An Application Protocol for Near Net Shape Technologies Implementation

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Abstract

The adoption of innovative Near Net Shape (NNS) manufacturing technologies can dramatically reduce costs and lead times in established manufacturing processes. However identifying candidate NNS processes and optimizing their implementation is frequently done in an ad-hoc manner without the benefits of a structured process of discovery and assessment.

Motivated by the need for more robust assessment of potential NNS applications this thesis presents a methodology for selecting NNS manufacturing technologies and optimizing their implementation in established manufacturing processes. The literature review highlights a lack of systematic methodologies that support a holistic approach to assessing the impact of an NNS process (in terms of machining time and raw material consumption) on an established manufacturing chain.

The methodology (known as the Near Net Shape Operative(NeNeShO) Protocol) is a three step pipeline that first creates a short-list of candidate processes, before selecting and, lastly, optimising the operational parameters. The first phase (Product Geometry, Manufacturing and Material Matching (ProGeMa3) is a quantitative methodology that selects a set of viable primary shaping process using a unique form of Process Selection Matrix (ProSMa), that associates processes with a range of materials and product geometry they can shape.

ProGeMa3 ranks the candidate processes (using fuzzy logic) by their ability to achieve target product requirements (e.g. tolerances, mechanical properties) in relationship to current process capabilities. The second phase (Differential Cost and Feasibility Analysis - DFCA)

combines technological feasibility (i.e. analytical, numerical or experimental approaches) and economic feasibility (theoretical, statistical derived, analogous cost models) to establish the ability of an NNS process to deliver the specified product requirements. The process models used in phase two are also applied in the third phase (Conditional Design Optimization - CoDeO) and, depending on the selected route, optimization algorithms (e.g. genetic algorithms) or statistical methods (e.g. Design of Experiment) are used to refine the implementation.

Case study applications and existing literature have been used to establish the completeness and effectiveness of the NeNeShO methodology. The resulting NNS selection system is believed to be the only quantitative and systematic procedure that can guide both the selection and optimization of feasible NNS processes in the context of an existing process chain.

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I would like to dedicate this thesis to the memory of Mr. David Cunningham, my second supervisor. His vision and talent were taken away too early from this world.

To my brother, because he will always be at my side.

To my mum and dad, because their happiness is mine.

To my grandparents, because deep in their roots, all trees keep their light.

To my family and friends, especially those who are far away, because their continuous support is the pillar of my strength.

To Alessandra, my north star in the sea of life, because my heart is in her hands.

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Acronyms and Abbreviations

CAD: Computer-Aided Design

CAM: Computer-Aided Manufacturing

CAPP: Computer-Aided Process Planning

CFD: Computational Fluid Dynamics

CNC: Computer Numerical Control

CoDeO: Conditional Design Optimization

CSA: Continuous Simulated Annealing

DE: Differential Evolution

DFCA: Differential Cost and Feasibility Analysis

DFM: Design For Manufacturing

DFX: Design For X

DoE: Design of Experiments

DP: Dynamic Programming

FEM: Finite Element Method

FGM: Functionally Grade Material

GA: Genetic Algorithm

HIP: Hot Isostatic Pressing

HRB: Rockwell B Hardness

HSS: High speed steel

LP: Linear Programming

MIM: Metal Injection Moulding

MRR: Machining Removal Rate

NeNeShO Pro: Near Net Shape Operative Protocol

NLP: Non-Linear Programming

NNS: Near Net Shape

OM: Optical Microscopy

ProGeMa3: Product Geometry, Manufacturing and Material Matching

ProSMa: Process Screening Matrix

RPM: Revolution Per Minute

RSM: Response Surface Methodology

SA: Simulated Annealing

SEM: Scanning Electron Microscopy

SSMC: Semi-Solid Metal Casting

STST: Stainless Steel

TEM: Transmission Electron Microscopy

TS: Taboo Search

UTS: Ultimate Tensile Strength

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Chapter 1

Introduction

Much of manufacturing industries recent development has been driven by society's desire for more individual products and consequently it has evolved to support small, varied and more production runs.

This evolution has resulted in changes to long established industrial methodologies and processes designed to enable mass production. In other words the mass production model, which provided low-cost products through large scale manufacturing, is adapting to support mass customization [Hu, 2013]. Mass customization was enabled by several important concepts and technologies, such as product family architecture, reconfigurable manufacturing systems, and delaying differentiation.

These mass customization methods all recognise that the flexibility of a product's process chain needs to be ensured to enable production of diverse products with different requirements. Because of this models for predicting the process chain behaviour are fundamental to dealing with the rapid changes in requirements and design. Indeed even in the dedicated process chains designed for mass products, the influence of the choice of process parameters on the overall manufacturing performances is very significant (e.g. in a high volume production environment, the influence process of parameters selection on process costs is much higher than in a flexible/batch production environment).

Technology (as well as consumer demands) has also driven changes to manufacturing industry. In the last thirty years, the extensive use of programmable machines and robotic applications has made it possible to fully integrate numerical simulations into production processes and optimization at any stage of the manufacturing chain by enabling virtual environments and in-line process control. Lately, the term Industry 4.0 has been used to describe a fully digital manufacturing process, enabling seamless cyber interaction between the manufacturing components. The aim is to create a virtual clone of the manufacturing process, which can be digitally monitored and manipulated. Currently real time data and prediction models can be integrated into a fully controllable manufacturing environment in some cases. Ultimately this computerization and virtualization of manufacturing will enable another evolutionary step: from mass customization to personalized production [Hu, 2013]. This cybernetic revolution has also coincided with the appearance of new materials (i.e. composites and high strength alloys) and new technological frontiers (e.g. forming of high strength alloys or machining of brittle materials). As a result a whole new categories of processes, dedicated to specific materials or shapes/designs, have emerged and continue to reveal new approaches for specific applications. The dichotomy between the flexibility of the classical processes and the complexity of the new ones is combined in very complex manufacturing and supply chains, particularly for complex applications (e.g. aerospace sector).

Lastly management practises have also impacted on manufacturing industry. In a globalized economy, new concepts about quality management and the design of manufacturing supply chain have impacted dramatically on the competitiveness of industry. Ideas of Total Quality Management combined with the concepts of Lean and Six Sigma have become fundamental tools for aiming both to reduce costs (i.e. zero defects) and to improve quality [Flynn et al., 1995].

Other drivers of efficiency improvement are the increasing cost of raw material and machining processes, which are also combined with the social demands for sustainable processes and reduced environmental impact. In this context, the amount of raw material used to make a product has a great impact on the process energy efficiency. There are many different aspects to be considered, for example: scrap material is a triple loss for the manufacturing process because of: 1) the energy loss of transforming the material scrappage with a primary shaping process; 2) then the loss of energy used for machining out the material; and 3) the energy used for recycling the scrappage. Indeed recycling the scrappage has become both an economic necessity and a frequent request of society. However, scrappage recycling is not a substitute for the optimization of raw material usage and machining time.

These changes and the necessity of working on different materials have made primary shaping process selection a critical phase of supply chain management. Process modelling, process parameters optimization and their ability to satisfy target product requirements, has become a major field of study. However, the selection and optimization of materials, product and process design is rarely structured and often related to researcher/manager intuition [Altan, 2015].

1.1 Near Net Shape Manufacturing

In the last thirty years, the concept of manufacturability has been applied to many different processes in numerous industries. This has resulted in the emergence of several different Design for Manufacturing (DFM) methodologies which have in common the aim of reducing production costs through the application of empirical and knowledge based rules. Near net shape (NNS) technologies have expanded these concepts, targeting mainly primary shaping process, such as casting or forging. The desired outcomes of manufacturability analysis for near-net-shape processes are cost and lead/time reduction through the minimization of process steps (in particular cutting and finishing operations) and raw material savings. Product quality improvement, variability reduction and functionality enhancement (e.g. longer component life) are also achievable through NNS optimization.

Process parameters, product design and material selection are the changing variables in a manufacturing chain that interact in complex, non-linear ways. Consequently, modelling and simulation play important roles in the investigation of alternative approaches. However defining the manufacturing capability of different processes is also a moving target because the various NNS technologies are constantly improving and evolving so there is challenge in accurately reflecting their requirements and capabilities. In the last decade, for example, CAD, CNC technologies and innovation in materials have impacted enormously on the development of NNS technologies. This thesis reviews the different methods reported for NNS manufacturability assessment and examines how they can make an impact on cost, quality and process variability in the context of a specific production volume. The discussion identifies a lack of structured approaches, poor connection with process optimization methodologies and a lack of empirical models as gaps in the reported approaches.

Manufacturing industry is constantly challenged to evolve in response to changing markets and social needs, although for many years the reduction of costs was the only goal. Currently, the growing demand for lower impacts on the environment has also started to drive manufacturing to improve processes, in terms of their sustainability and waste. Consequently the social (rather than economic) demand for the efficient use of resources is emerging as a business opportunity where highly efficient operations, in terms of energy and materials, will also meet regulatory requirements and enable access to high value markets of developed economies.

Given this context, changing manufacturing methods are increasingly motivated by a desire to reduce environmental impact rather than simply an opportunity to improve profits [Ward and Duray, 2000]. The continuous investigation of cost reduction and production improvement technologies has led to the emergence of a generic class of manufacturing technologies known as N**ear Net Shape** (NNS) that can enable the creation of lean, green enterprises

NNS as a distinct subject has its roots in the Design for Manufacturing (DFM) work of Boothroyd and Dewhurst [1983] in the 1980s. Their pioneering work on a systematic approach to Design For Assembly (DFA), directly influenced subsequent approaches to the improvement of process efficiency. For example (Ishii et al. 1989) developed a Design For Injection Molding (DFIM) system which was directly implemented in a CAD system. The knowledge based system was able to screen drawings associated with mechanical components and apply DFIM rules to make suggestions to improve their shapes for manufacturing by injection molding. Many other authors have reported the implementation of similar DFM codes in CAD/CAE system. Following Tateno [1984], Hwang and Stoehr [1988], Mathur et al. [1989], Doege and Thalemann [1989] and other pioneering studies, Altan and Miller [1990] were the first to clearly define the aims and boundaries of NNS design. They first discussed the conceptual design stage where a feasible part/process design is not achieved until a balance is achieved among functional requirements, production volume, part geometry, process capabilities, material properties, tooling requirements, equipment requirements and other factors. Many alternatives need to be explored in this phase, responding to every what-if question. But, they suggest, it is at the detailed design stage, that design for manufacturability needs to be evaluate. Altan and Miller [1990] define three possible forms of manufacturability evaluation:

1. The modifications, or evolution, of a design after the specific combination of material (i.e. its chemistry, psychical and mechanical properties) and manufacturing process is defined.

