds and repairs.

7.2 Conclusions

Based on the analysis, the eighth and the tenth hypotheses (H_8 and H_{10}) were proven true (see section 1.2); cloud computing platforms and mobile devices can be utilised for the digitalisation of some shop-floor operations in the South African TDM sector. Hence the research question of the study was answered: Mobile and cloud computing platforms can be utilised strategically to digitalise the cost estimation, process planning and production time data collection processes in the South African TDM industry.

7.3 Summary of Contributions

The major contribution of this research to the engineering body of knowledge was the development of a different, novel methodology for real-time shop-floor data collection and manipulation for distributed decision-making in the South African TDM industry. The developed Shop-floor Management System (SMS) is unique in addressing the requirements South African TDM firms have established which include:

- Interfacing shop-floor workers with tool-room managers;
- Real-time shop-floor data collection by toolmakers;
- Distributed information sharing in a tool-room environment;
- Generation of order progress reports;
- Information storage of order histories;
- Automated computation of actual costs incurred;
- Automated reporting and email functions; and
- Cost analytics of estimated vs actual costs per job.

Due to the unique features the SMS possesses, the Western Cape Province TDM sector has shown interest in the adoption of the system (see Appendix 6-17). Plans are currently in place to present the entire system to industrial captains in the TDM sector. Thereafter, the system will be rolled out to interested industry stakeholders for full implementation as explained by McEwan (2017) (see Appendix 6-17). Therefore, this research also adds to the industry by being practically applicable within the South African TDM sector.

7.4 Future Research

More work can still be conducted in exploring the concept of digitalisation within the TDM industry. The developed SMS application was only implemented within one company. However, since the tool is a distributed system using mobile devices, future work can be conducted on extending the application to the domain of TDM customers and suppliers. That way, customers will be able to enter their requirements and request for quotations while suppliers consistently communicate on the services and products they supply (with current updated prices). Hence, future work can be done in also deploying the application to TDM customers and suppliers.

Furthermore, the same study can be implemented at a national level, with the systems analysis conducted for TDM firms in different provinces within South Africa. The output of the study may give a different result using this approach. The developed Shop-floor Management System can be classified as disruptive technology (Christensen, 1997) due to the novel features it carries in changing the shop-floor data collection methodology. Therefore, future work can be conducted in determining the disruptive characteristics of the developed solution to improve it adoption rate in industry. One emerging requirement in the TDM industry is the need to track part flow during production. Radio Frequency Identification (RFID) technology has the potential to fulfil that requirement, as discussed in the literature review (chapter 2). The major drawback in the use of RFID technology is the huge capital investment required for such a project. Hence, future work can be done on how locational data can be digitalised using RFID technology in the South African TDM industry.

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Appendix 1-1: Research sub-questions breakdown

In this section, the major research sub-questions are broken down into smaller, more specific questions.

1. Tool, Die and Mould Making industry (TDM) in South Africa

i. What characteristics define the South African TDM industry-specific context?
ii. Which competitive performance objectives are of prime importance in the TDM industry in South Africa (i.e. quality, delivery reliability, and time-to-market, product cost or flexibility)?
iii. Which manufacturing policy is adopted by firms in the tooling industry?
iv. Which facility layout is used by firms in the tooling industry?
v. What are the current business trends affecting the local tooling industry firms?
vi. What are the most prevalent operational disturbances experienced in the sector and how do they affect business performance?
vii. Who are the experts in a TDM industry?
viii. How does a TDM production manager or expert do their shop-floor management?

2. Digitalisation in the tooling industry

i. How is the concept of digitalisation defined in the context of tooling?
ii. Which business processes in the South African tooling environment have the potential to be improved by digitalisation?
iii. Which available information and communication technologies can be employed for digitalisation of the South African tool room shop floors?

3. System analysis and design

i. Who are the decision-makers or experts in the South African tooling industry?
ii. What operational decisions are made on a day-to-day basis by experts in the tooling industry?
iii. What knowledge is deemed key on the South African TDM industry shop floor?
iv. Which information is required to generate this knowledge?
v. How is the information currently presented, i.e. which reports are used by experts in the tooling industry?
vi. Which data should be collected and processed to produce this information (smart data)?
vii. How is the data currently being collected and manipulated?
ix. What is the system scope and context?
x. What are the key system requirements?
xi. Which key functions should the system serve?

xii. What parameters are of importance and need reckoning?
xiii. How will the parameters be reckoned in the envisaged system?

4. Shop-floor Management System

i. Which modules are required in the system?
ii. How will the data be manipulated by the system?
iii. Which is the best system design and architecture orientation/structure?
iv. Which sensory devices will be used to reckon the parameters in the World of Interest?
v. What interaction/cooperation protocols can be used between modules?
vi. Which programming languages are the best for system design and deployment?
vii. How will the system be developed, tested and deployed?

5. Cyber physical systems (Internet of Things)

i. What is the Internet of Things?
ii. Which business processes within the TDM sector need to be improved?
iii. What information is needed to support decision-making in the identified business processes?
iv. Which reports or dashboards are required to present the required information?
v. What data must be collected to support/generate this information?
vi. Which devices are required to collect this data?
vii. Which software platforms and hardware devices will be used for the data collection and manipulation?
viii. Which programming languages can be employed?
ix. Which cloud-computing or intelligence platform can be employed?
x. What data must be collected to support/generate this information?

Appendix 1-2: Ethical Clearance Certificate

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Approval Notice

New Application

13-Oct-2014
Dewa, Mncedisi MT

Proposal #: HS1131/2014
Title: Development of a Holonic Control System for the Tool, Die and Mould-making (TDM) industry in South Africa

Dear Mr Mncedisi Dewa,

Your **New Application** received on 03-Oct-2014, was reviewed by members of the Research Ethics Committee: Human Research (Humanities) via Expedited review procedures on **08-Oct-2014** and was approved.
Please note the following information about your approved research proposal:

Proposal Approval Period: **08-Oct-2014 – 07-Oct-2015**

Please take note of the general Investigator Responsibilities attached to this letter. You may commence with your research after complying fully with these guidelines.

Please remember to use your **proposal number** **(HS1131/2014)** on any documents or correspondence with the REC concerning your research proposal.

Please note that the REC has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor the conduct of your research and the consent process.

Also note that a progress report should be submitted to the Committee before the approval period has expired if a continuation is required. The Committee will then consider the continuation of the project for a further year (if necessary).

This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki and Guidelines for Ethical Research: Principles Structures and Processes 2004 (Department of Health). Annually a number of projects may be selected randomly for external audit.

National Health Research Ethics Committee (NHREC) registration number REC-050411-032.

We wish you the best as you conduct your research.

If you have any questions or need further help, please contact the REC office at 0218089183.

Included Documents:
REVISED_interview schedule
Informed consent form
DESC application
Questionnaire

Research proposal

Interview schedule

Response to stipulations

Global competiveness Centre

Sincerely,

Clarissa Graham

REC Coordinator

Research Ethics Committee: Human Research (Humanities)

Appendix 3-1: Current shop-floor practices and operational disturbances impact questionnaire (adapted from Islam *et al.*, 2012)

Introduction

The main goal of this survey is to determine the current work flow procedures and information systems adopted by the Tool, Die and Mould Making companies in South Africa. Furthermore, the survey aims to identify the main operational disturbances tool-making companies experience on a day-to-day basis and their impact on business performance. A disturbance is an undesirable or unplanned event that causes the deviation of system performance in such a way that it incurs a loss. The findings will be used to develop methods to minimise these events so as to improve overall system performance and company productivity.

Instructions on answering the questionnaire

- For Likert scale type statements and multiple choice questions, indicate your answers with an (X) in the appropriate box.
- For the open-ended questions, express yourself freely.

Section A: Company details

The purpose of this section is to establish the general profile of the enterprise and the respondent

Approximate number of employees	
Product range	
Main product(s)	

Section B: Operational details

The following questions are meant to establish the competitive performance objectives in your company:

Question 1: Which of the characteristics listed below make your products sell more in the market?

Product quality ☐ Lower product cost ☐ Due date conformance ☐

Time-to-market ☐ Volume flexibility ☐

Other; please specify:

……

……

……………………………………………………………

Question 2: Does your firm have an information system?

Yes ☐ No ☐

Question 3: If your answer in question two is yes, please indicate the type of system you use.

Manual ☐ Computerised ☐

Other or computerised; please specify:

……………………………………………………………………………………………

Question 4: Which of the operational disturbances listed below do you normally experience?

	Level of frequency				
Operational disturbance	*Never*	*Rarely*	*Sometimes*	*Often*	*Always*
Shortage in raw materials					
Defective raw materials					
Rush orders					
Machine breakdown					
Equipment damage					
Unavailability of power					
Accidents					
Operator absenteeism					
Defective products					

Other; please specify:

………

………

……………………………………………………

Question 5: Which factors do you think have caused the operational disturbances you highlighted above?

Late delivery by suppliers ☐ Supplier production problems ☐

Supplier quality problems ☐ Transportation problems ☐

Shortage of skill ☐ Industrial action (strikes) ☐

Lack of worker commitment ☐ Lack of motivation ☐

Wrong operation ☐ Incorrect tool adjustment ☐

Lack of maintenance ☐ Worker conflict ☐

Rush orders ☐ Customer demand increase ☐

Incorrect information ☐ Incomplete information ☐

Delayed information ☐ Wrong production plan ☐

Other; please specify:

……………………………………………………………………………………………

Question 6: Which of the following problems has your production plant encountered in the past?

	Level of frequency				
Problems	*Never*	*Rarely*	*Sometimes*	*Often*	*Always*
Defective products					
Lower throughput rate					
Delayed delivery to customers					
Excessive changeover time					
Increased downtime due to breakdown maintenance					
Missed shipment date					
Production stopped					
Increased production cost					
Increased material wastage					
Increased accident cost					
Increased maintenance cost					
Increased inventory cost					
Poor relationship with some buyers					
Poor relationship with some suppliers					
Physical damages of products					
Physical damages of equipment					

Please give any other recommendations that would enable the minimisation of the operational disturbances highlighted:

………
………
………………………………………………………

Thank you for your cooperation

Appendix 3-2: Workflow analysis interview and observation guide

Introduction

The main goal of this interview and observation guide is to determine the work flow procedures, and information systems adopted by the Tool, Die, and Mould Making (TDM) companies in South Africa. The findings will be used to develop a digital solution which will best suit the observed firms. Digitalisation in this context is defined as the implementation of modern Information and Communication Technology (ICT) to improve operational excellence.

Instructions on completing this guide

- For Likert scale type statements and multiple choice questions, indicate your answers with an (X) in the appropriate box.
- For the open-ended questions, express yourself freely.

Section A: Company details

The purpose of this section is to establish the general profile of the enterprise and the respondent

Approximate number of employees	
Product range	
Main product(s)	

Section B: Manufacturing process and policy

The following questions are meant to establish the manufacturing processes and policies adopted in the TDM industry:

Question 1: Which of the following manufacturing policies is adopted on the shop floor?

Make-to-stock ☐ Make-to-order ☐ Assemble-to-order ☐

For each, specify examples of products:

………

………

……………………………………………………

Question 2: Which shop-floor facility layout is used?

Flow shop ☐ Job shop ☐

Process based ☐ Product based ☐

Question 3: For any major products, outline the manufacturing process (stages) from customer enquiry to product delivery.

Stage	*Role responsible*	*Process time (approximate.)*

Other; please specify:

………

………

……………………………………………………

Question 4: Does your firm have an information system?

Yes ☐ No ☐

Question 5: If your answer in question four is yes, please indicate the type of information system you use.

Manual ☐ Computerised ☐

Please specify the name where applicable:

…………………………………………………………………………………………

Question 6: Does the firm use the internet during production planning, scheduling or communication?

Yes ☐ No ☐

Question 8: Are the process plans and schedules always adhered to?

	Level of frequency				
	Never	*Rarely*	*Sometimes*	*Often*	*Always*
Due date and delivery responsiveness accuracy					

Please give any other recommendations that would ensure that the process plans and schedules are always followed.

………
………
………
…………………………………….

Question 9: If your answer to question 8 ranges from sometimes - often, which reasons cause the failure to stick to the process plan?

Late delivery by suppliers	☐	Supplier production problems	☐
Supplier quality problems	☐	Transportation problems	☐
Shortage of skill	☐	Industrial action (strikes)	☐
Lack of worker commitment	☐	Lack of motivation	☐
Wrong operation	☐	Incorrect tool adjustment	☐
Lack of maintenance	☐	Worker conflict	☐
Rush orders	☐	Customer demand increase	☐
Incorrect information	☐	Incomplete information	☐
Delayed information	☐	Wrong production plan	☐

Other; please specify:

………
………
………
………
……………………………………………………………………………………………………

Thank you for your cooperation

Appendix 3-3: Mobile technology choice validation

Introduction

Mobile technology has the potential to improve the operational excellence of data collection in manufacturing firms, especially SMMEs. The main goal of this research is to gather initial information on how mobile technology can be used in a tool room during the processes of cost estimation, planning and production. The findings will be used to develop a technical specification document for Mobile Data Collection (MDC) implementation in a South African tooling workshop.

Instructions on answering the questionnaire

- For Likert scale type statements and multiple choice questions, indicate your answers with an (X) in the appropriate box.
- For the open-ended questions, express yourself freely.

Section A: Company details

The purpose of this section is to establish the general profile of the enterprise and the respondent.

Approximate number of employees	
Product range	

Section B: Operational details

Question 1: What is the nature of data being collected during tool making operations?

Quantitative ☐ Qualitative ☐

Other; please specify:

………

………

………………………………………………………

Question 2: For each of the indicated business functions, indicate the percentage of quantitative and qualitative data collected.

Business function	Quantitative data collected (%)	Qualitative data collected (%)
1. Cost estimation		
2. Production planning and scheduling		
3. Job cards and time sheets		
Overall average		

Question 3: For each of the indicated business functions, indicate the approximate number of times it is conducted per annum.

Business function	0 -10 times	11- 99 times	100 – 299 times	Over 300 times
1. Cost estimation				
2. Production planning				
3. Job cards and time sheets				

If necessary, specify any reasons for your answers:

………

………

………………………………………………………

Question 4: For each of the indicated business functions, indicate whether the data collection is once-off or repeated.

Business function	Always once-off	Sometimes repeated but mainly once-off	Sometimes once-off but mainly repeated	Always repeated
1. Cost estimation				
2. Production planning				
3. Job cards and time sheets				

If necessary, specify any reasons for your answers:

………

………

………………………………………………………

Question 5: For each of the indicated business functions, indicate if the access to data or information is time-sensitive.

Business function	Yes, access to data is time-sensitive	No, access to data is not time-sensitive
1. Cost estimation		
2. Production planning		
3. Job cards and time sheets		

If necessary, specify any reasons for your answers:

………

………

………………………………………………………

Question 6: For each of the indicated business functions, comment on the complexity of the data collection logic.

Business function	Survey logic is simple	Survey logic is complex
1. Cost estimation		
2. Production planning		
3. Job cards and time sheets		

If necessary, specify any reasons for your answers:

………

………

……………………………………………………………

Question 7: For each of the indicated business functions, specify any additional features which may need to be reckoned.

Business function	Additional features
1. Cost estimation	
2. Production planning	
3. Job cards and time sheets	

If necessary, specify any reasons for your answers:

……………………………………………………………………………………………………

Thank you for your cooperation

Appendix 3-4: Software and hardware decision matrix for platform selection (adapted from Satterlee et al., 2015)

A 3-4.1: Existing capacities in company

Existing capacity	Yes/No	Implications
Does the organisation already have a stock of devices (smartphones, tablets, etc.) which can be used for data collection?		
Does the organisation have people with skills for using particular programs for data management, analysis, visualisation etc.?		