2. The evaluation of several potential candidate process/material combinations when the component design is fixed.

3. The re-design of a part for a new manufacturing process.

However importantly the authors asserts all these scenarios can be interpreted as requiring a process which will start with an initial representation of the design and then transform it, if necessary, into another part which meets all of the functional requirements and can also be produced [Altan and Miller, 1990]. This insight is fundamental to all NNS methodologies reported in the literature surveyed in this thesis. Chapter 2 charts the evolution of NNS concepts across the last 25 years and recognises distinct streams, or patterns, in the research and also identifies the principal (and most effective) approaches to the investigation of NNS processes.

Near net shape manufacturing is a multi-disciplinary task and consequently approaches are varied and often driven by the nature of the specific application. Although initially the phrase was only used in reference to plastic injection process, the authors who pioneered this field of research [Kudo, 1990, Altan and Miller, 1990, Boothroyd and Dewhurst, 1983] extended NNS concepts to plastic deformation, casting and powder technologies, also providing an implicit justification of many specialist forming processes (e.g. flow forming, hydroforming, SSMC), powder technologies (HIP, MIM) and additive layer manufacturing systems . Indeed today the term NNS is frequently used to convey the generic capabilities of manufacturing technologies that distinguish them from systems that aim to deliver finished components. The literature also highlights that NNS has been associated with the creation of advantageous processes and material combinations for particular designs whose form has been manually tailored for that purpose. This thesis propose a new definition of NNS: **Near Net Shape manufacturing is a relative, rather than absolute, propriety of a combination of product geometry (to be produced), material and manufacturing process that delvers production targets while minimizing raw material utilization and finishing machining operations in comparison with alternative combination of processes.**

1.1.1 Benefit of the NNS approach

As mentioned, the global desire to reduce energy, material consumption and emission continuously push companies to adopt more automated techniques in their process operations to eliminate wastages and maintain productivity in the face of variable demand.
In this context, NNS main targets consist of eliminating (or at least confining to the finishing steps) the machining operations and reducing raw material usage for an existing process. With these aims, the following three main variables and their correlation determine the final effect [Altan and Miller, 1990]

- Manufacturing process chain design (including primary shaping process selection and chain process parameters setting)
- Material selection
- Product design

As pointed out by several authors (e.g. Cominotti and Gentili [2008]) the NNS application advantages consists of:

- Cost reduction impact (e.g. material wastage and machining).
- Increasing efficiency (e.g. reducing machining steps).
- Reducing variability and so increasing quality (i.e. by shortening the manufacturing chain).
- Batch manufacture of multiple components in a single piece.
- Faster production and low welding, connection and assembly operations (reducing the possibility of mistakes).
- Possible reduction of lead-time.

- Improving technological characteristic.

However although there are common features of NNS processes it should be noted that the quantification of these impacts is dependent on the application.

1.1.2 Challenges

Many authors who ahve investigated NNS technologies have reported using various form of differential analysis in their research, for example [Witulski et al., 1994, Morita et al., 1991]. Similarly studies of different combinations of processes and product designs [Bewlay et al., 2003] or even different combinations of processes, product designs and materials [Cominotti and Gentili, 2008] have been reported. The comparison criteria reported include process economics [Cominotti and Gentili, 2008] and technological output evaluations [Witulski et al., 1994, Morita et al., 1991, Bewlay et al., 2003]. The technological output evaluation considers product quality, product conformity and the generic proprieties (e.g. part weight, required final product features). The latter are final product characteristics which are not described as quality or conformity requirements (i.e. depending on the specific product application). Manufacturing engineers are frequently asked to select the best process for creating components, but often the judgement is qualitative rather than quantitative. For example in recent years, the application of additive layer manufacturing technologies has increased dramatically, although the resultant product characteristics of these process have not been fully investigated in many applications. Similarly the casting/forging dichotomy is usually approached in a qualitative rather than quantitative manner; furthermore, the analysed processes are often limited to the classic forging (e.g. impression die forging, open die forging) and casting procedures (e.g. sand casting, die casting) without taking to consideration innovative processes (e.g. hydroforming, flow forming). The latter are always confined into their original and niche applications, limiting their potential, because of a lack of knowledge or quantification of their capabilities.

Furthermore the interaction between material, process and material design is often very complex, both at the process selection, chain definition and process parameters selection stages. For this reason, many of the authors exclude some of these interactions and focus only on the investigation of specific fields, thus losing the holistic view of the overall process chain. The few authors who have approached this problem in a systematic way (as examined in Chapter 2) often analysing the problem in a qualitative way or limit their investigation to a single application. The demand for customization of products has impacted drastically on the process parameters definition and process design. For example, the capabilities of process simulation and material characterization has enabled the forming processes and products to be customizable. Some properties, such as fatigue resistance, can be set in the forging process operation by changing the process parameters and so consequently control the microstructure [Tekkaya et al., 2015]. This level of control is possible only when models can replicate thoroughly the mechanics of processes and materials. This level of knowledge is not often available or generalizable to every process because of the material/process combination adopted and modelling complexity.

1.2 Research Pathway: Gap and Aims

1.2.1 Research Gap

The complexity of the interaction between process, material and design, constrains the possibility of modelling these relationships and consequently "Near net shape is not a formal theory and cannot exist without an application"[Altan, 2015]. This point of view, creates the necessity of finding applications on which the variables relationships can be modelled and optimized. This is the first challenge that the NNS approach tries to solve. Ideally the NNS approach needs to act on an existing process line (i.e. case study), in order to quantify the impact of a potential change in process, material or product design changes.

In many of the research papers, NNS is not treated as a general approach but a process attribute. In industry, some processes are called NNS when they are dedicated to a certain design or materials (e.g. flow forming of rocket nozzles made in high alloy steel). For example, the additive layer manufacturing processes became NNS by definition. In certain ways, this contradicts the NNS primordial definition: the implicit raw material and machining saving are often achieved without taking into consideration the product requirements (i.e. achievable by the usage of other processes) and process current performances (e.g. lead time) as well as its optimization. Likewise, this definition does not take into consideration the process and product interaction with material. When considering the possibility of changing a process, the impact on a products design and material also need to be validated through feasibility analysis. This validation depends on the variables to be changed (i.e. process chain parameters, material and design attributes) and the correlation between them. This thesis presents a solution to this problem using a method that combines differential analysis (i.e. economic feasibility), material, design and process feasibility analysis (i.e. technological feasibility). The selected material, the process design and the nature of the primary shaping process influence the choice of feasibility analysis method. The feasibility analysis should be able to assess the practicality of producing the needed requirements with the new variables (i.e. process, material and/or product design) configuration.

Process and product design optimization are often treated separately by researchers and consequently no systematic approaches have been reported which connect the feasibility models, either technological (analytical, experimental or numerical) or economic (theoretical, analogous, statistical), with optimization methodologies.

Similarly no general framework or holistic methodologies have been reported by researchers which guide practitioners (or academics) in the application of NNS approach, including the selection, feasibility and optimization stages.

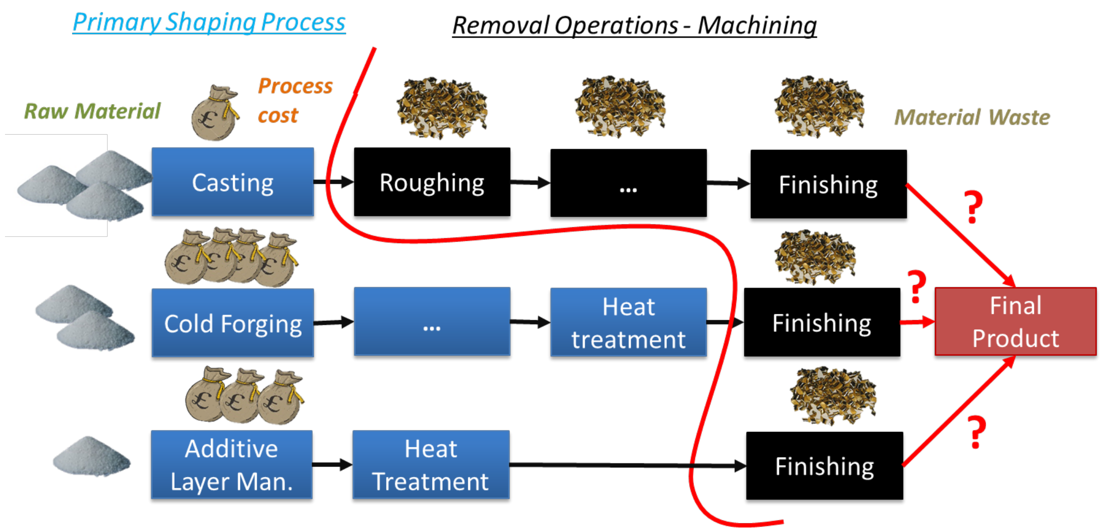


Figure 1.1: Primary shaping process change: impact on the manufacturing line.

1.2.2 Research Aim

In the context of a NNS process for established manufacturing lines, the possibility of changing the primary shaping process needs to be considered first. Figure 1.1 illustrates the impact of a new primary shaping process on the manufacturing chain. The schematic shows that raw material required (i.e. cost and usage), process cost and machining needs for reaching the final product (i.e. material waste) is different depending on the primary shaping process (i.e. in this case alternative casting, forging and additive layer manufacturing processes are considered). The final product of each of these potential NNS process chains needs to converge to the final product requirements.

The aim of this research is to enable the systematic assessment of potential NNS methods in the context of an industrial environment, thus enabling the feasibility of adopting new primary shaping process for existing products to be established and its application optimized.. The investigated processes include casting, forming and additive layer manufacturing processes, with the scope of materials considered limited to metals and their alloys.

In other words the aim is to create a methodology that can determine quantitatively the best primary shaping process and material for a particular production task where the component shape and production volume are the input parameters. Such a systematic methodology should also be able to assist the selection of material and primary shaping processes using a knowledge of a product's characteristics and requirements, thus connecting them with the material and process capabilities.

Such a methodology would also allow potential reductions of machining and raw material consumption to be quantified in parallel with evaluating the economic and technological feasibility of the a NNS process. The technological feasibility of different approaches needs to be done relative to existing research and available models. Likewise the economic feasibility needs to be linked with the previous investigation, in order to use technological data for estimating cost. The economic and technological models need to verify the requirements and the production targets are achievable for any candidate process. A systematic method should guide the selection of the investigative approaches, building the technological feasibility model for understanding if the NNS process satisfies the component requirements, as well as connecting this model with the manufacturing chain cost models (i.e. including the primary shaping and machining processes).