A 3-4.2: Choosing the appropriate software platform

Critical questions and implications for software choice

Number	Project needs and context	Y/N	Implications for software choice
1.	Does the project require the data to be used by existing data management, analysis or visualisation tools?		If yes, give strong preference to software that is easily compatible with the other software that you have expertise in using. If no proceed
2.	Does the data collection require workers to take photos, graphics or video that is recorded within the dataset?		If yes, limit your software options to those that support pictures within the dataset. Note, however, that if pictures do not need to be inside the actual dataset (if you simply want pictures from the field), no software support is necessary. If no, proceed.
3.	Does the data collection seek to record GPS data?		If yes, limit your software options to those that support GPS data being recorded in the dataset. However, you may also use other means for GPS positions and input the coordinates as a separate question. If no, proceed.
4.	Does data need to be uploaded directly from the field by workers?		If yes, inquire how large the files that the software creates are. You may experience significant problems trying to upload large files from the field. Also find out how the software deals with mini-second losses of connection, as some software does not identify these and uploads lead to small intermittent gaps in the data. These problems are especially

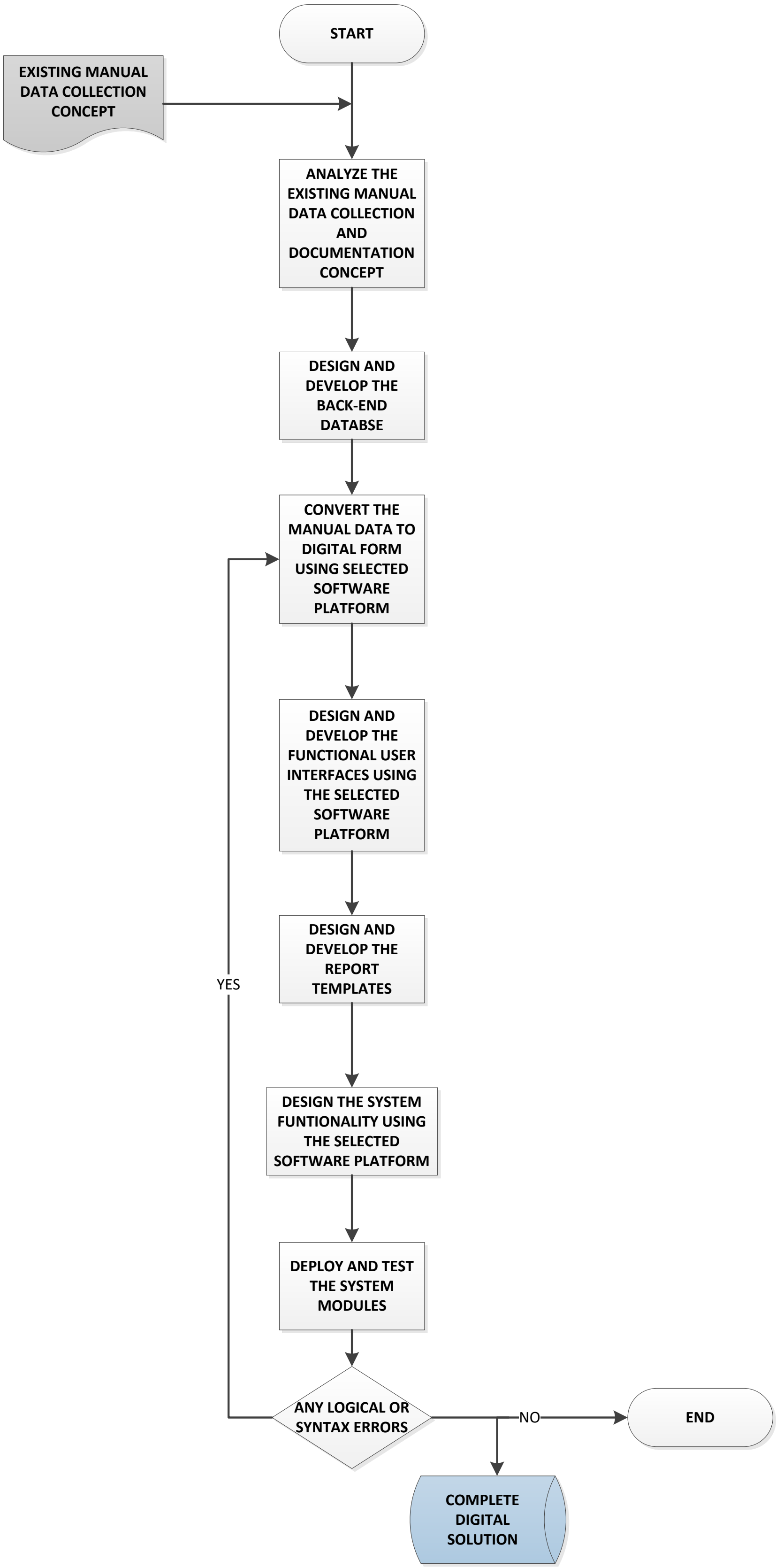
			pertinent in areas that have low quality internet. If no, proceed.
5.	Does the data collection include large amounts of filter logic, including section skips or filtering through multiple variables?		If yes, make sure that the software option supports the type of filters that you want to build for your data collection algorithm. Complicated skips are also easier to code in some software as opposed to others, so try to search for an example of how what you want to do looks like in the software. Also check how the complex skips affect loading times in the platform, as in some software it can lead to significant delays. If no, proceed
6.	Do you estimate that you will need external support in case where there are problems during the data collection process?		If yes, you may want to give preference to software that has a dedicated support service (generally, customer service). However, freeware often also has forums where users assist each other and support may be found. If no, proceed
7.	Will you need to merge the incoming data with other datasets?		If yes, you will want to make sure the data collection forms are compatible with your existing datasets in advance of selecting software. If no, proceed to hardware selection questions

A 3-4.3: Hardware selection decision matrix

Number	Project needs and context	Y/N	Implications for software choice
1.	(Skip if you are assessing your current hardware) Is the device compatible with the software you have chosen?		If yes, proceed. If no, choose another device
2.	Does the data collection require workers to take photos, image or video?		If yes, limit devices to those that have built-in cameras. The quality of the camera depends on the level of analysis you require from the pictures, but note that higher quality pictures also take more space. If you are operating in areas with low quality internet, having large pictures may make uploading from the field extremely difficult. If no, proceed to the next question.
3.	Does the data collection seek to record GPS data?		If yes, limit devices to those that have GPS capability. Note that some devices take location coordinates by triangulating from telecommunications towers (requires SIM) or through a GPS, both of these forms have limitations that could limit your ability to acquire coordinates. In contexts where towers are not present, make sure the phone can connect to actual satellite positioning using GPS (different from AGPS). Alternatively, buy a separate GPS locator and input coordinates as a separate variable. If no, proceed to the next question.
4.	Does data need to be uploaded directly from the field?		If yes, limit devices to those that can connect to either a cellular network or

			WiFi (depending on availability and reliability in your context). If no, proceed to the next question.
5.	Does the survey include large amounts of filter logic, including section skips or filtering through multiple variables?		If yes, give preference to devices that have a decent amount of processing power, as low-speed processors may cause increased loading times during the survey (however, most new smartphones have more than enough processing power to meet these needs).

Appendix 3-5: System design and development phases



Appendix 4-1: Tooling roles definition

1. Tool Maker

The tool and die maker remains a central skill within the tool-making value chain. Tool and die makers are highly skilled workers in the manufacturing industry. Most tool and die makers attend a four to five year apprenticeship/learnership program to achieve the necessary qualification. Further experiential training is also required to gain the necessary experience to operate as a toolmaker. Some of the job functions of a tool and die maker consist of producing jigs, fixtures, form tools, dies, moulds, cutting tools, and many other mechanical items used in the manufacturing process. In modern tool and die making techniques the toolmakers' most important function is during the assembly, finishing and verification of the tool or die.

2. Project Manager

Timeous delivery of a quality tool or die within the allowed budget is non-negotiable when competing within the global context. The management of the complete value chain to achieve this requires trained and experienced project managers. Planning, scheduling and controlling a project also entails managing project financing and constant interaction with suppliers and customers. Project managers are either degreed or diploma'd engineers, with at least three years' experience, who can deliver these attributes within the tool-making environment.

3. Tool Designer

Up to 80% of the cost and quality success of a tool is determined during the tool design process. The Tool Designer therefore plays a critical role in the tool development process. Tool designers can be either a degreed or diploma'd engineer with a major in design. Sufficient experience in a tool and die field, such as injection moulding, blow moulding, press tooling, die casting or any other tooling field, is a necessity. Competency with respect to the effective use of the latest 3D Computer Aided Design (CAD) technologies is also a requirement. The Tool Designer works in a close relationship with both the toolmaker as well as the Project Manager in the total process of taking the tool to completion.

4. Computer Aided Manufacturing/Computer Numerical Control (CAM/CNC) Programmers

In the tool-making process, 3-axis and 5-axis Computer Aided Manufacturing (CAM) technologies are widely utilised. Computer Numerical Control (CNC) Programming of these machines is another specialisation skill essential to the successful manufacture of tools and dies. CNC programmers must be competent in the principles of tool making, as CNC programming requires knowledge of programming language, tool materials, cutting operations and process accuracies. Staying abreast with the latest CNC technologies is also important.

5. Milling and Turning Operator

Conventional milling and turning is still a skill required within the modern skills value chain. For the purposes of tool-making precision, milling and turning is often required. Milling and turning qualifications can be obtained as part of a tool-making apprenticeship or as a stand-alone apprenticeship.

6. Wire Electrical Discharge Machining (EDM) and Electro Sparking Operator

Electrical Discharge Machining (or EDM) is a machining method primarily used for hard metals or those that would be impossible to machine with traditional techniques. One critical limitation, however, is that EDM only works with materials that are electrically conductive. EDM can cut small or odd-shaped angles, intricate contours or cavities in extremely hard steel and exotic metals such as titanium, hastelloy, kovar, inconel and carbide. EDM operators must be competent in the principles of tool making, as EDM operation also requires CNC programming, knowledge of tool materials and process accuracies.

7. Tool Room Manager

The Tool Room Manager has a strong line management function to co-ordinate tool room activities. A competent manager will ensure that all resources, human and infrastructure, are optimally and efficiently utilised. This contributes to work quality and short turn-around times.
The Tool Room Manager himself will be a trained and experienced toolmaker. He works closely with the Project Manager to ensure tight control on project progress. Good tool room managers must have strong leadership and organisational skills, and must have adequate tool-making experience.

8. Metallurgist

Tool-making challenges often require the use of special materials and material heat treatment techniques. Metallurgists with knowledge and experience in tool making have become an essential competency in the tool-making skills value chain.

9. Metrologist

Metrology is the science of measurement, measurement techniques and measurement analysis. In the tool and die making, dimension tolerances and accuracies are measured in micrometres (microns). Sophisticated methods and equipment are used to validate and verify manufactured component dimensions to design data. Metrology is a specialisation field that contributes directly to successful tool and product development. Toolmakers, Tool Designers and Metrologists work in a close relationship to accomplish geometrical accuracies required in quality tool making.

10. Engineering Analyst

Simulation of the material conversion process through computer aided simulation tools have become common place in the tool-making process. The analysis of material behaviour from a molten state through the solidifying process, with the accompanying effect on final product integrity is an important input toward tool design. Also, the behaviour of metals when being deformed through a pressing process can be simulated beforehand and results are used to optimise press tool design. Such simulations are executed by engineering analysts with both a proper understanding of the process being analysed as well as a thorough understanding of the underlying programming and numerical principles used in the simulation software. Good results from a thoroughly conducted simulation are invaluable during the tool development process.

11. Cost Estimator

A major challenge in tool and die development is the estimation of costs, for quotation purposes, before the tool design has been finalised. Cost estimators have to address this challenge by relying on their experience in the tool-making industry, as well as relying on the input of toolmakers and tool designers. This makes the process of cost estimation very subjective, sometimes leading to inconsistent results.

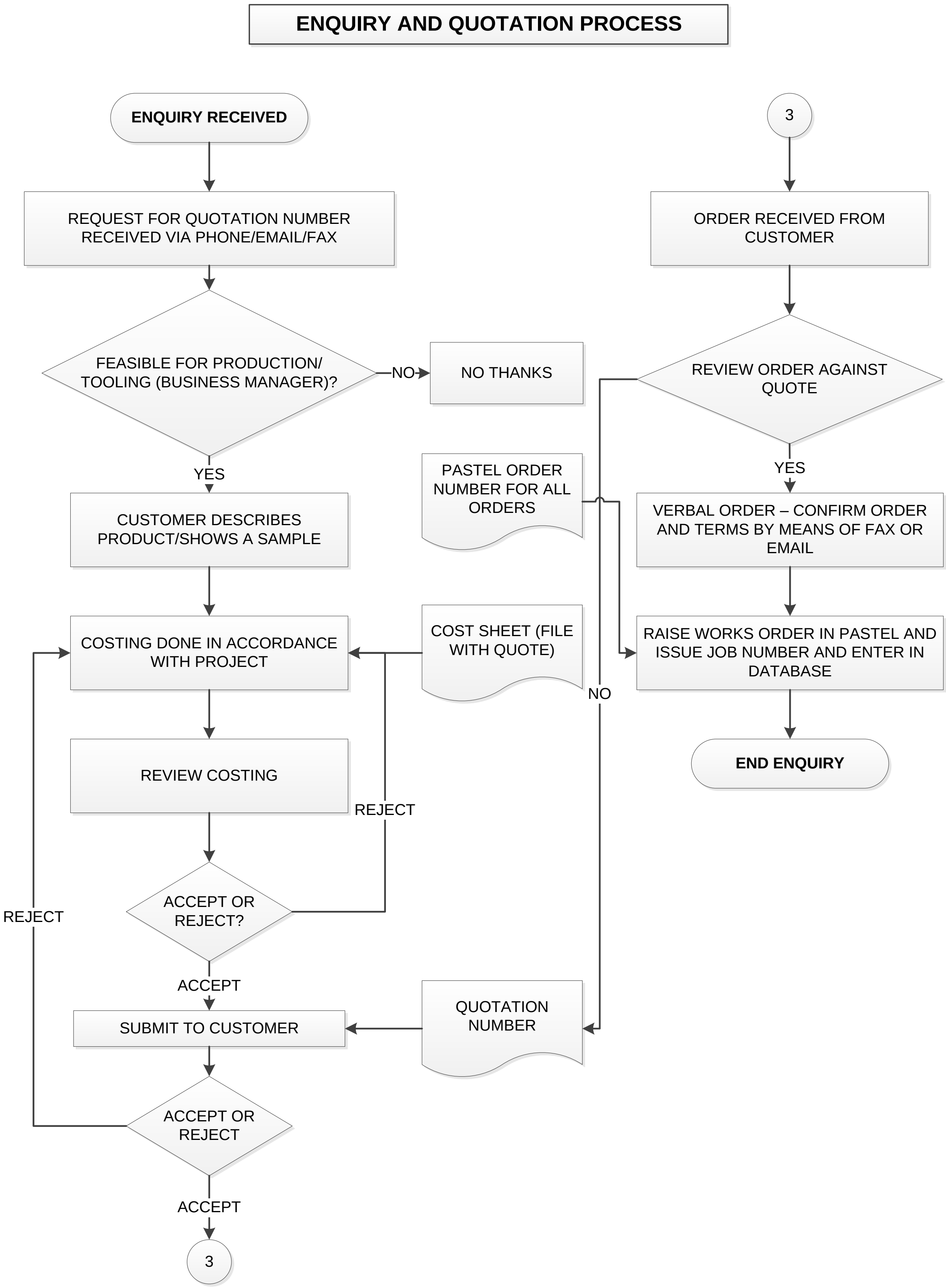
12. Heat Treatment Operator

In tool making, the technique of heat treatment is almost always used to modify the mechanical hardness of tool metals. This process is normally one of the last activities that takes place before a tool is completed. It is also a very sophisticated and sensitive process. A mistake at this stage impacts the timely completion of the tool. Heat treatment operators therefore have the great responsibility of making sure that the process is executed successfully.