Such models (describing the primary shaping process and the rest of the manufacturing chain) can be systematically combined with optimization methodologies so these combinations can optimize the selection of product design and process parameters in parallel. The number of variables to be optimized depends on the models used, although a general optimization strategy can be formulated for NNS chains. The choice between single, or multi-criteria, optimization depends on the process nature, however the global cost should always be one of the targets. The manufacturing chain model should be composed of the primary shaping process and the machining models.

In conclusion, the research aims to provide a systematic approach to researchers or practitioners, who aim to

1. Change the primary shaping process (NNS process) or material of an existing component's production process, (i.e. to save machining operations or raw material).

2. Evaluate feasibility of a potential NNS process investigation approach (i.e. for both technological and economic feasibility), in comparison with product requirements and production targets.

3. Determine the product and process design optimization methodology for the selected conditions

These aims are associate with the objective described in Sub-section 1.2.3.

1.2.3 Research Objectives

1. Build a holistic and quantitative methodology able to investigate a components **manufacturing process chain**, with the aim of proposing the NNS primary shaping processes for the selected material and product's requirements.

2. Build a holistic and quantitative methodology for assessing the feasibility of **applying a new process**, both technologically and economically, depending on the process nature, product requirements and productivity targets.

3. Build a holistic methodology for **optimizing** (single or multi-objective optimization, using cost as first optimization target) the process parameters and production design, by selecting an optimization methodology (depending on the primary shaping process nature and existing investigations).

4. **Connect systematically**:

    - Process/material selection and process modelling.

- The technological and economic modelling for a manufacturing process.
- The process investigation method with manufacturing chain modelling and its optimization.

1.2.4 Research Question

Inherent in these objectives are the following research questions

- How can a primary shaping process and material be systematically varied in an existing process chain to creating a NNS process chain?
- How can the technological and economic feasibility of a new process be systematically assessed depending on the product requirements and production target using a NNS approach?
- How can process chain and product designs be systematically optimized by selecting the optimization approach and modelling the process chain using developed process models (i.e. including economic models)?
- Can a quantitative methodology be developed for applying NNS techniques to existing manufacturing lines?

1.2.5 Research Significance

The "contribution to knowledge" of this research would partially fill the identified knowledge gap in NNS research (Sub-section 1.2.1). The systematic approaches also have the potential to impact on the case study companys manufacturing processes in the following way:

- Application to case study company: identifying potential components in relation with requirements and targets of a multi-national corporation.

- First holistic framework for process/material selection, process feasibility and product/process design optimization based on NNS approach.
- Systematic and holistic protocol for process feasibility and investigation methodology selection, including the connection between economic and technological models as well as connection between investigations and product requirement and production targets.
- Systematic approach to process and product design optimization based on stochastic algorithm and statistical experimental approaches.

The possible outcomes of this research are:

- Academic: contribution to knowledge through academic literature production (i.e. conference papers, journal articles and thesis).
- Industrial: enhance the case study company's implementation NNS manufacturing.
- Praxis: a formal protocol that can be used by practitioners and researchers.

1.2.6 Research Methodology

Figure 1.2 shows a flowchart that gives an overview of the investigation's research structure is presented.

The research approach can de defined by its ontology [Easterby-Smith et al., 2012, Bryman, 2008], mode [Duffy and Cotts, 2014, Buckley, J. W. and Chiang, 1976], strategy [Buckley, J. W. and Chiang, 1976, Yin, 2003] and technique [Kohlbacher, 2006]. The used ontological approach is objectivism [Creswell and Miller, 1997, Easterby-Smith et al., 2012]. The selected mode is deductive, because the approach attempt to validate theory and test its applicability to a specific problem [Gill and Johnson, 2010]. The strategy approach used is analytical (by the use of internal logic to break down the problem into its component parts in order to discover its true nature and the causal relationships among variables [Duffy and Cotts, 2014]), because inside every phase of the developed framework the relationships between material, process capabilities and design (including parameters) and product design need to be developed.

For developing it, two techniques are used in this research: case studies and mathematical modelling. Mathematical modeling is the process of using various mathematical structures represent real world situations. The mathematical models are used for acquiring the case studies and in the case studies itself. Case study research design can consist of single, or multiple, case studies.

in this case, the developed methodology (operative protocol) is tested on multiple case studies, aiming to evaluate its capabilities in different applications. The reason is to explore the diverse procedures (or routes) developed for different investigative approaches, whose selection depends on the NNS process. The scope of the case studies is to test the validity of both the overall protocol and its individual stages on existing industrial lines. To do so, manufacturing lines of existing components from a case study company (The WEIR Group PLC) are analysed using the developed NNS methodology. Analysing WEIR's product portfolio, three case studies are developed for proposing alternative NNS processes. After selecting the process, the methodology identifies possible routes for assessing process application and optimize process and product design. The methodology associates identified technologically feasible approaches (analytical, numerical and experimental) with economic modeling, and subsequently optimisation techniques (numerical and statistical) based on their minimization.

Investigative results are evaluated qualitatively, in terms of comparison with existing approaches from the literature, and quantitatively, in terms of the effectiveness of NNS application.

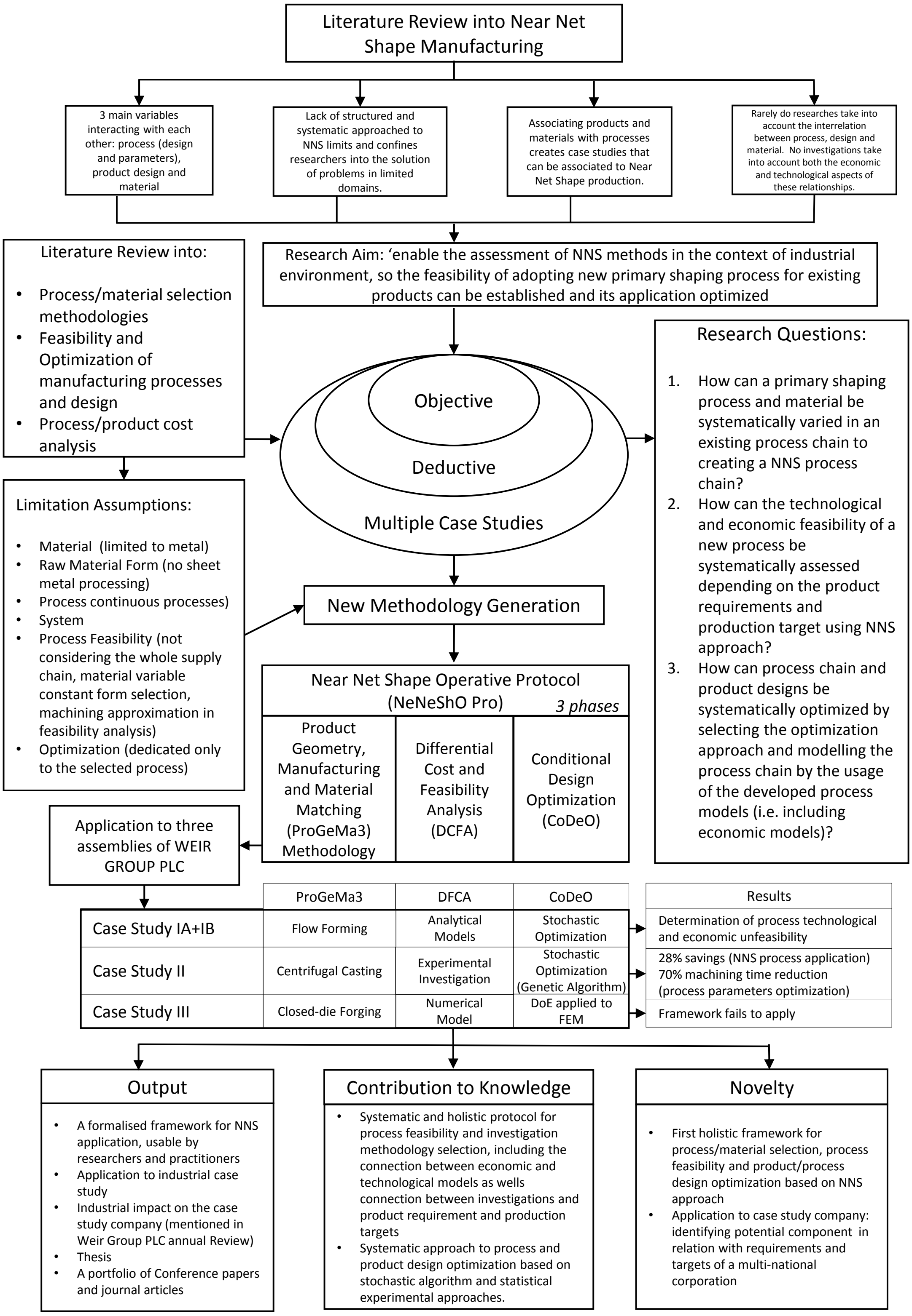


Figure 1.2: Flowchart giving the overall structure of the research.

1.2.7 Limitations Assumptions

The following assumptions (limitations) have been made to limit the scope of the research aim and objectives and ensure they are achievable with the time and resources available.

- **Material limitation**: the materials class investigated need to be limited to metal and alloys. Although Adding ceramics, polymers and composites could expand the framework and generalize the approaches, it would also require many more connections between process, material and designs to be taken into account.
- **Raw material form limitation**: similarly, sheet metal production has not been considered. Only solid metal (e.g. bulk) components products (e.g. regular stock round, bar or tubes and the derived complex geometries) have been investigated. The main reason for this limitation is that the metal sheet production has a series of dedicated processes, which have to be considered separately (e.g. Incremental Sheet Forming or Superplastic Forging) because of their unique applications.
- **Process limitation**: the manufacturing process search need is limited to casting, forming and additive layer manufacturing (Appendix B) associated with bulk metal forming. The only exclude manufacturing process are the continuous production processes (e.g. continuous extrusion, rolling)
- **System limitation**: although the material and process selection both need to be used, the level of complexity and interactions between processes variants and materials mean that the selection need to be made separately. The material selection need to be done prior to the process selection. The process selection uses the selected material as an input. The selected material has influence on the process selection, although after its selection it is considered as constant.
- **Process feasibility limitation 1**: in the process selection, steps involving feasibility

analysis and optimization step, supply chain management (e.g. using a different supplier) is not considered. Similarly, the production output is assumed to be constant, even considering with a possible quality enhancement (i.e. not considering a derived increasing of selling).