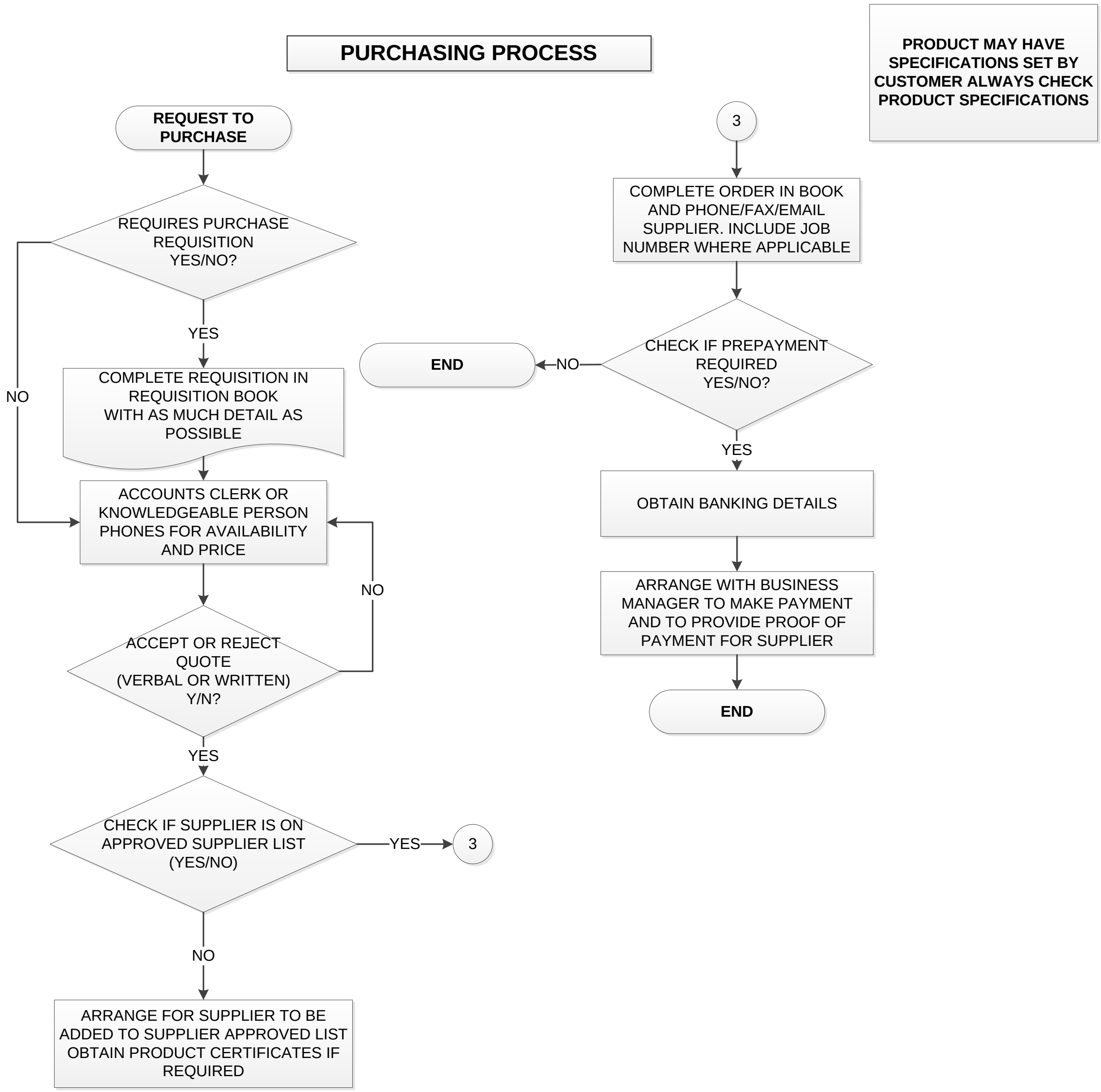
13. Polisher

Polishing is the process of creating a smooth and shiny surface by using rubbing or a chemical action. Tool surfaces that define product surface finish are normally polished. Accurate and intricate tool interfaces often also require polishing for proper tool functionality. Tool polishing is a skill that requires hand skills as well as knowledge and the ability to utilise the available machining and chemical technologies to achieve the required result. In most cases, one individual can assume the majority of the above stated competences, especially in small to medium sized tool rooms. Therefore, with many different roles working together on a selected project, tool making is usually a distributed venture requiring great collaboration. In most cases, these various skills/roles may be located in different geographical areas.

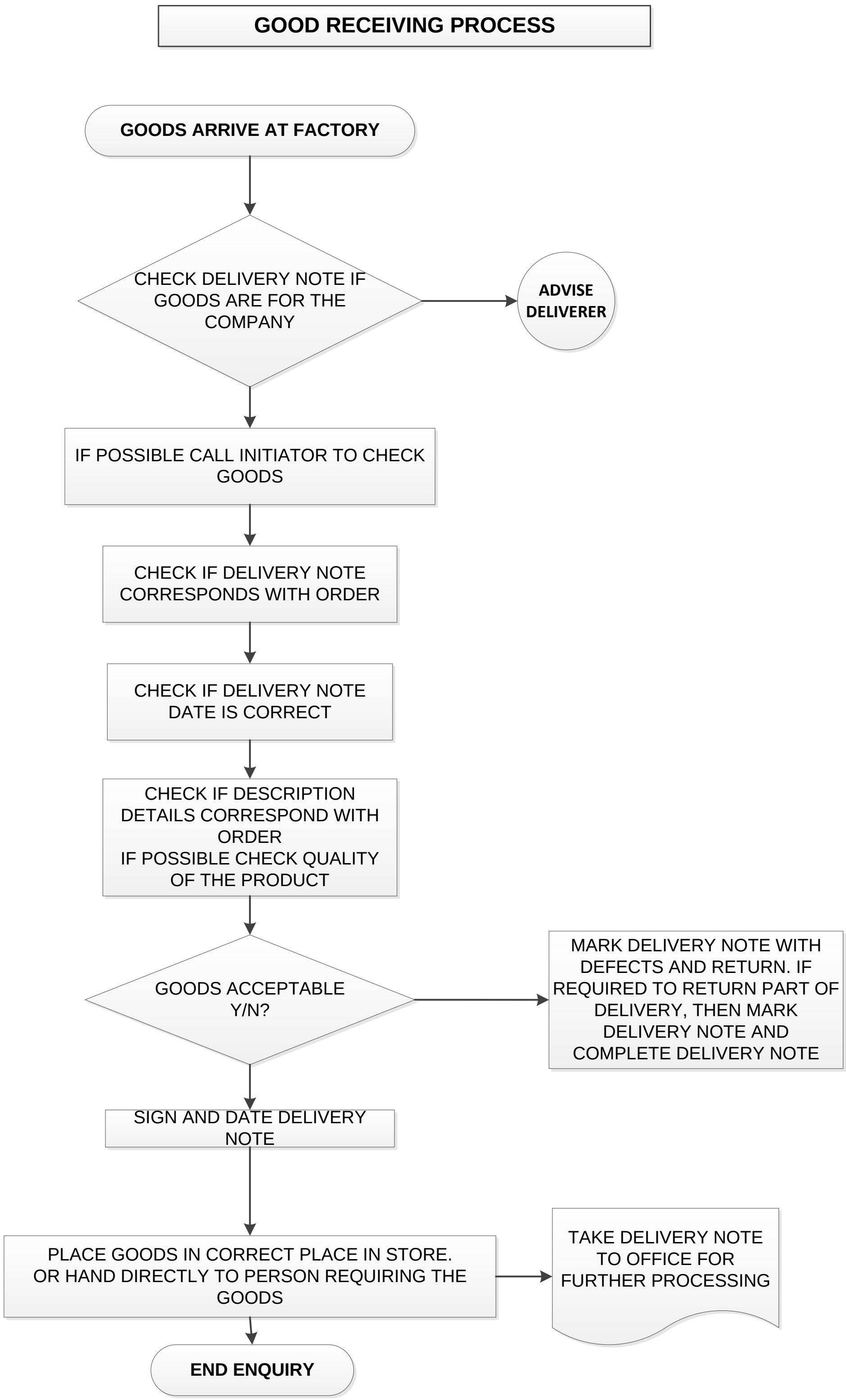
Appendix 4-2: Enquiry and quotation process