- **Process feasibility limitation 2**: material interaction has been considered in the feasibility phase (i.e. feasibility depends on the selected material), although it has been considered only in cases where the primary shaping process can be modelled analytically in the optimization phase.

- **Process feasibility limitation 3**: feasibility cost model needs to consider machining contribution on cost (if needed for reaching the final shape. An approximated cost can be derived on a simplified model based on volume difference (between pre-machined and final geometries) and removal rate. In the subsequent optimization phase, complete machining model and parameters can be formulated for decreasing costs and reaching optimization targets.

- **Optimization limitation**: the design and process optimization is limited to the selected case. This optimization is conditioned by previous selections and can be only relative to specific variables combinations (i.e. process, material and design), approaches and models selected. Process investigation and optimization techniques used for selection need exploit previous reported investigations and literature.

- **Search space (optimization) limitation**: the machining is assumed to be done on components in NNS manufacturing condition. In this condition, the finishing operations (e.g. finishing turning) are considered to remain constant during the systematic variations of product design and process pentameters (i.e. NNS process and design optimization). This assumption can be made because the search space of the optimization functions (i.e. selected range of the variables) is close to the current design variable set. In particular, the search interval for every design variable to optimize is a neighbourhood of the current dimensions, constrained by other design factors (e.g. non-interference or proximity to other components in th assembly).

1.2.8 Research Hypothesis

Given the limitations assumptions stated in this chapter, the research hypothesis can be stated as: "It is possible to define a holistic methodology, limited to metal and bulk components, for selecting a NNS process, given the material, the component design and product requirements. in such a methodology, the technological and economic feasibility of adopting a new primary shaping process for existing products can be established by selecting the appropriate investigation methodology and modelling method. Furthermore the selected model, the process application and product design can be optimized, using statistical and numerical methodologies."

1.3 Thesis Structure

The thesis' structure is composed of the following sections

- Chapter 1 - Introduction: In this chapter, the evolution and current status of manufacturing industry is briefly discussed. Then the main concepts and definitions of NNS manufacturing are introduced and the seminal academic literature on the subject identified. The chapter also introduces the research path and gives an initial statement of the works aims and objectives (i.e. they will later be adjusted in the research methodology chapter to take into consideration the literature review outcomes). The research questions and possible outcomes are then formalized. The chapter defines the applied research approach and the limiting hypothesis to be applied for limiting the research scope. In its conclusion the chapter gives a complete overview of the thesis structure as a roadmap for the reader.

- Chapter 2 - Literature Review: this chapter reviews the literature concerning NNS and synthesize the approaches and outcomes presented subsequently. A review of process/material selection, feasibility/optimization of manufacturing processes and product costing approaches is also presented. The aim is to define the pillars and fundamentals concepts on which the thesis stands.

- Chapter 3 - Near Net Shape Operative (NeNeShO)Protocol: in this chapter, the proposed methodology is detailed in its three phases: Product Geometry, Manufacturing and Material Matching (ProGeMa3) Methodology, Differential Cost and Feasibility Analysis (DCFA) and Conditional Design Optimization (CoDeO). The details of each are described in the associated sections.

- Chapter 4 - Validation: Product Geometry, Manufacturing and Material Matching (ProGeMa3) Methodology Application: the developed framework is applied to the case study company. The ProGeMa3 methodology is applied the case study company's productions, associating existing components to new NNS manufacturing processes. Four case studies were developed, applying three NNS manufacturing processes.

- Chapter 5 - Validation: Case Study IA and IB - Flow Forming of Valve Seat and Riser Pipe.

- Chapter 6 - Validation: Case Study II Centrifugal Casting of Valve Cages.

- Chapter 7 - Validation: Case Study III Closed-die Forging of a Valve Body.

- Chapter 8 - Discussion: in this chapter, the developed case studies are evaluated qualitatively. The framework is evaluated comparing it with other existing manufacturing methodologies. All three parts of the framework are individually compared to similar systematic approaches present in literature.

- Chapter 9 - Conclusions

Chapter 2

Literature review

The first section of this chapter reviews the last thirty years of academic research into to NNS manufacturing of metal. It starts describing the review methodology and research areas. Given the wide range of technologies and techniques, the review synthesis identifies six research classes of NNS investigations: process innovation, process design, product design, material characterization, differential analysis and applied framework. The NNS investigations are categorized in these different classifications and the general research trends are discussed (i.e. concluding remarks). The review identify knowledge gaps in NNS research, in particular regarding the quantitative methodologies for process selection, feasibility and optimization. In the second section, a literature review investigating process and material selection is presented. Methods for assessing the feasibility and optimization of manufacturing processes are also reviewed to determine appropriate approaches employed. Methodologies of product costing classification and some examples are also presented in the same section. The aim is to identify the main approaches that can be used for developing a quantitative methodology for NNS process selection and implementation.

Table 2.1: Articles searching and selection strategy

Search words		*Refined by*		*Time span*	*Articles number*	*Search Engine*
All fields		*Subject Areas*	*Topic*			
Near Net Shape AND Manufacturing		Engineering, Material Science, Design		All years	6006	Scopus (Elsevier)
Near Net Shape AND Manufacturing			Process, Process Technology, Material Processing, Design		550	
Keywords/ Title/ Abstract	*All fields*					
Near Net Shape	Process	Engineering, Design		All years	249	Scopus (Elsevier)
Near Net Shape	Material	Engineering, Design			269	
Near Net Shape	Design	Engineering, Design			105	
Keywords/ Title/ Abstract		*Refined by: Abstract Verification*				
Near Net Shape AND Manufacturing AND (Material OR Process OR Design)		All fields	Material, Design, Process, Processing Technology	All years	135	Scopus (Elsevier, Google Scholar)

2.1 Near Net Shape Manufacturing of Metal

Table 2.1 details the searching strategies for the selection of NNS papers included in this survey. A number of different search terms and screening approaches were employed. A broad search was followed by a process of verification based on the papers abstract that allowed the scope to be limited to papers and articles related to metal manufacturing processes.

Figure 2.1 illustrates the rate and focus of NNS research reported over the last thirty years. Since the peak of NNS research activity (between 1995 and 2005) the variety of materials under investigation has dramatically increased. The cost of composites and ceramic components appears to have motivated much of this recent work. Similarly industries that use titanium, or complex metal alloys, have provided easiest justifications of NNS approaches and allowed

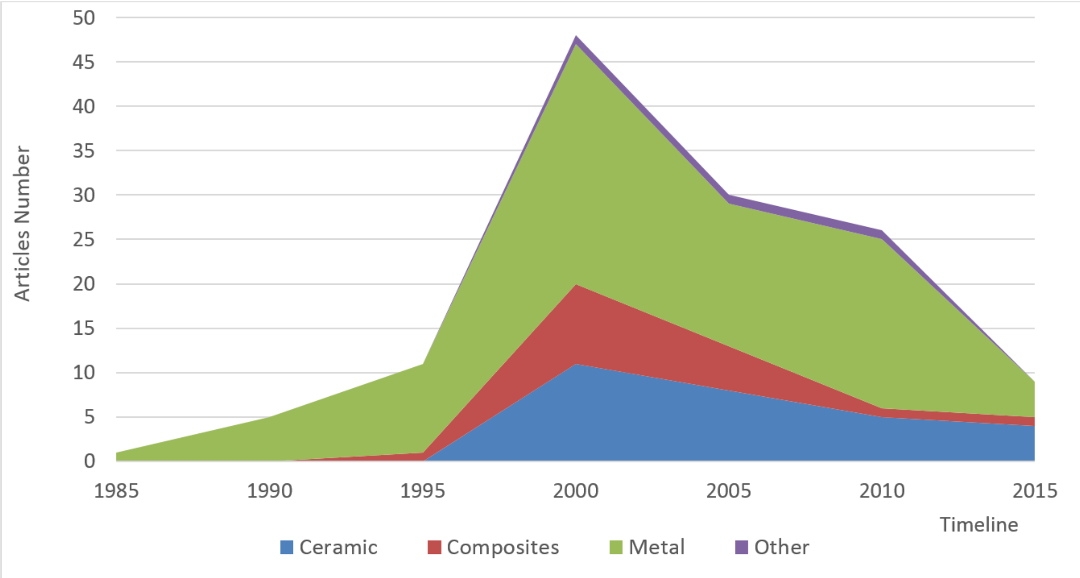


Figure 2.1: Annual publication volume of academic papers reporting NNS investigation classified by materials (1985-2015) [Table 2.1].

the subsequent spread of successful applications to other, less costly, materials. Only a few NNS investigation relating to exotic materials, such as rhenium or amorphous alloys, have been published. Given the high costs of such metals it is likely that commercial confidentiality has restricted dissemination of this work.

2.1.1 Review Synthesis

The articles have been categorized in terms of the research methodologies applied (i.e. experimental, analytical, review meta-analysis, etc.). Figure 2.2 shows how the approaches adopted by researchers have varied over the years and demonstrates the predominance of the empirical approach.

Figure 2.3 details the distribution of papers in terms of the industry sectors: aero-space/aeronautical, multi-sector application (gears, spline shaft, connecting rods, magnet production), automotive, electronic/robotic, nuclear/energy, academic research, military and others (mold fabrication, heavy industry, ingots production, ecologic productions, biomedical). Figure 2.4

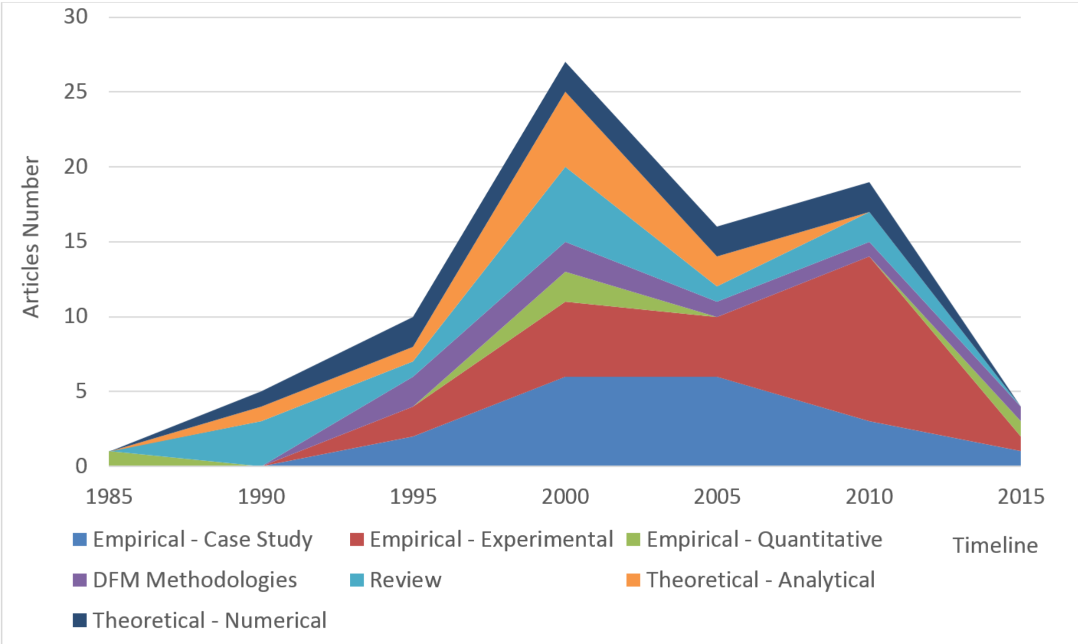


Figure 2.2: Annual publication volume of academic papers reporting NNS investigation categorized by research method (1985-2015) [Table 2.1].

shows the percentage of NNS papers associated specific processes: forging (hot, cold, precision, closed-die forging, including hot extrusion and indirect extrusion), forming (including flow forming, hydroforming, semi-solid metal casting, semi-solid metal extrusion, rolling and strip casting), casting (sand, investment, centrifugal, high and low pressure casting), additive layer manufacturing (ALM) processes (including blown powder and metal bed technologies), powder technologies (including hot isostatic pressing, Metal Injection Molding).

The literature survey on NNS of metal is presented in Appendix A. The literature review identifies the main papers on NNS and classifies their research approaches, dividing them into:

- Theoretical (analytical and numerical)
- DFM methodologies
- Reviews

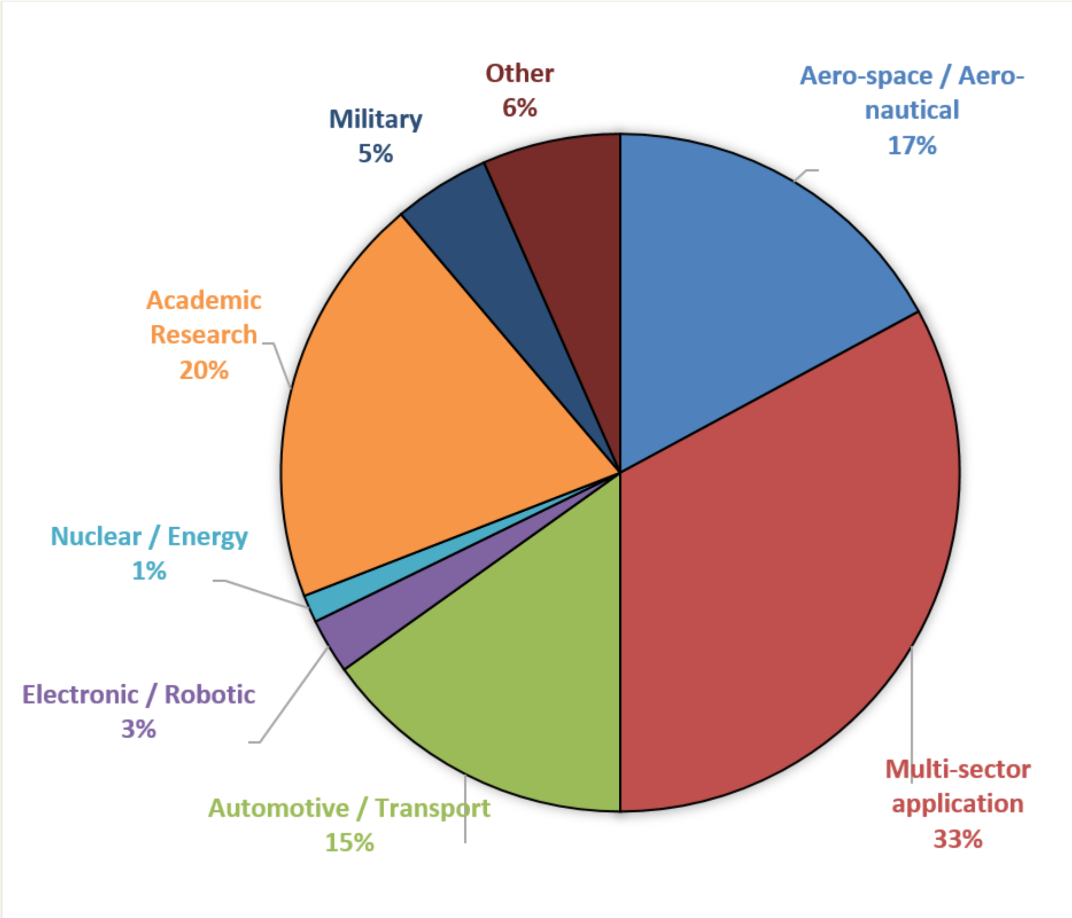


Figure 2.3: Papers distribution by applications [Table 2.1].

- Empirical (experimental, case studies and quantitative)

The high variety of process, material and approaches make impossible to find a common NNS application strategy or investigative approach. However, even dealing with many different NNS technologies, the discussed papers can be classified into five distinct classes (Table 2.2). The NNS can be classified as:

- Process innovation
- Process design
- Product design

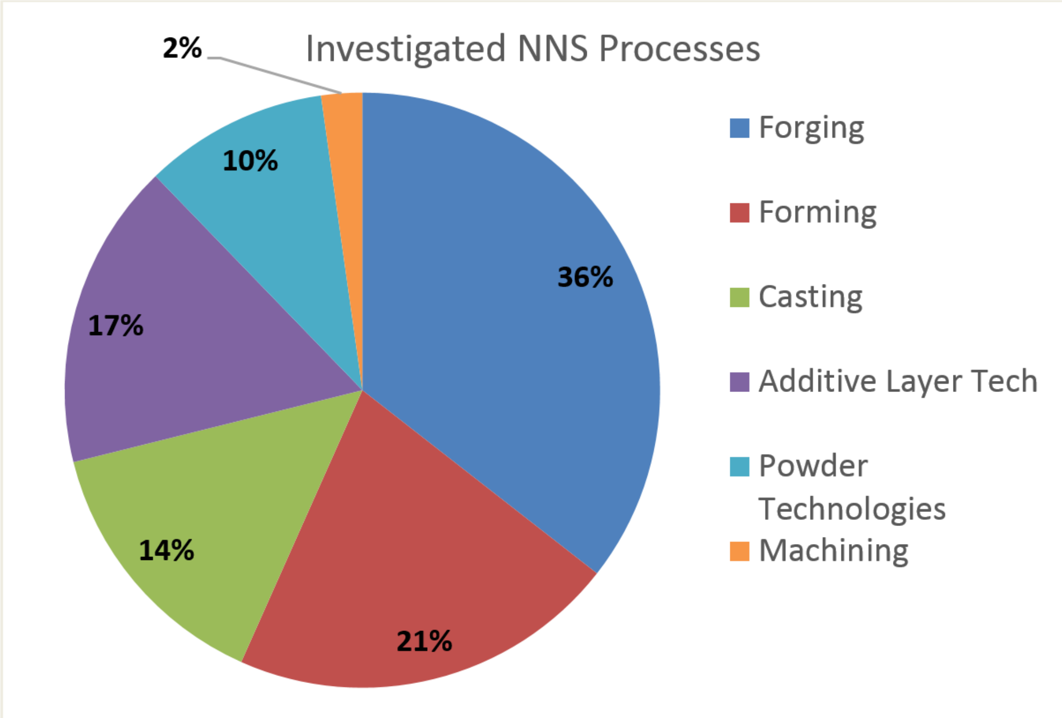


Figure 2.4: Percentage of NNS papers by Manufacturing Process [Table 2.1].

- Material characterization
- Differential analysis
- Applied framework

The first three categories show similarity with Altan and Miller [1990]'s definition of NNS variables. Altan and Miller [1990] observed that part design, material and process play fundamental roles in NNS technology. However, the authors dealt with *process innovation* (introducing a new processes) or *design* (optimizing process parameters and capabilities) in isolation, without considering different material or design opportunities. The first category aim to determine the feasibility of a process, the second to its optimization (both for a single combination of production design and material). Similarly, the papers in the *material characterization* class aim to define material characteristics only for a certain process and design combination. *Product design*'s papers deal with systematic shape variation for a certain category of processes. In the *differential analysis* category, the authors compared different processes and product designs by evaluating their different impact on costs and product quality. This comparison however is always restricted to a maximum of three processes, usually in the same manufacturing category (e.g. considering only casting processes). The a*applied frameworks* show the few systematic approaches developed specifically for NNS technologies. These methodologies are often limited by two factors: being qualitative and applied only to specific processes (e.g. closed die forging). The NNS categories are summarized in Table 2.2 and detailed in the following subsections.

Process Innovation

The *Process Innovation* papers introduce a new process [Schlienger et al., 1998, Kruth et al., 1998, Mac Donald and Hashmi, 2002, Janney et al., 1998] or illustrate its capabilities and main variables for a defined range of products [LaSalle and Zedalis, 1999, Groenbaek and Birker, 2000, Klug et al., 2004, Behrens et al., 2007, Dean, 2000, Moriguchi, 1992, Yoshimura and Tanaka, 2000, Shi et al., 2007, Vilotić et al., 2007] and materials [Milewski et al., 1998, Lewis and Schlienger, 2000, Klug et al., 2004, Kruth et al., 1998, Janney et al., 1998]. The process innovations classification is dominated by work on forging/forming [Groenbaek and Birker, 2000, Behrens et al., 2007, Vilotić et al., 2007, Dean, 2000, Moriguchi, 1992, Yoshimura and Tanaka, 2000, Mac Donald and Hashmi, 2002, Shi et al., 2007] and additive layer manufacturing [Schlienger et al., 1998, Lewis and Schlienger, 2000, Milewski et al., 1998, Kruth et al., 2007, Mudge and Wald, 2007] processes, although a few articles investigate novel powder technologies [LaSalle and Zedalis, 1999, Janney et al., 1998] and casting [Klug et al., 2004] processes. The majority of the papers in this category present case studies [Groenbaek and Birker, 2000, Milewski et al., 1998, Klug et al., 2004, Behrens et al., 2007, Vilotić et al., 2007, Dean, 2000, Yoshimura and Tanaka, 2000] and reviews [Moriguchi, 1992, Kruth et al., 1998, Mac Donald and Hashmi, 2002, Mudge and Wald, 2007], although some experimental investigation are reported for powder technologies [LaSalle and Zedalis, 1999, Janney et al., 1998] and additive layer manufacturing [Schlienger et al., 1998, Lewis and Schlienger, 2000]. The applications motivating work in this area are the forging of gears [Groenbaek and Birker, 2000, Moriguchi, 1992, Dean, 2000], similar high performance automotive components [Behrens et al., 2007, Vilotić et al., 2007, Yoshimura and Tanaka, 2000] (i.e. bearings, cardan shafts, rods) and impellers [LaSalle and Zedalis, 1999, Shi et al., 2007]. Tool design [Yoshimura and Tanaka, 2000], particularly die-design for forging [Groenbaek and Birker, 2000, Moriguchi, 1992, Dean, 2000], and new process configuration [Mac Donald and Hashmi, 2002] is also frequently investigated by authors. Process parameters and variables for new processes are determined by several authors [Vilotić et al., 2007, Kruth et al., 1998, Mac Donald and Hashmi, 2002, Janney et al., 1998, Dean, 2000], again mainly for forging processes and powder technologies.