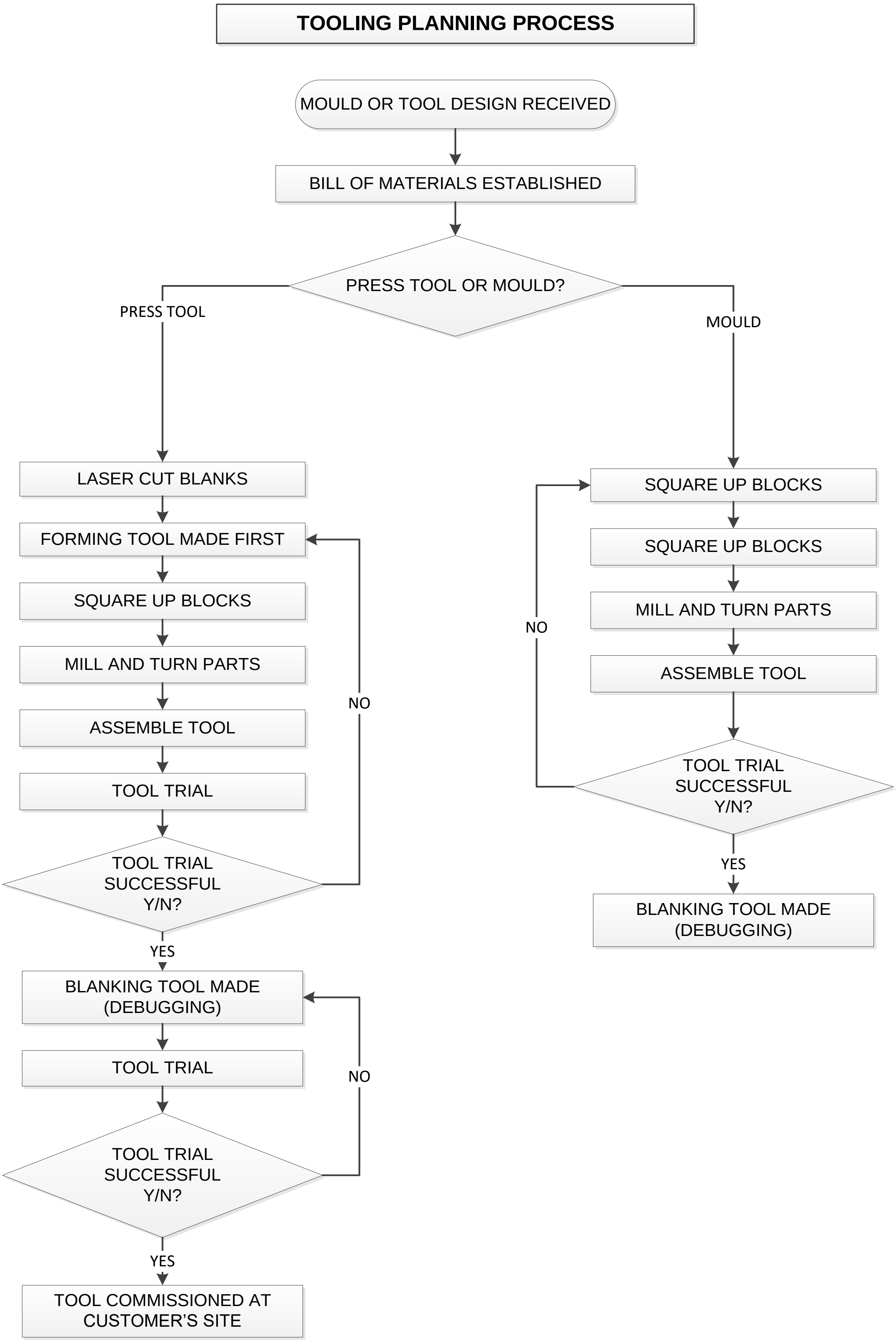
Appendix 4-3: Purchasing process



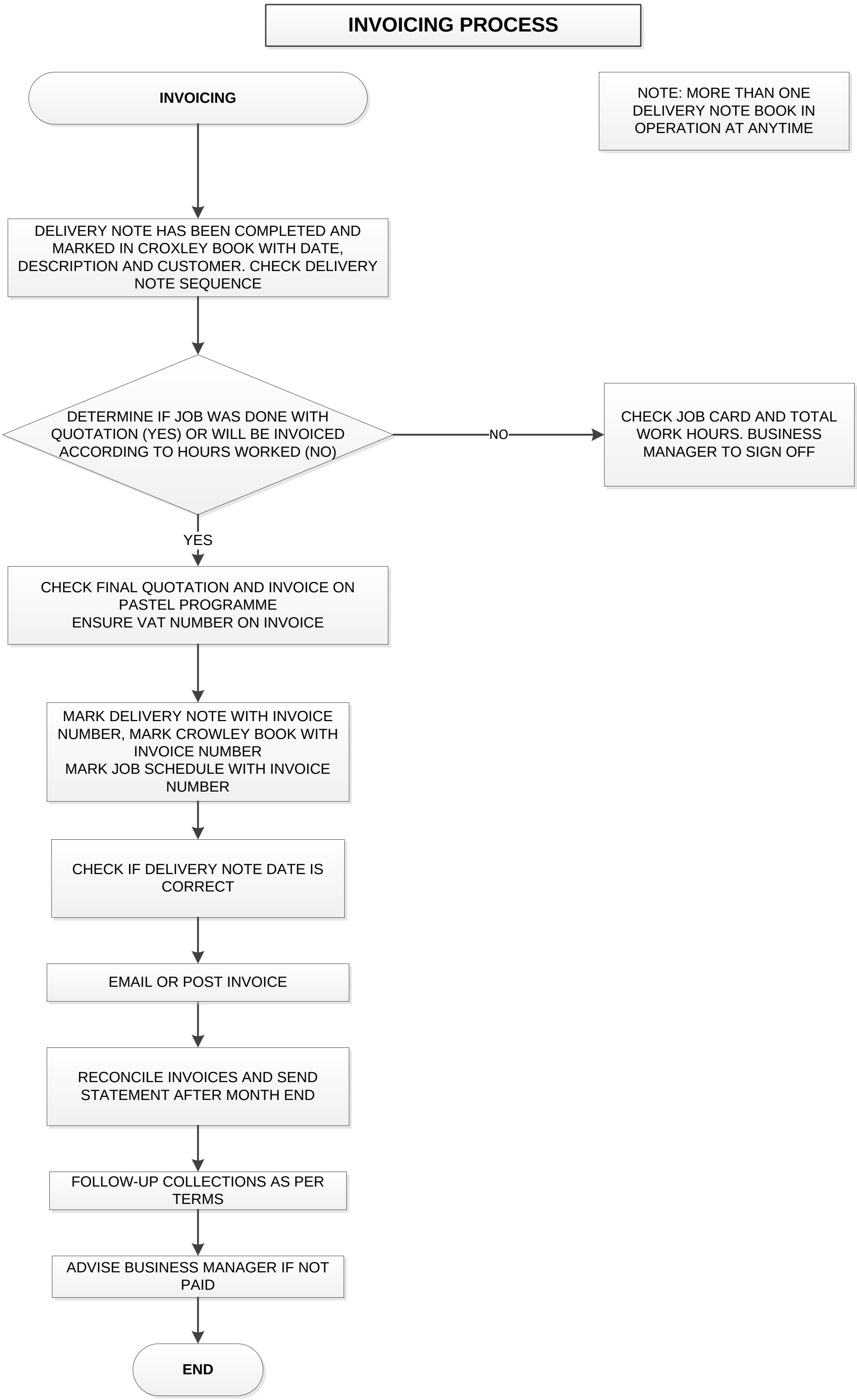
Appendix 4-4: Goods receiving process



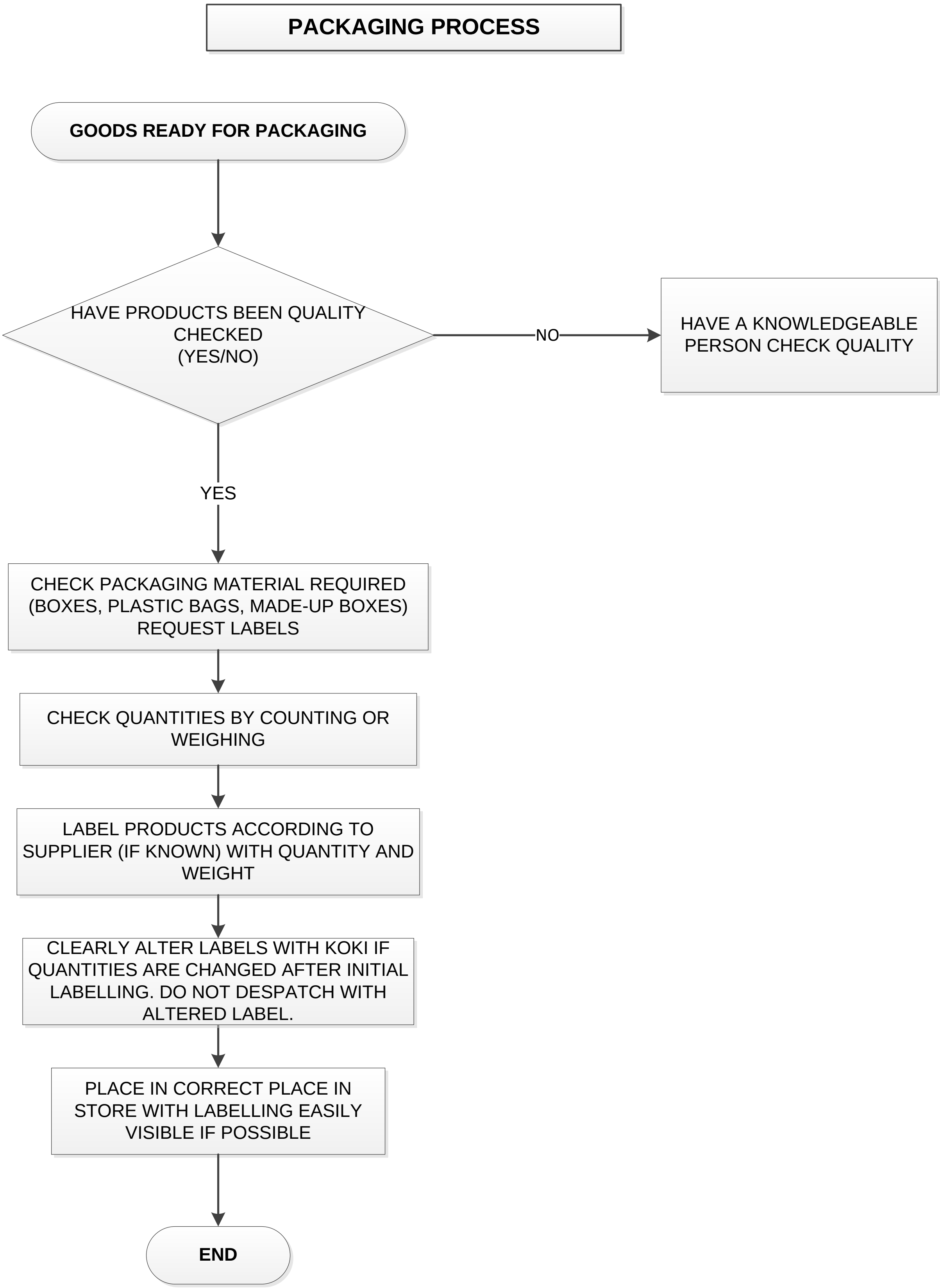
Appendix 4-5: Tooling planning process



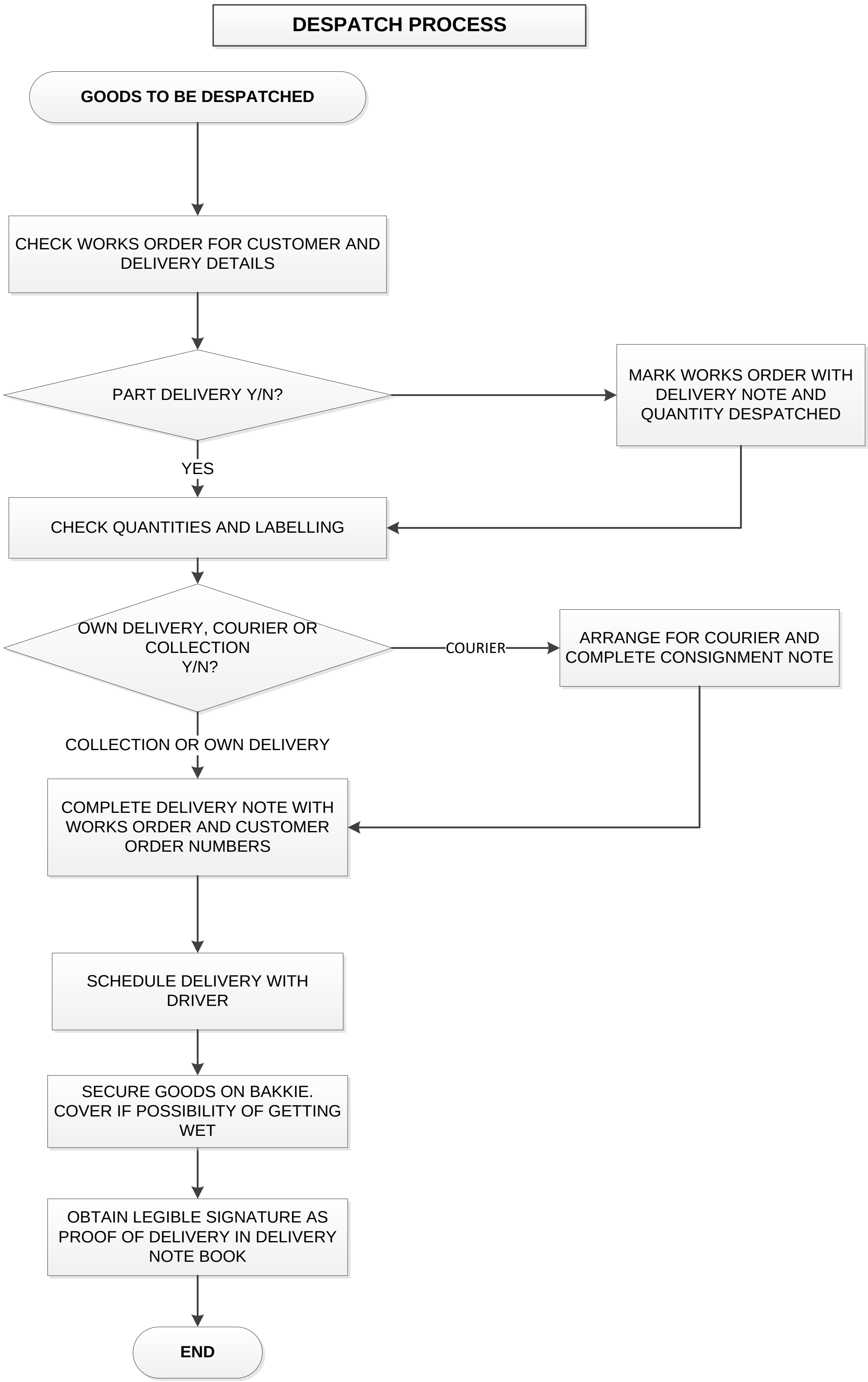
Appendix 4-6: Invoicing process



Appendix 4-7: Packaging process



Appendix 4-8: Despatch process



Appendix 6-1: Tool or Mould Quote Sheet

Tool Quote Sheet

RFQ#	
RFQ Date	
RFQ Due Date	
Date	

Part Number(s)		Tool Shop Name	
Part Name(s)		Tool #	
Program Name		Quote #	

Tool/Process Description

Cavities		Base Material:		Mould Saty:	
Machine Size (Tons)		Actions/Tool:		Cavity-Core Steel Type	
Cycle Time (seconds)		Hyd. Cylinders:		Manifold Make or Type:	
Texture Type		Pressure Trans:		Manifold:	
Mould Flow/Mould Cool		Sliding Cores		Valve Gates Y/N:	
Tool Build Duration to 1st Parts (Weeks)		Gate Type:		Special Inserts Y/N:	

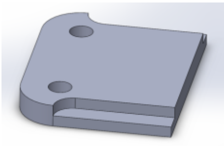
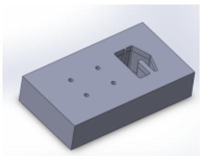
LABOUR FUNCTION	Hours	×	Rate	=	Total	Comments
1 DATA MANAGEMENT					R 0.00	
2 MOULD DESIGN					R 0.00	
3 COMPUTER SIMULATIONS					R 0.00	
4 ADVANCED ENGINEERING					R 0.00	
5 CNC MACHINING					R 0.00	
6 GENERAL SHOP LABOUR					R 0.00	
CMM PARTS (Outsource only)					R 0.00	
SUB TOTAL (LABOUR):					R 0.00	

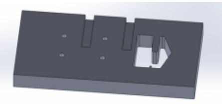
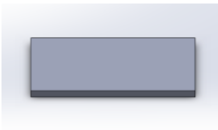
MATERIALS AND SERVICES				COMMENTS
8 MOULD BASE			R 0.00	
9 COPPER (Electrodes)			R 0.00	
10 CAVITY-CORE STEEL			R 0.00	
11 HEAT TREATING OR PLATING			R 0.00	
12 MANIFOLD/HOT RUNNER			R 0.00	
13 COMPONENTS			R 0.00	
14 TEXTURE			R 0.00	
15 OTHER (Specify)			R 0.00	
16 TOOLING (CUTTERS/INSERT)			R 0.00	
17 SAMPLE MATERIAL			R 0.00	
18 TOOL DELIVERY			R 0.00	
SUB TOTAL MATERIALS AND SERVICES			R 0.00	
		VAT 14%		
		TOTAL TOOL COST	R 0.00	
		TOTAL TOOL or MOULD COST	R 0.00	

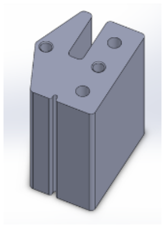
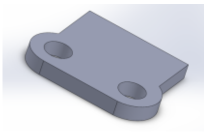
Appendix 6-2: Process planning template

PROJECT:	**HUHTAMAKI INJECTION MOULD**	**CREATED ON:**	
Customer:		**DUE DATE:**	
JOB NO:			

WEEK 1						
M	T	W	T	F	S	S
G.P P.J						

Drawing	Parts	Description	Procedure	Machine	Assigned Person	Estimated Hrs
	Bottom Bolster	Bottom Die Plate	Design	Please Pick one...	L.W	1
		No hardening	Rough Milling	Ctek CNC Mill	S.Z	4
			Surface Grinding	Surface Grinder 1	U.	1
			CNC Milling	1P Haas CNC Mill	J.S	5
			Drill and Bore Holes	1P Haas CNC Mill	A.L	2
	Die Plate		Design	Please Pick one...	L.W	1
			Rough Milling	Ctek CNC Mill	S.Z	4
			Surface Grinding	Surface Grinder 1	L.W	1
			CNC Milling	1P Haas CNC Mill	J.S	2
			Heat Treament	Please Pick one...		
			Regrinding	Surface Grinder 1	G.P	2
			Wire Cutting	Wire Cutter	L.W	6
	Strip Guides	No hardening	Rough Milling	Ctek CNC Mill	S.Z	4
			Surface Grinding	Surface Grinder 1	I.	1
			Drill and Ream Holes	Conventional Mill 3	G.P	1
			Finishing	Conventional Mill 3	A.L	1
			Design	Please Pick one...	L.W	1

	Strip Guides	No hardening	Rough Milling	Conventional Mill 1	G.P	4
			Surface Grinding	Surface Grinder 1	U.	1
			Drill and Ream Holes	Conventional Mill 2	P.J	1
			Finishing	Conventional Mill 2	J.S	1
			Design	Please Pick one...	L.W	1
	Bridge Stripper Plate		Rough Milling	Conventional Mill 2	L.K	4
			Surface Grinding	Surface Grinder 1	J.S	2
			CNC Milling	VF-2 Haas CNC Mill	J.S	2
			Heat Treament	Please Pick one...		
			Regrinding	Surface Grinder 2	A.L	2
			Wire Cutting	Wire Cutter	L.W	3
			Assembly	Conventional Mill 4	G.P	1
			Design	Please Pick one...	L.W	1
	Punch Holder	No hardening	Rough Milling	Conventional Mill 1	J.S	4
			Surface Grinding	Surface Grinder 1	U.	2
			CNC Milling	VF-2 Haas CNC Mill	J.S	2
			Wire Cutting	Wire Cutter	L.W	3
			Design	Please Pick one...	L.W	1
	Pressure Plate		Rough Milling	Conventional Mill 2	G.P	4
			Surface Grinding	Surface Grinder 2	J.S	1
			Drill and Ream Holes	Conventional Mill 2	P.J	1
			Finishing	Conventional Mill 1	P.J	1
			Design	Please Pick one...	L.W	1
			Please Pick one...	Please Pick one...		1

	Punches		Rough Milling	Conventional Mill 1	J.S	4
			Surface Grinding	Surface Grinder 1		2
			Drill and Tap Holes	Conventional Mill 1	J.S	2
			Heat Treament	Please Pick one...		
			Regrinding	Surface Grinder 1	G.P	2
			Wire Cutting	Wire Cutter	L.W	5
			Regrinding	Surface Grinder 1	G.P	1
	Top Bolster		Design	Please Pick one...	L.W	1
			Rough Milling	VF-2 Haas CNC Mill	S.Z	4
			Surface Grinding	Surface Grinder 1	J.S	1
			CNC Milling	1P Haas CNC Mill	J.S	2
			Drill and Bore Holes	1P Haas CNC Mill	J.S	1
			Please Pick one...	Please Pick one...		
			Please Pick one...	Please Pick one...		
			Please Pick one...	Please Pick one...		
			Please Pick one...	Please Pick one...		
			Please Pick one...	Please Pick one...		
	All		Assembly	Conventional Mill 4	G.P	4
			Drill and Ream Holes	Conventional Mill 1	G.P	2
			Finishing	Conventional Mill 2	G.P	2
			Tool try-out and Debugging	Please Pick one...	J.S	24
			Please Pick one...	Please Pick one...		
			Please Pick one...	Please Pick one...		
			Total Estimated Time			**138**

Appendix 6-3: Production Job card

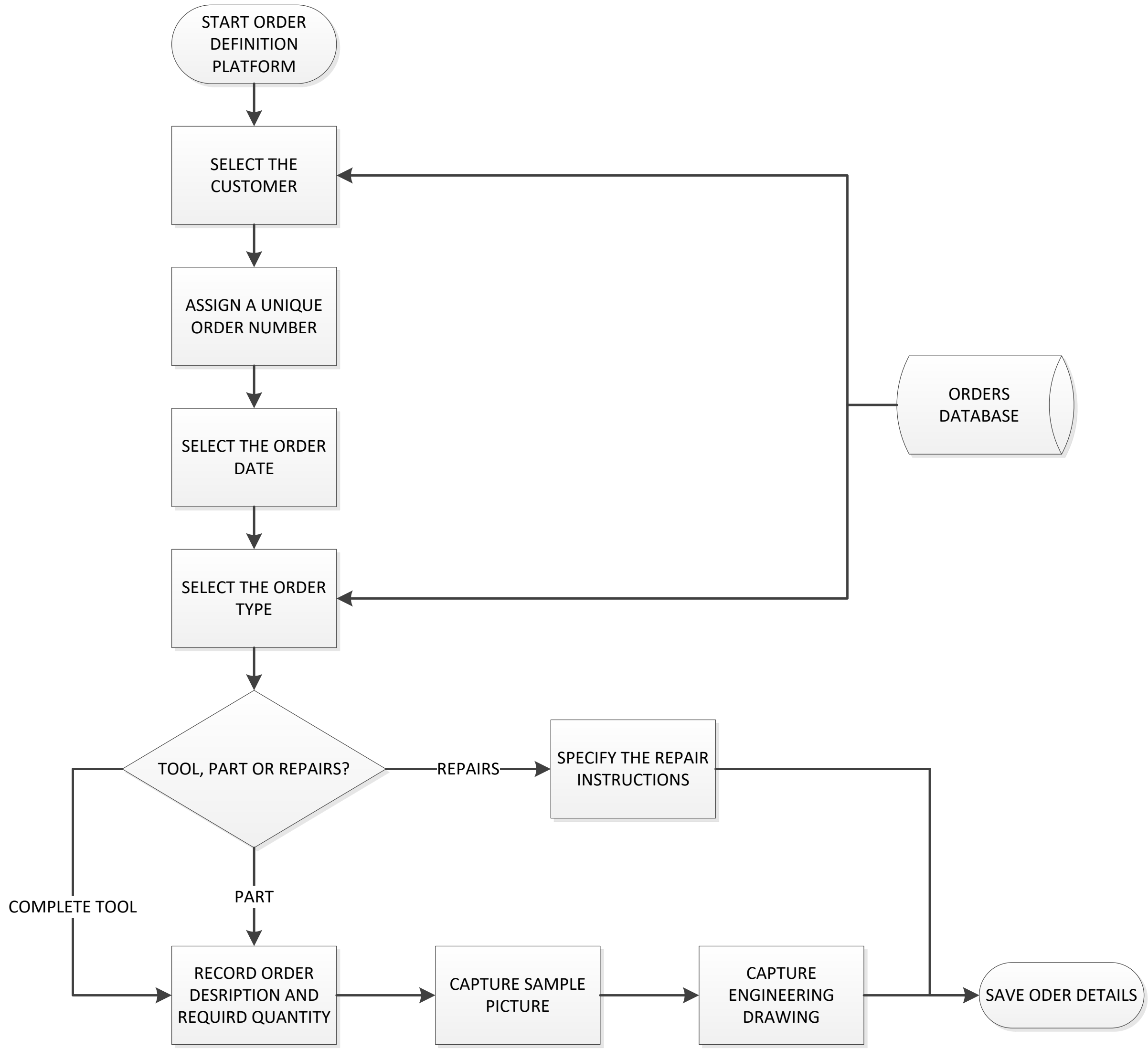
				Job No./	2026B
				Invoice No.	**1234**
Customer Name	Huhtamaki	**Product**	Insert	**Delivery Note No.**	5678
Date in	10/10/2016	**Expected Date out**	10/11/2016	**Date Out**	03/12/2016
Order Quantity	4	**Total In-house Job Hrs**	39:40:00	**Stock Quantity**	