Process Design

Process design papers aim to into establish [Hirt et al., 1997, Chitkara and Bhutta, 1995, 1996, Chitkara and Kim, 1996, 2001, Jeon and Kim, 1999, Qi et al., 2010, Mamalis et al., 1998, Taminger and Hafley, 2006], optimize [Netto et al., 1996, Siegert et al., 1997, Kapranos et al., 2000, Kim et al., 2005b] or enhance [Li, 1995, Kang et al., 2003, Dirba et al., 2014] process capabilities in terms of technological quality [Hirt et al., 1997, Chitkara and Bhutta, 1995, Chitkara and Kim, 1996, Li, 1995, Kang et al., 2003, Dirba et al., 2014, Kapranos et al., 2000], geometric capabilities [Chitkara and Kim, 2001, Chitkara and Bhutta, 1996, Jeon and Kim, 1999, Qi et al., 2010, Mamalis et al., 1998], workable material [Netto et al., 1996, Siegert et al., 1997, Taminger and Hafley, 2006] or waste reduction. Investigations are mainly empirical (experimental and case studies) and analytical [Chitkara and Bhutta, 1995, 1996, Chitkara and Kim, 2001, 1996, Jeon and Kim, 1999, Netto et al., 1996]. The empirical ones focus on forming, particularly on enhancing and optimizing SSMC processes in terms of the technological quality [Kapranos et al., 2000, Kang et al., 2003, Hirt et al., 1997] or for additive layer manufacturing processes establish workable materials [Taminger and Hafley, 2006] or geometric capabilities [Qi et al., 2010]. Analytical papers are focused on determining achievable geometries [Chitkara and Kim, 2001, Chitkara and Bhutta, 1996, Jeon and Kim, 1999] and technological quality [Chitkara and Bhutta, 1995, Chitkara and Kim, 1996] as well as optimizing workable materials [Netto et al., 1996] in forging process applications. Analytical analysis on material optimization have also been conducted for powder technologies [Chitkara and Bhutta, 1995, 1996, Chitkara and Kim, 1996, 2001, 1996, Jeon and Kim, 1999, Netto et al., 1996]. Much of the work on numerical analysis enhance and optimize the quality of casting, particularly investment casting [Li, 1995, Kim et al., 2005b], and also defining the component shapes achievable by forging [Mamalis et al., 1998].

Product Design

Product design papers aim to evaluate, modify and establish the influence of product design on process performances [Takemasu et al., 1996, Konak et al., 2003], feasibility [Chu et al., 1993, De Sam Lazaro et al., 1993, Yin et al., 2001], design [Tomov and Gagov, 1999, Medellin et al., 2008, Yin et al., 2001] and final product quality [Konak et al., 2003]. DFM methodologies are mainly used in this category [Takemasu et al., 1996, Konak et al., 2003, Chu et al., 1993, De Sam Lazaro et al., 1993, Yin et al., 2001, Tomov and Gagov, 1999, Medellin et al., 2008], it is interesting to notice that only two papers have investigated forging with different methodologies, one numerically (i.e. regarding cost performances improvement [Takemasu et al., 1996]) and the other analytically (i.e. regarding process design [Tomov and Gagov, 1999]). DFM methodologies have also been applied for determining the feasibility of forming [Chu et al., 1993, De Sam Lazaro et al., 1993] and casting processes [Yin et al., 2001]. The approach is a powerful one and processes chains and process parameters have been designed using DFM methodologies for casting [Yin et al., 2001], forming and additive layer manufacturing [Medellin et al., 2008]. DFM methodologies have been used for predicting the final product quality (i.e. shrinkage) and performances (i.e. quantify ideal shape modifications) in powder technologies (HIP) [Konak et al., 2003].

Material Characterization

Material characterization papers define metal properties in connection with a new process [Kottman et al., 2015, Julien and Després, 2006] (e.g. Low pressure Metal Injection Molding, LMIM, and laser hot wire process, ALM process) or existing process [Blackwell and Wisbey, 2005, Okada et al., 2003, Yamamoto et al., 2010, Curle, 2010, Kim et al., 2005a, Arribas et al., 2008, Qi et al., 2009, Krishna et al., 2007] or products. Microstructure [Blackwell and Wisbey, 2005, Curle, 2010, Arribas et al., 2008, Qi et al., 2009, Krishna et al., 2007, Kottman et al., 2015, Julien and Després, 2006, Yamamoto et al., 2010] mechanical properties [Blackwell and Wisbey, 2005, Qi et al., 2009, Krishna et al., 2007, Julien and Després, 2006], plastic flow/behaviour [Okada et al., 2003] and other material processing parameters (e.g. fluidity, strain curve) [Arribas et al., 2008, Yamamoto et al., 2010, Kim et al., 2005a] are commonly investigated material properties. Titanium [Blackwell and Wisbey, 2005, Yamamoto et al., 2010, Curle, 2010, Kim et al., 2005a, Arribas et al., 2008, Kottman et al., 2015] is the most investigated material, because of its excellent mechanical proprieties, versatility and high cost but it is not the only focus and other papers investigate specific alloys such as: Aluminium-Titanium Okada et al. [2003], Nickel-Titanium Krishna et al. [2007] and Inconel alloys [Qi et al., 2009, Krishna et al., 2007]. The majority of the articles are experimental [Kottman et al., 2015, Julien and Després, 2006, Curle, 2010, Arribas et al., 2008, Qi et al., 2009, Krishna et al., 2007] or case study Blackwell and Wisbey [2005], Kottman et al. [2015], although it is surprising to note that only one uses a Design of Experiments approach [Qi et al., 2009]. Two papers investigate Titanium behaviour for centrifugal casting [Kim et al., 2005a] and semi-solid metal casting (Okada et al. 2003) with numerical models. Forming [Arribas et al.,

Stream	*Process Innovation*	*Process Design*	*Product Design*	*Material Characterization*	*Differential analysis*	*Applied Framework*
Construct variants	Process analysis, Process definition	Process Characterization, Process Modeling, Process Optimization	Adaptive design, Design For X, Parametric Design, Design Analysis, Virtual Prototyping	Microstructure analysis, Microstructure development	Experimental analysis, Differential cost analysis	Expert System, Framework, Flowchart, Algorithm
Description	Introducing a new process or describing its capabilities and main variables for a defined range of product and materials	Establish, optimize or enhance process capabilities in terms of technological quality, geometric capability, workable material and waste reduction	Evaluate/modify/establish influence of product design on process performances/feasibility/ design and final product quality	Material properties (microstructure, mechanical, plastic behavior ...) definition in connection with a developed or existent process/product.	Compare different processes and/or product designs and/or materials by considering economic and/ or technological output (product quality/ conformity/ proprieties)	Introducing general models or dedicated procedures in order to act on manufacturing variables (process, product design, material) and obtaining resources saving
Key Concepts	Process capabilities mapping, Process variables, Innovative process configuration and equipment (e.g. new die design)	Experimental characterization, Design of Experiments, Process Modeling (FEM, Analytic),	Geometric modeling, Geometric feasibility, Process feasibility, Preform design	Formability, Mechanical properties, Fluidity, Recrystallization, Product quality	Process comparison, Economic evaluation, Economic model,	General Model, Systematic Approach, Multi-subject approach, Adaptive frame
Papers number	24 (29% of the total)	29 (35% of the total)	7 (9% of the total)	11 (13% of the total)	7 (9% of the total)	6 (7% of the total)
Main Works	Schlienger et al.(1998); LaSalle & Zedalis (1999); Groenbaek & Birker (2000); Lewis et al. (Lewis et al. 1997); Milewski et al. (2004); Behrens et al. (2007); Vilotić et al. (2007); Dean (2000); Moriguchi (1992); Kruth et al. (1998); Yoshimura & Tanaka (2000); Mac Donald & Hashmi (2002); Mudge & Wald (2007); Janney et al.(1998); Shi et al. (2007)	Li (1995); Hirt et al. (1997); Kim et al. (2005); Chitkara & Bhutta (1995); Chitkara & Kim (2001); Chitkara and Bhutta (1996); Chitkara & Kim (1996); Netto et al. (1996); Jeon & Kim (1999); Siegert et al. (1997); Kapranos et al. (2000); Kang et al. (2003); Qi et al.(2010); Taminger & Hafley (2006); Dirba et al.(2014); Mamalis et al. (1998)	Takemasu et al. (1996); Tomov & Gagov (1999); Chu et al.(1993); De Sam Lazaro et al. (1993); Yin et al. (2001); Konak et al. (2003); Medellin et al. (2008)	Blackwell & Wisbey (2005); Kottman et al. (2015); Okada et al. (2003); Yamamoto et al. (2010); Curle (Curle 2010); Kim et al. (2005); Arribas et al.(2008); Qi et al. (2009); Krishna et al. (2007); Julien & Després (2006)	Tateno (1985); Bhatkal & Hannibal (1999); Cominotti & Gentili (2008); Witulski et al. (1994); Morita et al.(1991); Campbell (2000); Bewlay et al. (2003)	Onodera & Sawai (1992); Castro et al.(2004); Altan & Miller (1990); Caporalli et al. (1998); Löwer et al. (2015); Kudo (1990)

Table 2.2: Overview of the NNS research: Process innovation, Process Design, Product Design, Material Characterization, Differential Analysis, Applied framework.