Employee Name	Description Of Operation	Start Date & Time (yyyy/mm/dd hr:mm)	Finish Date & Time (yyyy/mm/dd hr:mm)	Setup Time *(hrs)*	Overnight /Other Downtime *(4pm-7am)*	Estimated Process Time *(hrs)*	Actual Process Time *(hrs)*	Drawing
LW	Design	10/10/2016 08:45	10/10/2016 13:30	00:30:00		05:30:00	5:15:00	
SZ	Turning	10/10/2016 08:00	10/10/2016 14:30	01:00:00		2:30:00	7:30:00	
SZ	Turning	11/10/2016 08:30	11/10/2016 10:00			5:00:00	01:30:00	
AS	Milling	12/10/2016 07:30	12/10/2016 09:45			5:00:00	2:15:00	
AS	CNC Milling	13/10/2016 07:30	13/10/2016 16:45		0:50:00	06:00:00	8:25:00	
JS	Grinding	20/10/2016 07:00	20/10/2016 17:15			3:30:00	10:15:00	
JS	Tryout	21/10/2016 07:00	21/10/2016 11:30			3:45:00	4:30:00	
							0:00:00	
							0:00:00	
							0:00:00	
							0:00:00	
							0:00:00	
							0:00:00	
							0:00:00	
							0:00:00	
							0:00:00	
						31:15:00	39:40:00	

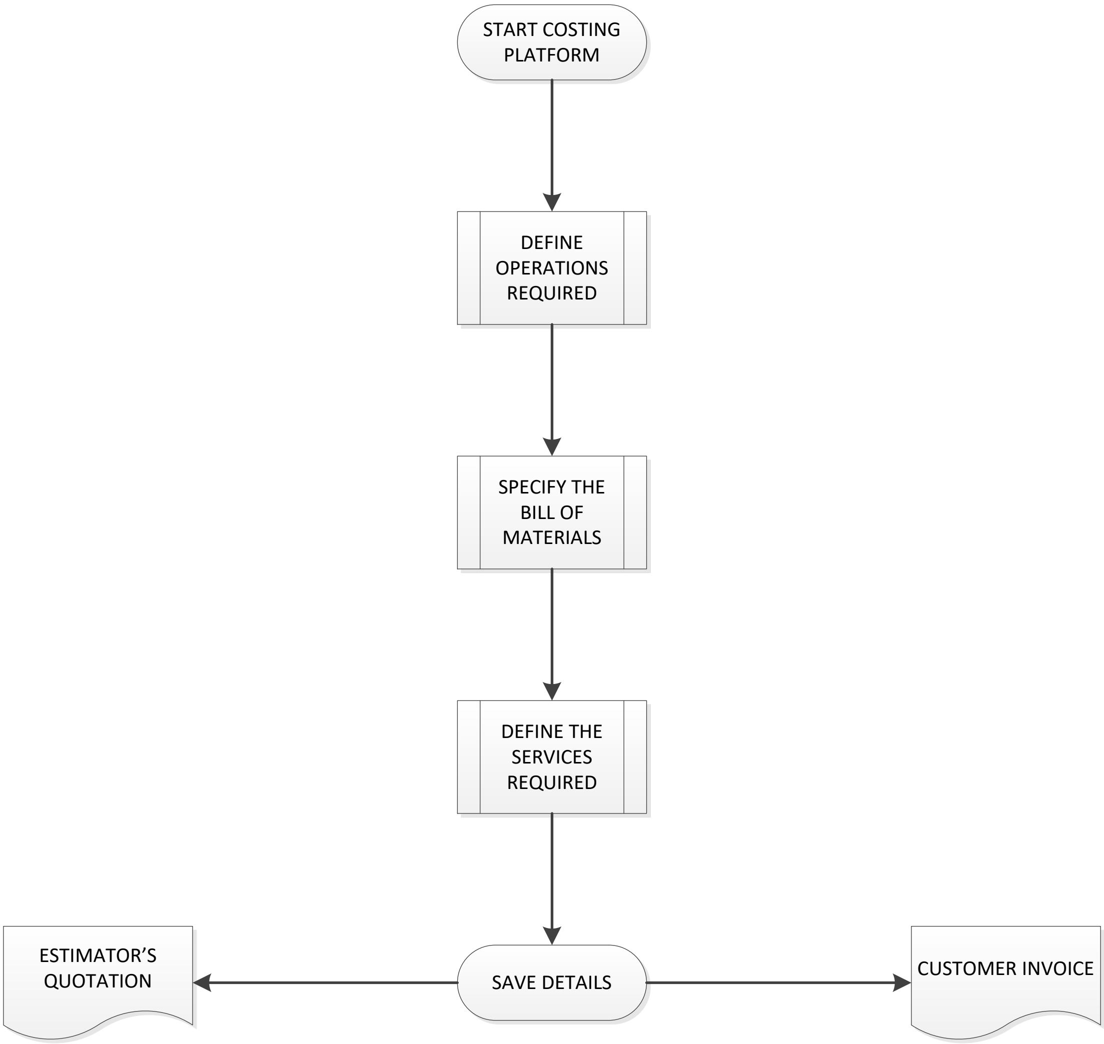
Outsourced Services	Company	Date In	Date Out	Actual Hours	Planned Hours
				0:00:00	00:00:00
Total Outsourced hours				0:00:00	00:00:00

	Materials	Estd/Input Qty	Actual/Used Qty	Price	Order Number	Material Cert.
1	Copper	4	4	R 200.00		
2	(testing)	3	5			
3						
4						
5						
6						
7						
8						
Total		7	9	R 200.00		

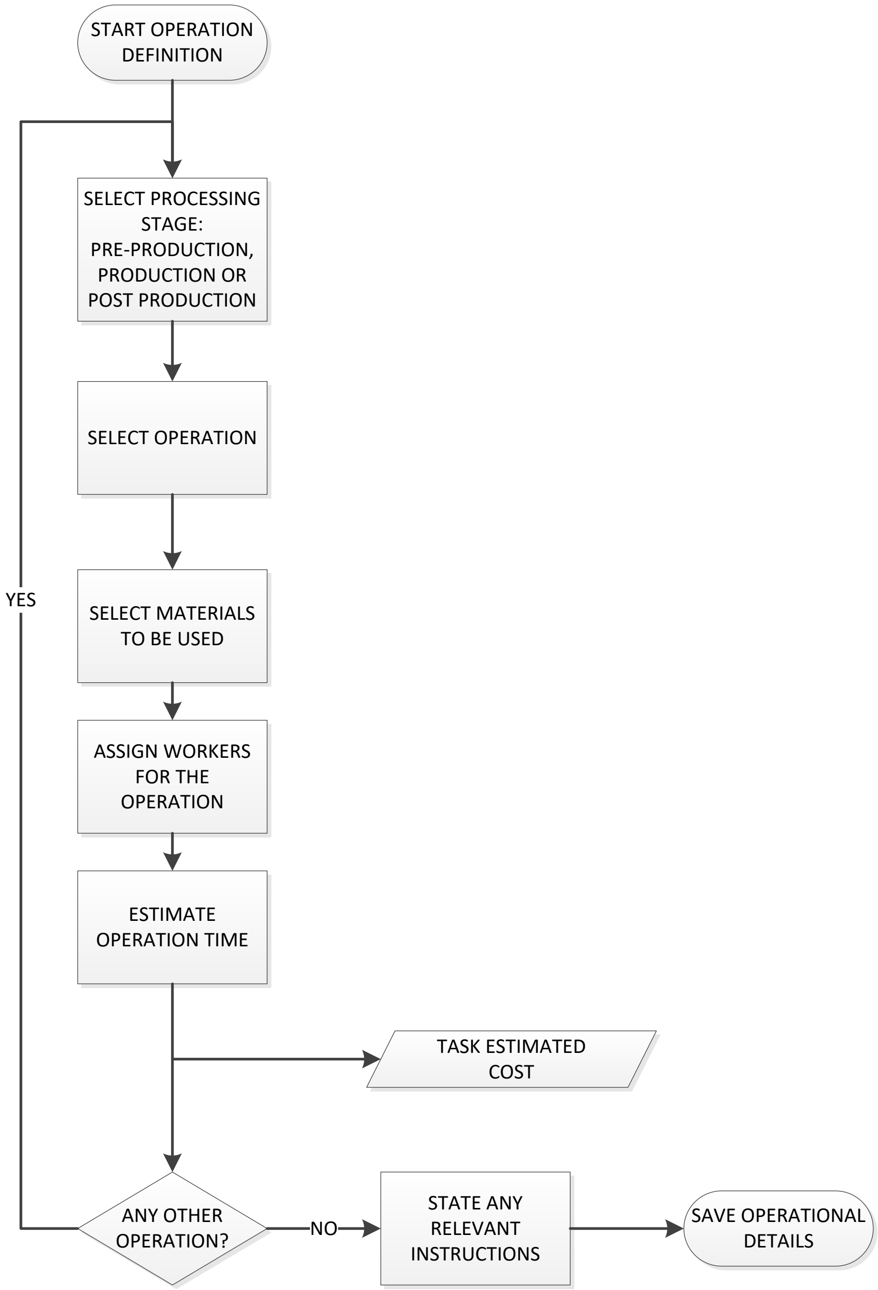
Appendix 6-4: Order definition algorithm



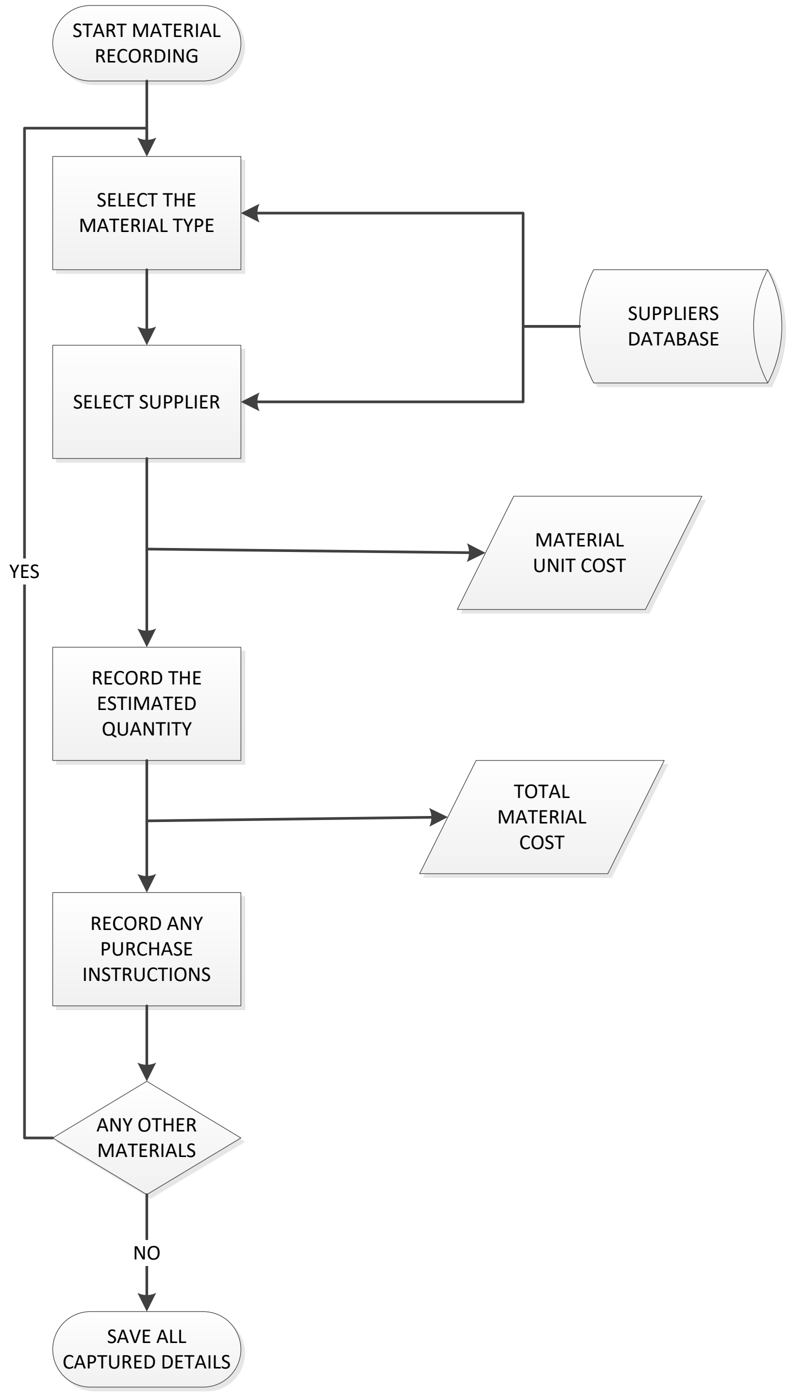
Appendix 6-5: Cost Estimation algorithm



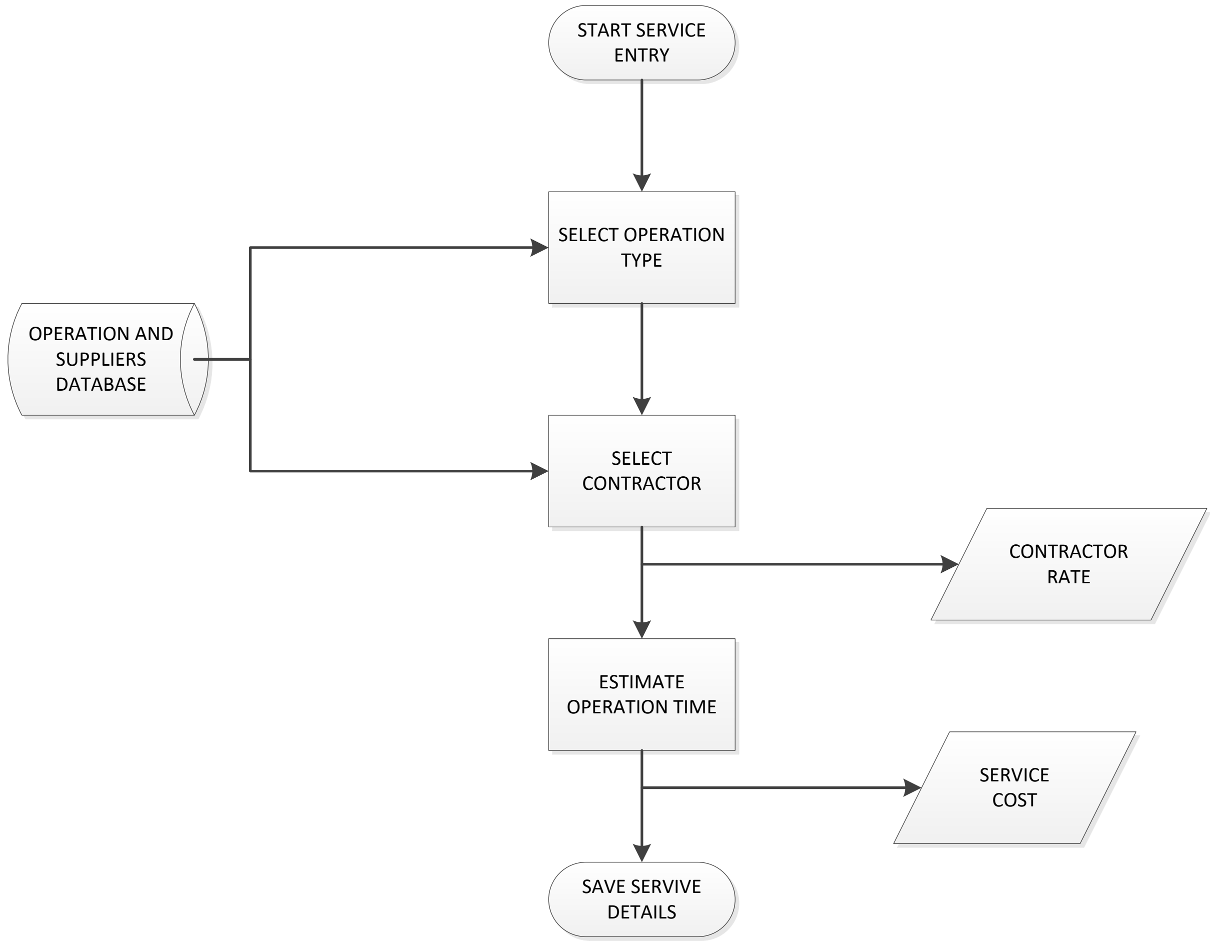
Appendix 6-6: Operations definition algorithm



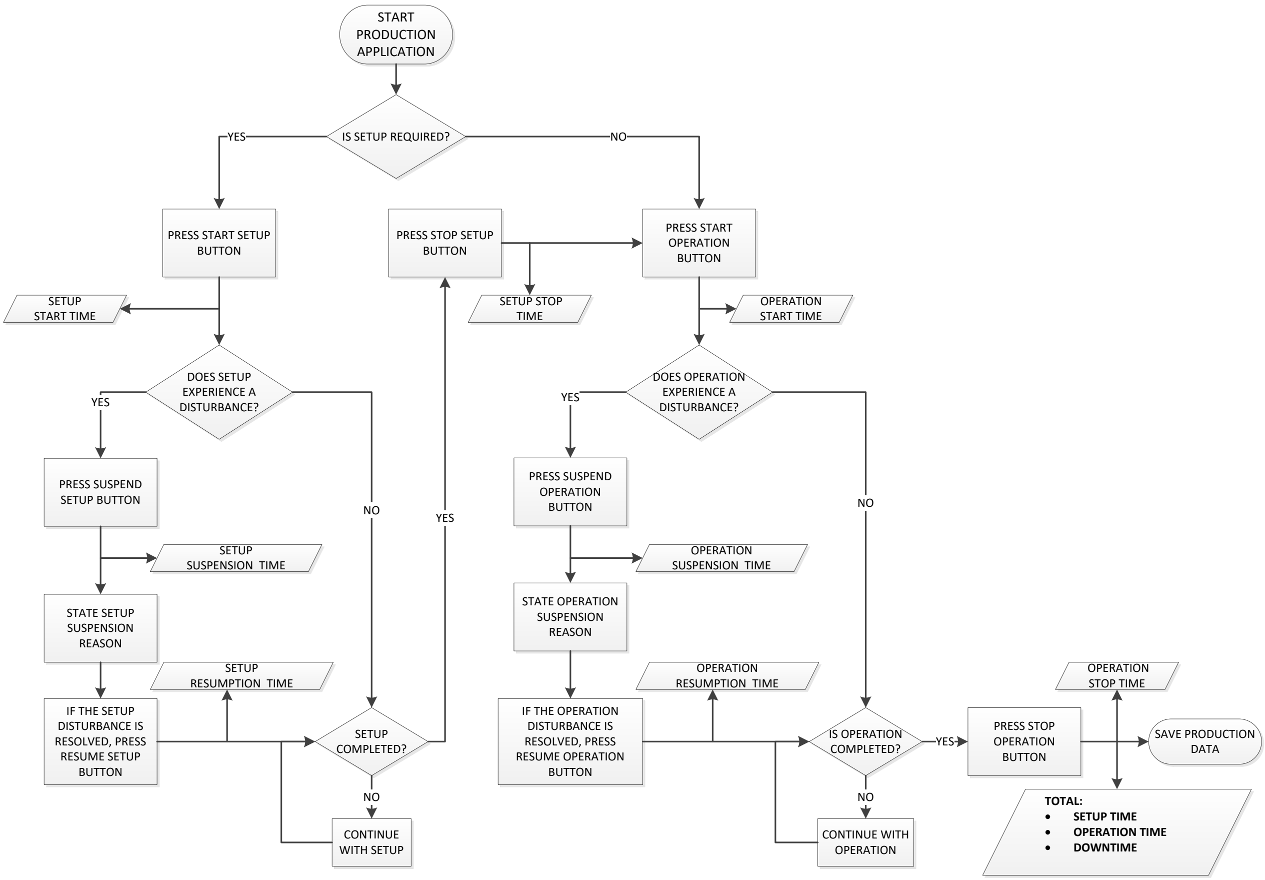
Appendix 6-7: Materials definition algorithm



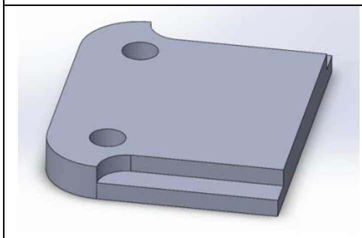
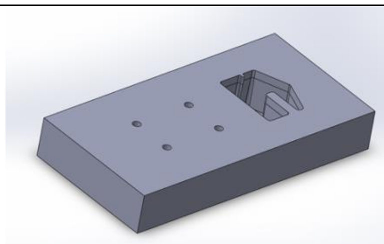
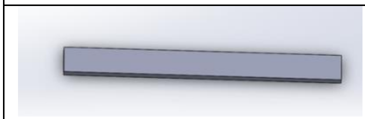
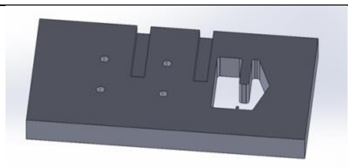
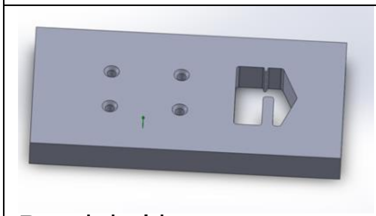
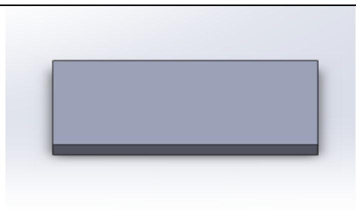
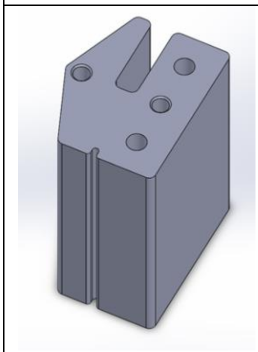
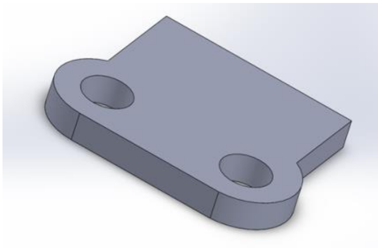
Appendix 6-8: Service definition algorithm



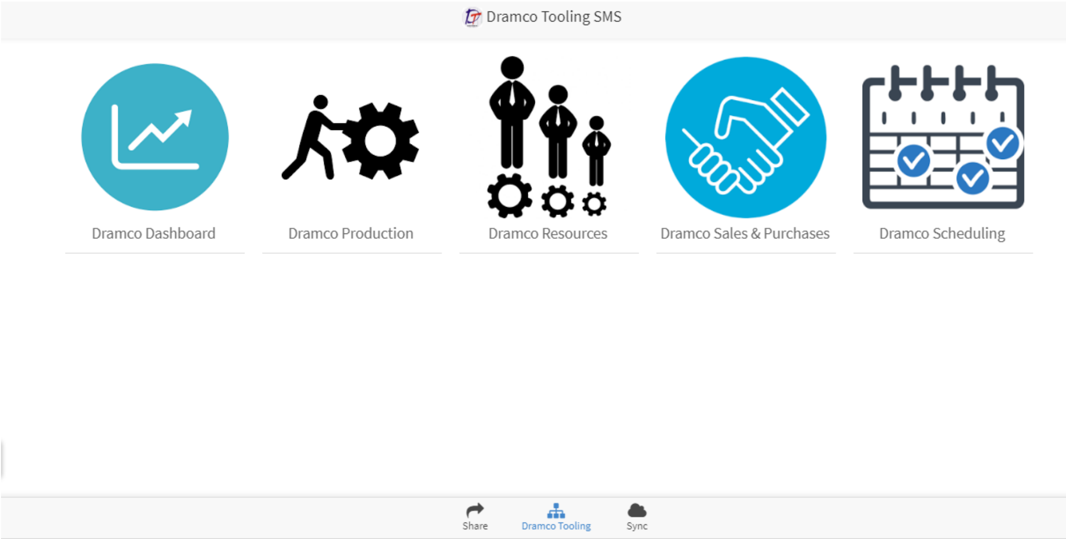
Appendix 6-9: Production Time Sheet entry algorithm



Appendix 6-10: The parts of the Huhtamaki Injection mould

Components and description	
 Bottom bolster	 Die plate
 Strip guider (two required)	 Bridge stripper plate
 Punch holder	 Pressure plate
 Puncher	 Top bolster

Appendix 6-11: Resources module: system user interfaces

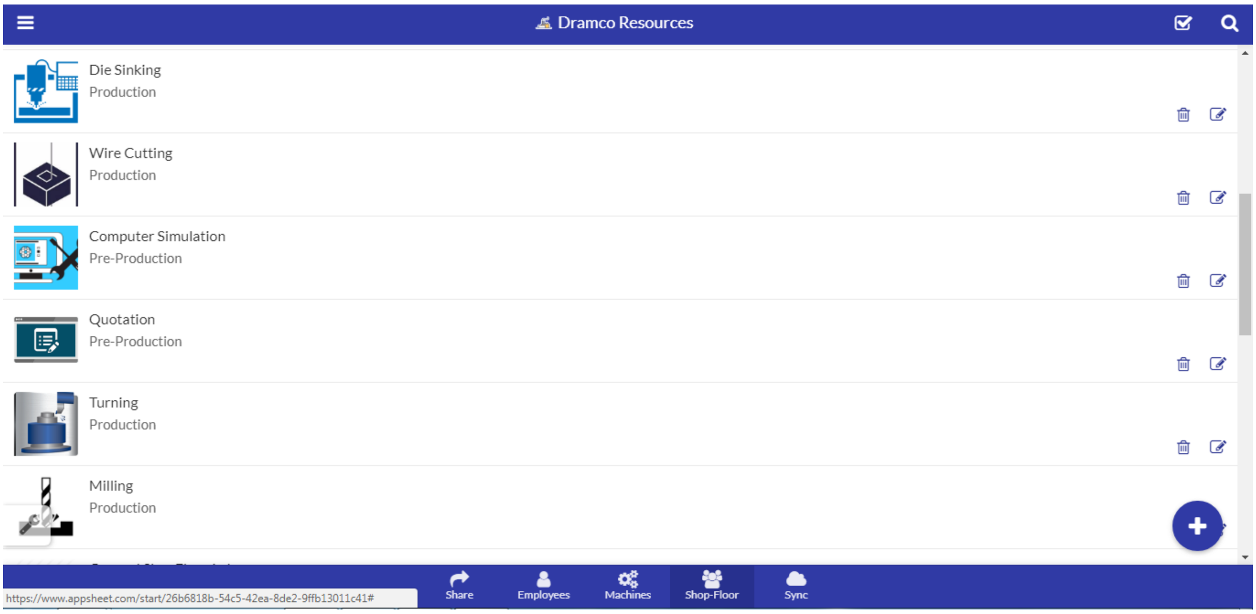


Main Switchboard

The main switchboard allows access to all the other five modules through the icons shown. Users can only access a sub-system if the administrator grants them user permission. In some cases, only the relevant icon is deployed to the user (e.g. toolmakers only receive the Production icon for access to the Production sub-system).

Machine details update

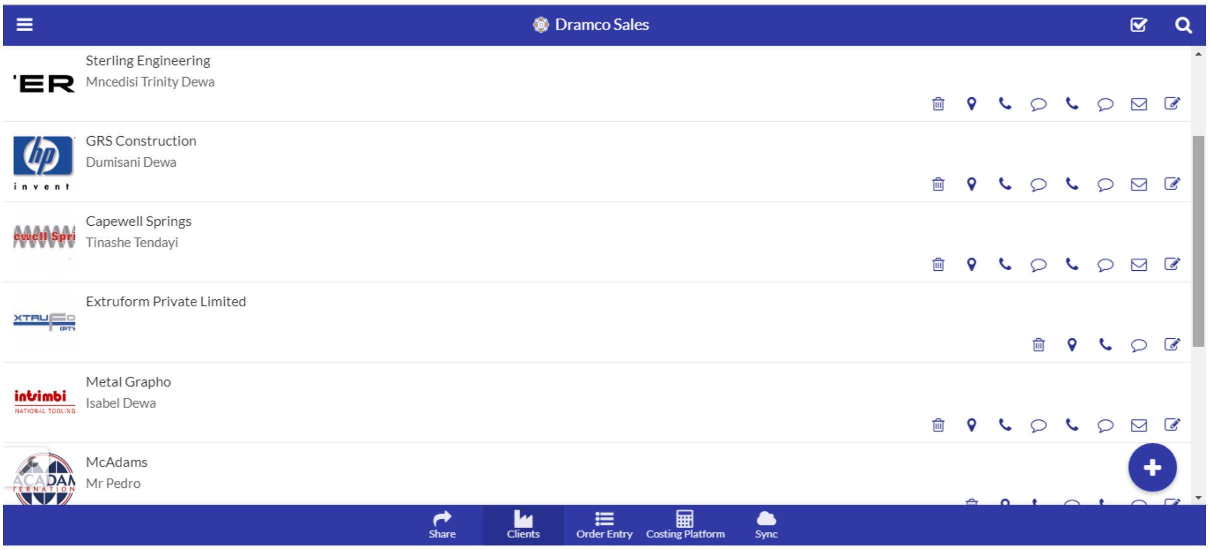
This interface allows for update available machine details. Entries include: machine types and the hourly rates for each resource.



Shop-floor operations update

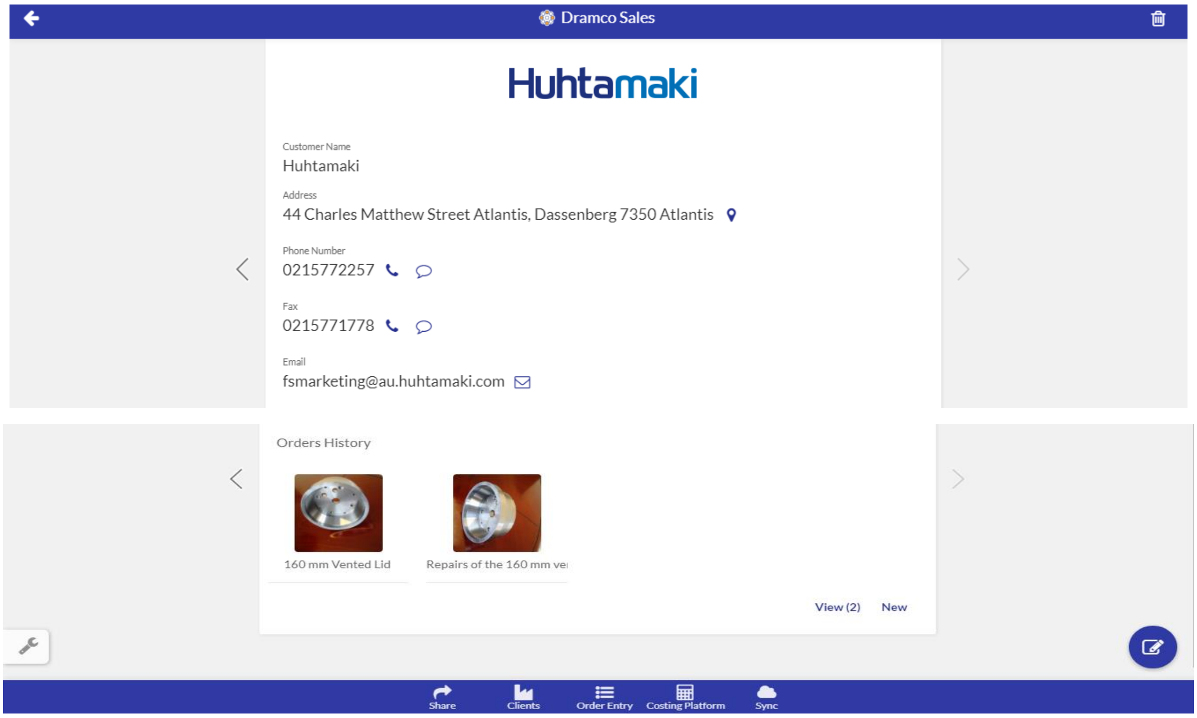
This interface allows for users to define the operations conducted on parts in a tooling environment. These operations will then be used during the cost estimation and scheduling phases processes.