2008], particularly SSMC [Okada et al., 2003, Curle, 2010], additive layer manufacturing and powder technologies processes are the most investigated for material characterization.

Differential Analysis

In the category *Differential analysis*, papers compare different processes [Bhatkal and Hannibal, 1999, Witulski et al., 1994, Morita et al., 1991] or different processes with different product designs [Campbell, 2000, Bewlay et al., 2003] or even different combinations of processes, product designs and materials [Tateno, 1984, Cominotti and Gentili, 2008]. Authors use comparison criteria which include process economics [Tateno, 1984, Cominotti and Gentili, 2008] and technological output evaluations [Bhatkal and Hannibal, 1999, Witulski et al., 1994, Morita et al., 1991, Campbell, 2000, Bewlay et al., 2003]. The technological output evaluation considers product quality, product conformity and the generic proprieties (e.g. part weight, vibrational characteristics). The latter are final product characteristics which are not described as quality or conformity requirements (i.e. depending on the specific product application). Three papers use a quantitative approach [Tateno, 1984, Bhatkal and Hannibal, 1999, Campbell, 2000], comparing different casting processes [Campbell, 2000], casting and powder technologies (MIM) [Bhatkal and Hannibal, 1999] as well as casting and forging [Tateno, 1984]. Isothermal forging has been used as benchmark for comparison of several processes: experimentally for roll forging [Bewlay et al., 2003] and SSMC [Witulski et al., 1994] and numerically for closed die forging [Morita et al., 1991]. The only case study reports an economic comparison between flow forming and friction welding/machining [Cominotti and Gentili, 2008].

Applied Framework

Applied framework papers introduce general models [Löwer et al., 2015, Kudo, 1990, Altan and Miller, 1990] or adaptive procedures [Castro et al., 2004, Onodera and Sawai, 1992, Caporalli et al., 1998] for determining manufacturing variables (process, product design, material) in order to obtain resources saving [Castro et al., 2004, Altan and Miller, 1990, Löwer et al., 2015, Kudo, 1990], quality enhancing [Onodera and Sawai, 1992] or process design optimization (i.e. process parameters selection) [Castro et al., 2004, Caporalli et al., 1998, Altan and Miller, 1990]. The majority of the papers analyse process and product variable combinations [Onodera and Sawai, 1992, Castro et al., 2004, Kudo, 1990], but only one consider the combination of process, product and material [Löwer et al., 2015]. Two of them take into consideration process variation [Caporalli et al., 1998, Altan and Miller, 1990]. The main application of work in the class is the forging process [Altan and Miller, 1990, Castro et al., 2004, Onodera and Sawai, 1992, Caporalli et al., 1998], although two articles include casting [Löwer et al., 2015] and forming [Kudo, 1990] in their frameworks. Resource saving is the main motivation (i.e. raw material usage reduction [Castro et al., 2004, Altan and Miller, 1990, Löwer et al., 2015]), because of its high impact on forging cost. DFM methodologies [Caporalli et al., 1998, Löwer et al., 2015] and reviews [Kudo, 1990, Altan and Miller, 1990] have been used for constructing the frameworks, although the following report different approaches: an Ishikawa diagram for cold forging [Onodera and Sawai, 1992] is constructed through a case study and one analytical approach uses Genetic Algorithms [Castro et al., 2004] for developing a preform design methodology.

2.1.2 Closing Remarks

NNS manufacturing is a multi-disciplinary task and consequently approaches are varied and often driven by the nature of the specific application. The literature reflects how NNS philosophies have evolved over the years to include almost all the main manufacturing techniques. So although initially the phrase was only used in reference to plastic deformation processes, NNS concepts have now been extended to casting and powder technologies and are implicit in the justification of many specialist forming processes (e.g. flow forming, hydroforming, SSMC) [Cominotti and Gentili, 2008, Mac Donald and Hashmi, 2002, Witulski et al., 1994, Hirt et al., 1997, Kapranos et al., 2000, Kang et al., 2003, Okada et al., 2003, Curle, 2010], powder technologies (e.g. HIP, MIM) [Julien and Després, 2006, Bhatkal and Hannibal, 1999] and additive layer manufacturing systems [Schlienger et al., 1998, Lewis and Schlienger, 2000, Milewski et al., 1998, Kruth et al., 1998, Mudge and Wald, 2007, Qi et al., 2010, Taminger and Hafley, 2006, Blackwell and Wisbey, 2005, Kottman et al., 2015, Qi et al., 2009, Krishna et al., 2007].

Indeed the term NNS is frequently used to convey the generic capabilities of manufacturing technologies and distinguish them from systems that aim to deliver finished components. The literature also highlights that NNS has been associated with the creation of advantageous process and material combination for particular designs whose form has been manually tailored for that purpose. Interestingly there appears to be a lack of general frameworks or CAM/CAD tools to support the general process of Design for NNS (i.e. the reported tools [Ishii et al., 1989, Caporalli et al., 1998, Chu et al., 1993, De Sam Lazaro et al., 1993] are largely focused on support of specific processes such as casting, closed die forging and injection molding). Similarly the general interactions between material, design and process are only rarely formally investigated (even although this is an area of work suggested by many authors) [Altan and Miller, 1990, Kudo, 1990].

The literature demonstrates that innovative NNS systems are still emerging but although researchers frequently report new technologies the impact of these contributions on cost and the overall workflow in a manufacturing process is only rarely discussed [Cominotti and Gentili, 2008, Onodera and Sawai, 1992, Kudo, 1990]. Occasionally a competitive analysis might be undertaken for a number of candidate processes (usually no more than two) but the scope of such analysis is often limited by the lack of flexibility in a components material and design. A comparative cost analysis is a fundamental instrument for justifying every investigation into the desirability of NNS technologies. The few differential cost analysis reported in the literature are mainly case study [Cominotti and Gentili, 2008, Bhatkal and Hannibal, 1999], where only different process alternatives have been evaluated (i.e. without considering alternate materials or designs). There appear to be no reports of work connecting systematic methodologies for process (e.g. Swift and Booker [2013]) and material (e.g. Ashby [2000]) selection.

2.2 Manufacturing processes: selection, feasibility analysis and optimization

This part of the chapter is focused on investigate the main approaches adopted on process/material selection, feasibility and optimization of manufacturing process and design.

2.2.1 Process and Material Selection

The process and material selection has been investigated by the authors using several different methodologies. The generic **process selection** procedure usually has three steps: screening, ranking and a search for supporting information [Esawi and Ashby, 2003, Ashby M. F., 1993]. The selection of the best process for a given material, design characteristics and product requirements has been undertaken using the following strategies.

- Analytical
- Probabilistic (Fuzzy Logic)
- Knowledge Base System
- Manufacturing and Product complexity
- Methodological (Qualitative)
- Optimization Algorithms

- Topological (Numerical)

The **analytical** papers develop a multi-variable system of equations, quantifying the different process features. Usually, the quantification of the process capabilities needs to match with the component requirements. Allen and Swift [1990] develop a model based on manufacturing cost prediction. The model provides the material (i.e. considering the product volume and the material cost) and basic processing costs, depending on the selected processes and is calculated through the cost time and production volume, using empirical constants. This cost refers to the production of an ideal component design for the selected process and a coefficient (relative cost coefficient) corrects the process cost from the ideal component, considering the component to be produced. The coefficient is composed of four parameters (determined though empirical graphs), associated with geometrical shape, section reduction/thickness, tolerances and surface finish. The parameters give distance between the current and the ideal conditions. The process with the resultant lowest cost is considered as the best candidate. Swift and Booker [2013] use the Allen and Swift [1990] formula, introducing a matrix for a preliminary screen of the processes. The PRIMA matrix (Figure 2.5) allows selecting a cluster of feasible process, inputting the required component material and production volume. Other authors use cost functions and cost estimation for pre-selection screening: for example, [Karthik et al., 2003] provide a measurement of casting process compatibility for needed production volume, weight input, thick/thin sections, tolerances, and surface finish. A proportion between the available capabilities and the requirements give a compatibility score. Every characteristic is weighted, depending on its importance, with a qualitative system. The casting processes are so ranked depending on their compatibility values. Rao and Padmanabhan [2007] use graph theory and matrix approach for screening the additive layer manufacturing processes. The combination of these two methods are able to deliver a multi-criteria decision, defining the interactions between selection attributes. The attributes can be either qualitative or quantitative. The attributes value and their responses to the product requirements as well as their interrelation are summarized in an single index. The casting processes are ranked by their compatibility values. Esawi and Ashby [2003] use the cost function with compatibility ranges to identify the possible feasible processes and rank them. From these first two steps, the best process to take into consideration is selected. In a subsequent step, the process technological (tolerances, workable dimensions, surface roughness) and economical capabilities are matched, giving a complete overview of the process ability for produced the required product. The work is based on a previous investigation Esawi and Ashby [1998] developed comparing the attributes required by the design (the required material, size, shape, precision and cost) with those that lie within the capacity of a large number of processes, seeking the subset which is capable of making the component. The subset is then ranked by economic criteria.

The **probabilistic** approach aims to develop a statistical correlation between the process capabilities and product requirements. Particularly, the fuzzy logic is an artificial intelligence technology that is gaining in popularity and applications in control systems and pattern recognition. It is based on the observation that people make decisions based on imprecise and numerical information [Daws et al., 2008]. Fuzzy models, or sets, are mathematical means of representing vagueness and imprecise information, hence the term fuzzy [Kalpakjian and Schimd, 2009]. Differently from traditional probability, fuzzy sets are capable of representing, using and manipulating the data that has a range of values, due to their uncertainness. Hence, in fuzzy logic, the distinction between full compatibility (one) and incompatibility (zero) is gradual in the extreme ranges of the fuzzy set. Several authors applied slightly different versions of fuzzy approach to process selection and decision making in manufacturing [Giachetti, 1998, Daws et al., 2008, Perzyk and Meftah, 1998, Tsinopoulos and McCarthy, 2006, Sáenz et al., 2015].