Appendix 6-12: Sales module: system user interfaces

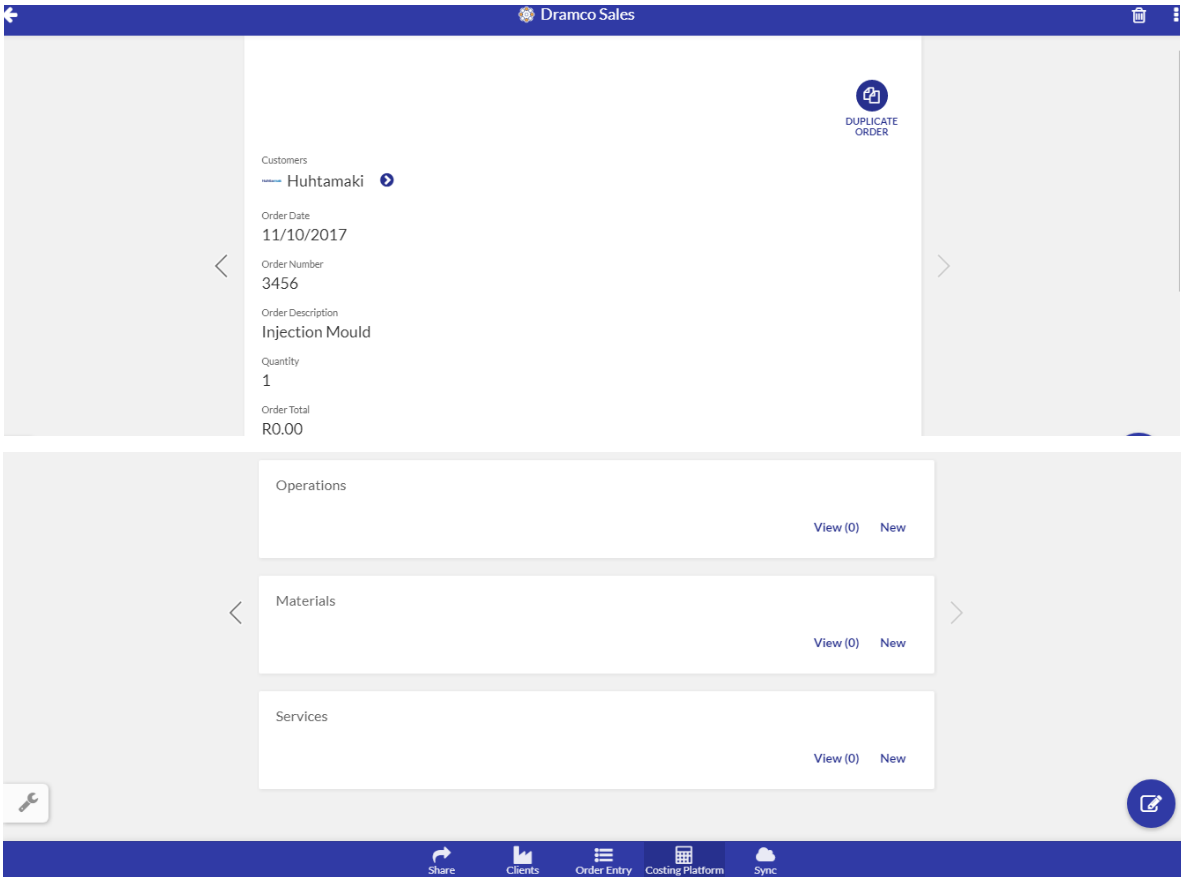


Customer details update

This interface allows users to define all Customer details. Upon clicking on a specific customer, users can obtain information about the customer and a history of all orders placed by the customer as shown below (example of the Huhtamaki customer details).

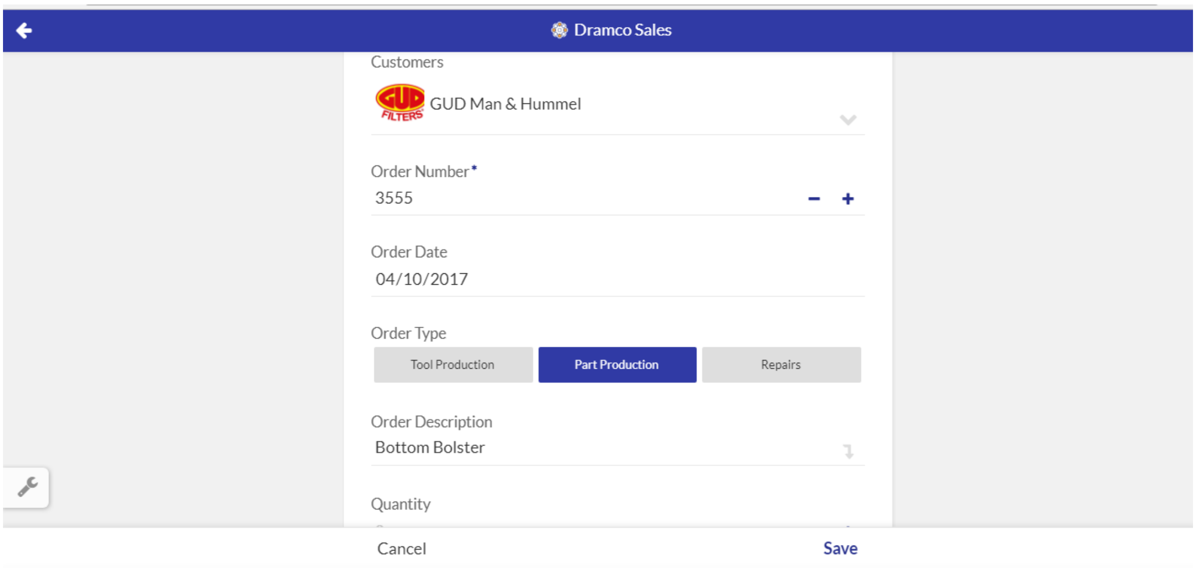


Customer Details update



Cost Estimation Platform

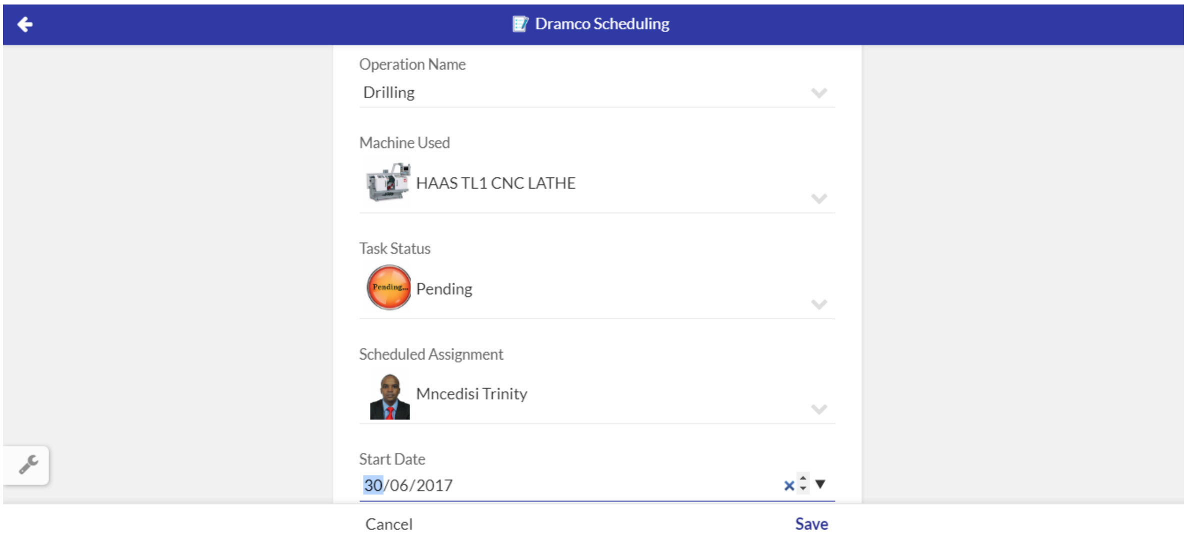
This interface allows cost estimators to define the operations, materials and services required for a job. The decision algorithms for these processes are illustrated in Appendices 6-5 to 6-8. The estimated price for an order is automatically generated as the user defines the operations, materials and services. Upon completion of the task, an automated email is sent to the cost estimator. The email will be having attached files of the quotation and invoice which can be sent to the customer.



Order Entry

This interface allows users to define an order according to customer specifications.

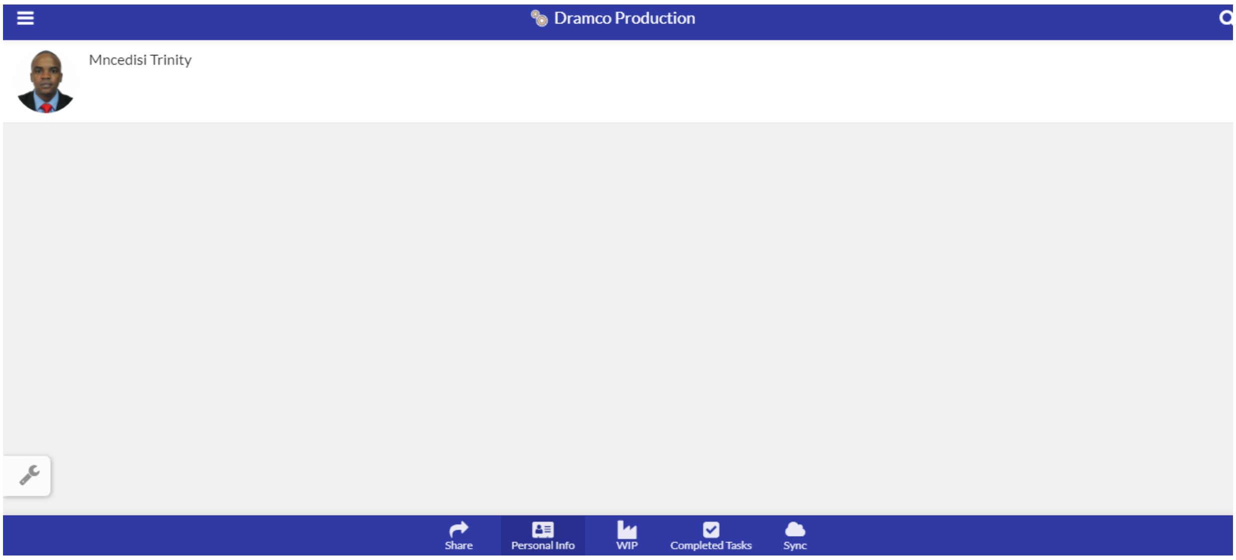
Appendix 6-13: Scheduling module: system user interfaces



Scheduling Interface

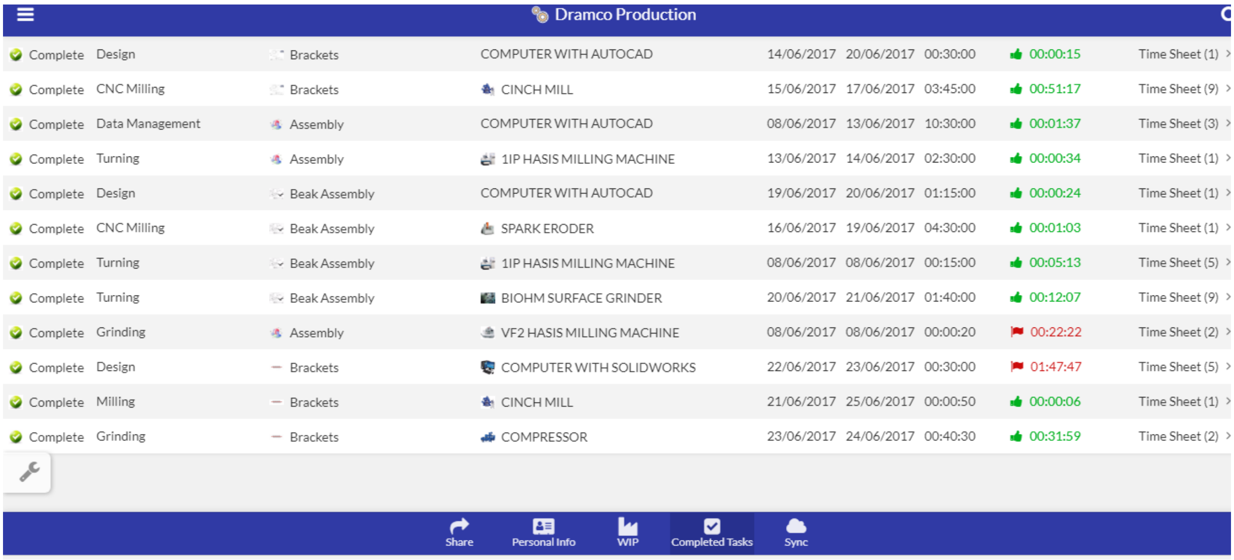
This interface allows process planners to assign tasks for approved orders to workers. Start dates and end dates are also defined for each task.

Appendix 6-14: Production module: system user interfaces



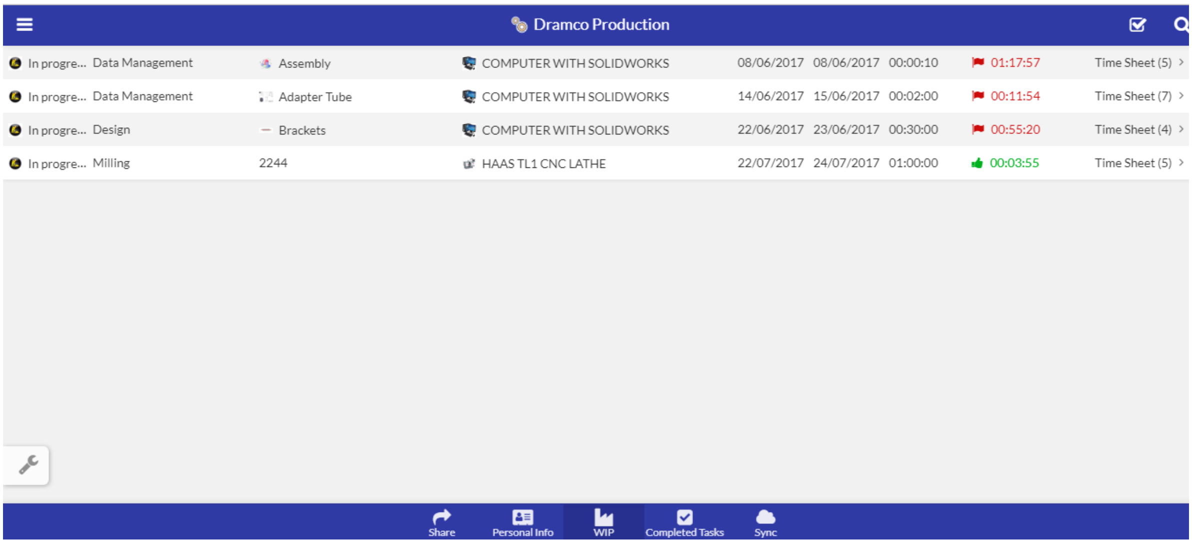
Toolmaker details

This interface allows workers to see their personal details as recorded by the Human Resources department. It is used to ensure that workers are only obtaining information related to their tasks.



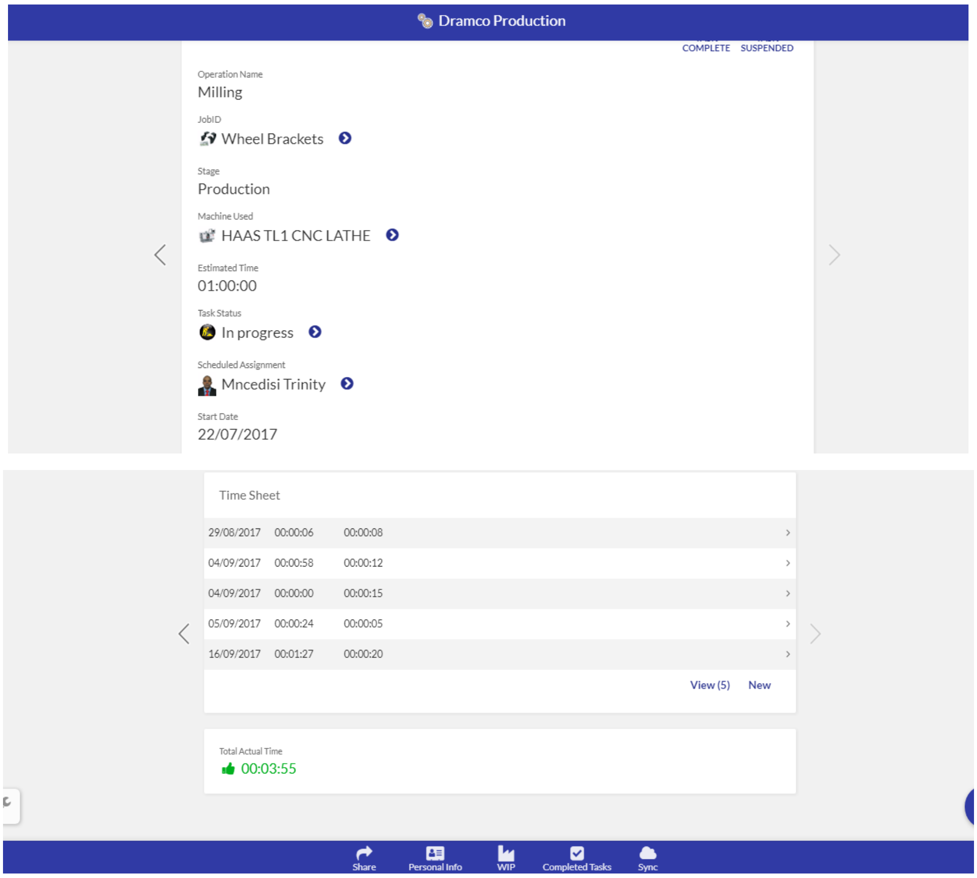
Completed tasks

This interface allows workers to see a history of all the tasks they completed.



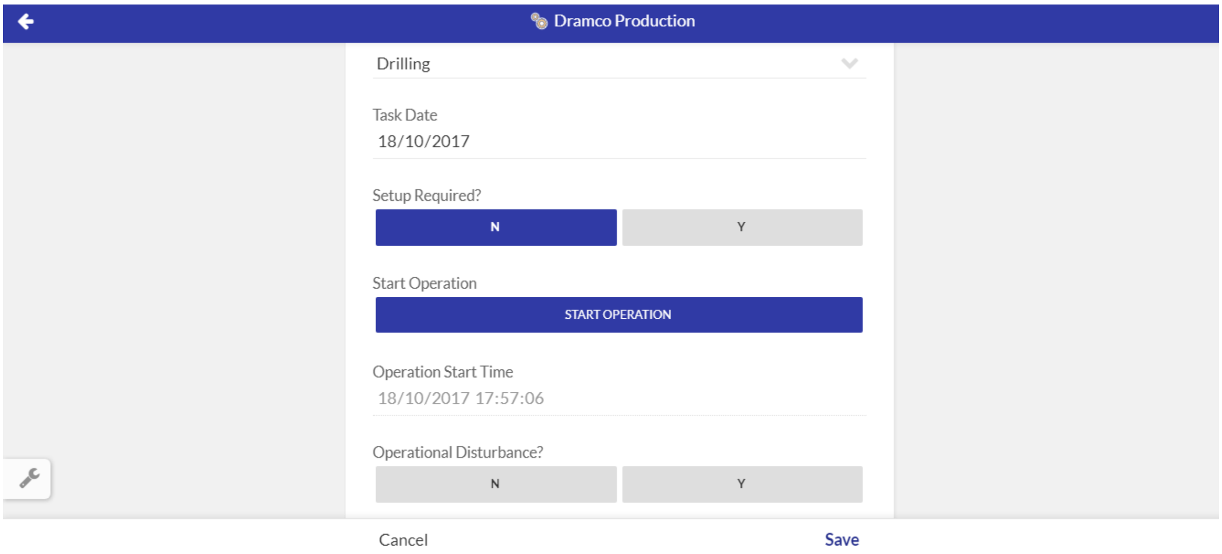
Work-In-Progress and task status update

This interface shows the worker the pending tasks assigned to them. Upon clicking on a task, workers can make the time sheet entries while conducting the task. Since workers login using their private details (password), each worker can only see tasks assigned specifically to them. Upon clicking on a task, the user can see the task time sheet update view shown below.



Task Time Sheet Update Screen

For each task, workers can see the actual time spent and compare it with the estimated time. Upon clicking on new, a new time sheet entry for the task can be conducted.



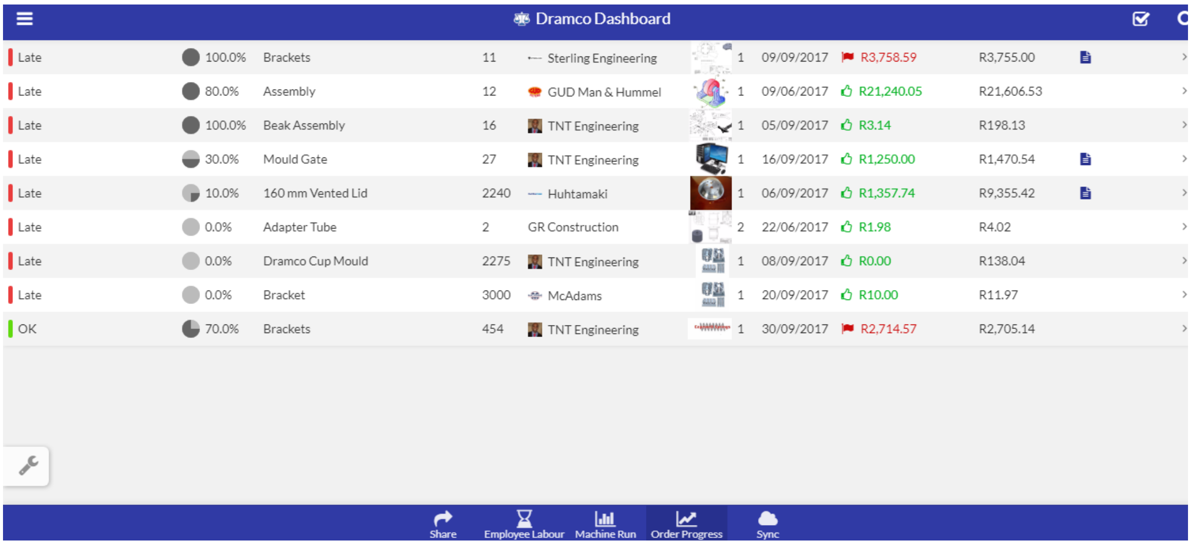
Time sheet entry

Workers use this section to define different timestamps while doing a task. The algorithm logic for this interface is illustrated in Appendix 6-9. Workers define timestamps for start and finish times for:

- Set-up;
- Actual operation; and
- Disturbances.

In cases of disruptions, workers also define (select) the cause of the disturbance (e.g. load shedding, power cut, machine breakdown etc.).

Appendix 6-15: Dashboard module: system user interfaces



Dashboard - Order Progress Dashboard

This interface allows top managers to see the progress for each job. Information on the order progress, actual vs estimated costs and due date conformance is granted in real time.

Appendix 6-16: Benchmarking visits (McEwan, 2016)

Page 6 WCTI NOVEMBER NEWSLETTER

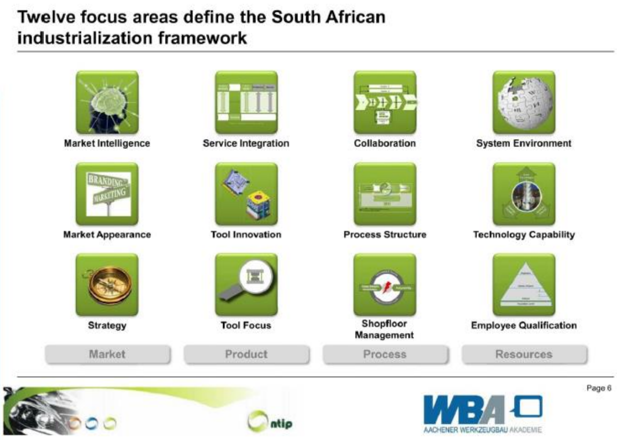
NTIP/WBA INTERVENTION PROJECTS

Intervention Projects have recently been implemented in Bowler Plastics and Dramco Tooling by WBA/NTIP through the WCTI. These intervention projects were based on the results of the Benchmarking Exercises which had previously been conducted by WBA/NTIP in each of these companies.

As a result of the many benchmarking exercises undertaken by WBA/NTIP in South Africa, twelve focus areas have been identified for the South African tooling industry as shown below, from which 3 or 4 critical areas of improvement are identified for each company undergoing an intervention project.

The intervention projects consist of 2 ½ days per company, of intense analysis of the current situation and defining action steps which can be implemented in order to improve efficiencies and competitiveness. This is done as a team consisting of representatives from the WerkzeugBau Akademie (WBA), the National Tooling Initiative Programme (NTIP), and personnel from the company.

Once the initial exercise is complete, then the company continues with the implementation process, with support from WBA, NTIP and the WCTI.



Quote from Riedwaan Roberts - Toolroom Forman at Bowler Plastics: *"The Benchmarking and Intervention Project has given us the opportunity to take a good look at ourselves and to start to implement the improvements which we had wanted to do, but had not yet got around to doing. The assistance from the WBA and NTIP has been a good catalyst for us to start our improvement process"*

ANY COMPANY WISHING TO PARTICIPATE IN FUTURE BENCHMARKING AND INTERVENTION PROJECTS, PLEASE CONTACT THE WCTI OFFICE.

From Left: Jens Helbig (WBA), Robyn Dramat and Lionel Dramat (Dramco), Megan van Aswegen (NTIP), Jan Wiese (WBA), Mncedisi Trinity Dewa (USB), Kevin Dramat (Dramco), Ryan Cairns (NTIP), and Michael Gwebu (NTIP)

From Left: Dirk Lumpp (Bowler), Megan van Aswegen, Jan Wiese, Jens Helbig, Michael Gwebu , Riedwaan Roberts (Bowler) and Ryan Cairns

Dramco Tooling cc | ntip NATIONAL TOOLING INITIATIVE PROGRAMME | WBA Aachener Werkzeugbau Akademie GmbH | Bowler Plastics (Pty) Ltd

Appendix 6-17: Validation testimonial (McEwan, 2017)

Issue 29
May 2017

WESTERN CAPE TOOLING INITIATIVE

NEWSLETTER

this issue

Foreword from CEO

Welcome to this Newsletter which is being published at an interesting time in our history in South Africa.

As we watch some of the political moves and try to comprehend what the downgrade to "Junk Status" really means for the local manufacturing industry, it is very interesting to note the outcomes of the recent NAACAM show which was held in Durban. To quote Mr Dave Coffey, NAACAM President, "*...want to take a few minutes to reflect on where we are going as an industry. It is important for us to understand that this is a sector that not only has the potential to deliver significant business gains, but just as importantly can contribute to solving some of the economic challenges as faced by our country. These include being used as a lever to address poverty, unemployment and inequality.*" Although we do not have a large automotive sector in the Western Cape, we do have some large players in the sector and there will definitely be opportunities developing in the sector for Western Cape businesses in the future. We are reporting on the NAACAM show in this Newsletter.

In line with our theme for 2017, of focusing on Technology developments and Matchmaking, we will have a presentation on PLM (or Intelligent Engineering) at our May Networking and also on cross border shipments of products from the Western Cape to potential African markets.

The presentation on PLM is being given by Mr Gary Longshaw of Intrinsys Intelligent Engineering, who are also the sponsors of the May Network Evening. We thank Gary and his team for this support. We have included an article in this Newsletter regarding using intelligent engineering to address the challenge of Industry 4.0, for your information.

We are also including an overview of a "shopfloor management system" which is being developed by Doctorate student, Mncedisi Trinity Dewa in conjunction with the WCTI, Stellenbosch University, Dramco Tooling and Dennes Engineering. We plan to present this system in more detail at our August Networking Evening.

We have a number of our TDM Powered Artisan students completing their training during the course of this year, and we are encouraging businesses to employ these well trained young people. Please see more details in the article in this Newsletter.

We trust that you enjoy this edition of our Newsletter and find it informative.

John McEwan, CEO: WCTI
johnmc@wctiweb.co.za

Phone: 021-931-0070
Fax: 086-649-1061
E-mail: bell@wctiweb.co.za

Facilitating Economic Opportunities

Development of Shop-Floor Management System (SMS)

Doctorate student, Mr Mncedisi Trinity Dewa, is currently developing a shop-floor management system in response to the concerns raised by many toolmaking companies and the findings of the benchmarking process in a number of companies with regard to costing, data capturing, scheduling, accuracy of quoting, time to quote, etc. this is being developed in conjunction with Mr Kevin Dramat of Dramco Tooling and in consultation with Mr Don Nash of Dennes Engineering.

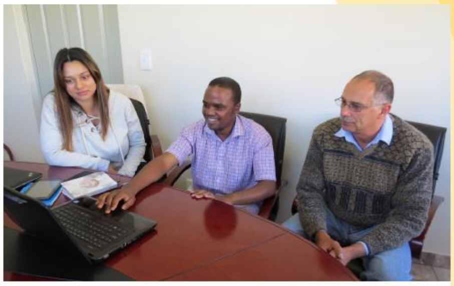
This system will address such elements as the capturing of manufacturing times for each job, the costing for each job, the scheduling of the manufacturing process, tracking of progress, measuring the accuracy of the quoting system, and tracking of on-time-delivery. It will also improve the quoting process.

We plan to have a demonstration system ready for the August Networking Evening.

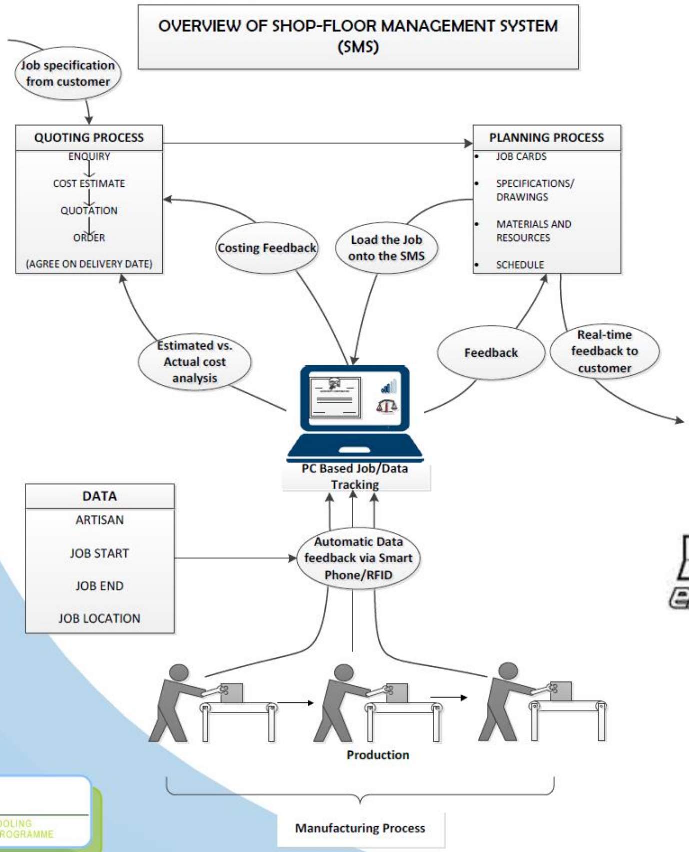
In the meantime, the system will be tested at Dramco Tooling over the next few months, as part of the NTIP/WBA Intervention Project which is being implemented at Dramco Tooling.

Once the system has been finalised and fully tested, we plan to make it available to industry.

Megan van Aswegen and Michael Gwebu of the NTIP who are assisting with the Intervention Project at Dramco Tooling



Trinity Dewa (centre) explaining the system to Robyn and Kevin Dramat of Dramco Tooling



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DENNES ENGINEERING

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Facilitating Economic Opportunities