Figure 2.6 illustrates the fuzzy logic approach. The capability values of the investigated processs feature are defined as:

QUANTITY \ MATERIAL	IRONS	STEEL (carbon)	STEEL (tool, alloy)	STAINLESS STEEL	COPPER & ALLOYS	ALUMINIUM & ALLOYS	MAGNESIUM & ALLOYS	ZINC & ALLOYS	TIN & ALLOYS	LEAD & ALLOYS	NICKEL & ALLOYS	TITANIUM & ALLOYS	THERMOPLASTICS	THERMOSETS	FR COMPOSITES	CERAMICS	REFRACTORY METALS	PRECIOUS METALS
VERY LOW 1 TO 100	[3.5][3.6][3.7][6M][7.1][7.4]	[3.5][3.7][4.10][6M][7.1][7.5][7.6]	[3.1][3.5][3.7][4.10][6M][7.1][7.5][7.6][7.7]	[3.5][3.7][4.7][4.10][6M][7.1][7.5][7.6]	[3.5][3.7][4.10][6M][7.1]	[3.5][3.7][4.7][4.10][6M][7.5]	[3.6][3.7][4.10][6M][7.1][7.5]	[3.1][3.7][4.10][6M][7.5]	[3.1][3.7][4.10][6M][7.5]	[3.1][4.10][6M][7.5]	[3.5][3.7][4.10][6M][7.1][7.5][7.6]	[3.1][3.6][4.7][4.10][6M][7.1][7.5][7.6][7.7]	[5.5][5.7]	[5.5][7.7]	[5.2][5.8][7.7]	[3.5][7.1][7.5][7.6][7.7]	[3.1][7.7]	[7.5]
LOW 100 TO 1,000	[3.2][3.5][3.6][3.7][6M][7.1][7.3][7.4]	[3.2][3.5][3.7][4.10][6M][7.1][7.3][7.4][7.5]	[3.1][3.2][3.7][6M][7.1][7.3][7.4][7.5][7.6][7.7]	[3.2][3.7][4.7][4.10][6M][7.1][7.3][7.4][7.5]	[3.2][3.5][3.7][3.8][4.5][4.10][6M][7.1][7.3][7.5]	[3.2][3.5][3.7][3.8][4.7][4.10][6M][7.3][7.4][7.5]	[3.6][3.7][3.8][4.10][6M][7.5]	[3.1][3.7][3.8][4.10][6M][7.5]	[3.1][3.7][3.8][4.10][6M][7.5]	[3.1][3.8][4.10][6M][7.5]	[3.2][3.5][3.7][4.10][6M][7.1][7.3][7.4][7.5]	[3.1][3.6][4.7][4.10][6M][7.1][7.3][7.4][7.5][7.6][7.7]	[5.3][5.5][5.7]	[5.2][5.3]	[5.2][5.3][5.8][7.7]	[7.1][7.3][7.5][7.6][7.7]	[7.7]	[7.5]
LOW TO MEDIUM 1,000 TO 10,000	[3.2][3.3][3.5][3.6][3.7][4.11][6A][7.2]	[3.2][3.3][3.5][3.7][4.1][4.3][4.10][4.11][6A][7.2][7.3][7.4][7.5]	[3.2][3.5][3.7][4.1][4.4][4.11][6A][7.2][7.3][7.4][7.5]	[3.2][3.5][3.7][4.1][4.3][4.7][4.10][4.11][6A][7.2][7.3][7.4][7.5]	[3.2][3.3][3.5][3.8][4.1][4.3][4.10][4.11][6A][7.2][7.3][7.4]	[3.2][3.3][3.5][3.8][4.1][4.3][4.7][4.10][4.11][6A][7.3][7.4][7.5]	[3.3][3.6][3.8][4.1][4.3][4.4][4.10][6A][7.5]	[3.3][3.8][4.3][4.10][6A][7.5]	[3.3][3.8][4.3][4.10]	[3.3][3.8][4.3][4.10]	[3.2][3.3][3.5][3.7][4.1][4.3][4.10][4.11][6A][7.2][7.3][7.4][7.5]	[4.1][4.7][4.10][4.11][6A][7.2][7.3][7.4][7.5]	[5.3][5.5][5.6][5.7]	[5.2][5.3][5.4]	[5.1][5.2][5.3]	[7.2][7.3][7.4][7.5]		[7.5]
MEDIUM TO HIGH 10,000 TO 100,000	[3.2][3.3][4.11][6A]	[3.9][4.1][4.3][4.4][4.5][4.11][4.12][4.13][6A][72][7.5]	[4.1][4.4][4.5][4.11][4.12][4.13][6A][7.2]	[3.9][4.1][4.3][4.4][4.5][4.11][4.12][4.13][6A]	[3.2][3.4][3.9][4.1][4.3][4.4][4.5][4.11][4.12][4.13][6A]	[3.2][3.3][3.4][3.9][4.1][4.3][4.4][4.5][4.11][4.12][4.13][6A][7.5]	[3.3][3.4][4.1][4.3][4.4][4.5][4.13][6A]	[3.3][3.4][4.3][4.4][4.5][4.13][6A]	[3.3][3.4][4.3][4.4][4.13]	[3.3][3.4][4.3][4.4][4.5][4.13][6A]	[3.1][3.3][3.4][3.5][4.11][4.12][4.13][6A][7.2][7.5]	[4.1][4.4][4.11][4.12][4.13][6A][7.2][7.5]	[5.1][5.3][5.5][5.6][5.10]	[5.1][5.3][5.10]	[5.1][5.3][5.9]	[4.11][4.12]	[4.12][4.13]	[4.5][4.12]
HIGH 100,000+	[3.2][3.3][4.11][6A]	[3.9][4.1][4.2][4.3][4.4][4.5][4.12][4.13][6A]	[4.12][6A]	[3.9][4.2][4.3][4.12][6A]	[3.2][3.9][4.1][4.2][4.3][4.4][4.5][4.7][4.8][4.11][4.12][4.13][6A]	[3.2][3.3][3.4][3.9][4.1][4.2][4.3][4.4][4.5][4.8][4.12][4.13][6A]	[3.3][3.4][4.1][4.3][4.4][4.8][4.13][6A]	[3.4][4.2][4.3][4.4][4.5][6A]	[3.4][4.3][4.4][6A]	[3.4][4.2][4.3][4.4][6A]	[4.2][4.3][4.12][6A]	[4.12][6A]	[5.1][5.6][5.10]	[5.1][5.3][5.4][5.10]	[5.9]	[4.7][4.11][4.12]	[4.12]	[4.5][4.12]
ALL QUANTITIES	[3.1]	[3.1][3.6][4.6][4.8][4.9]	[3.6][4.6]	[3.1][3.6][4.6][4.8][4.9]	[3.1][3.6][4.6][4.8][4.9][7.5]	[3.1][3.6][4.6][4.8][4.9]	[3.1][4.6][4.8][4.9]	[4.6][4.8][4.9]		[4.6]	[3.1][3.6][4.6][4.8][4.9]	[4.8][4.9]				[7.5]	[3.6]	[3.6]

KEY TO MANUFACTURING PROCESS PRIMA SELECTION MATRIX:

CASTING PROCESSES
[3.1] SAND CASTING
[3.2] SHELL MOULDING
[3.3] GRAVITY DIE CASTING
[3.4] PRESSURE DIE CASTING
[3.5] CENTRIFUGAL CASTING
[3.6] INVESTMENT CASTING
[3.7] CERAMIC MOULD CASTING
[3.8] PLASTER MOULD CASTING
[3.9] SQUEEZE CASTING

FORMING PROCESSES
[4.1] FORGING
[4.2] ROLLING
[4.3] DRAWING
[4.4] COLD FORMING
[4.5] COLD HEADING
[4.6] SWAGING
[4.7] SUPERPLASTIC FORMING
[4.8] SHEET-METAL SHEARING
[4.9] SHEET-METAL FORMING
[4.10] SPINNING
[4.11] POWDER METALLURGY
[4.12] METAL INJECTION MOULDING
[4.13] CONTINUOUS EXT (METALS)

PLASTIC & COMPOSITE PROCESSING
[5.1] INJECTION MOULDING
[5.2] REACTION INJECTION MOULDING
[5.3] COMPRESSION MOULDING
[5.4] RESIN TRANSFER MOULDING
[5.5] VACUUM FORMING
[5.6] BLOW MOULDING
[5.7] ROTATIONAL MOULDING
[5.8] CONTACT MOULDING
[5.9] PULTRUSION
[5.10] CONTINUOUS EXTRUSION (PLASTICS)

MACHINING PROCESSES
[6A] AUTOMATIC MACHINING
[6M] MANUAL MACHINING

NON-TRADITIONAL MACHINING PROCESSES
[7.1] ELECTRICAL DISCHARGE MACHINING (EDM)
[7.2] ELECTROCHEMICAL MACHINING (ECM)
[7.3] ELECTRON BEAM MACHINING (EBM)
[7.4] LASER BEAM MACHINING (LBM)
[7.5] CHEMICAL MACHINING (CM)
[7.6] ULTRASONIC MACHINING (USM)
[7.7] ABRASIVE JET MACHINING (AJM)

Figure 2.1: Manufacturing Process PRIMA Selection Matrix.

Figure 2.5: Process Information Mapping (PRIMA) matrix [Swift and Booker, 2013].

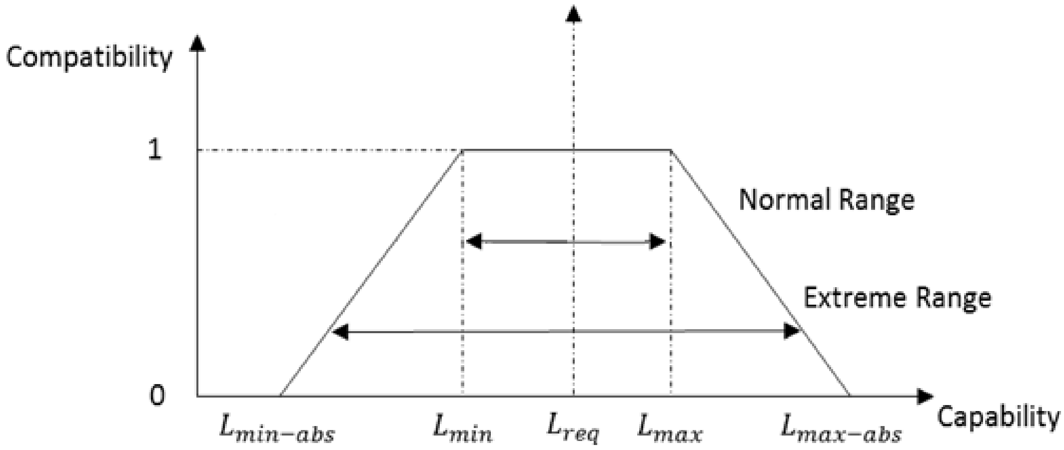


Figure 2.6: Fuzzy set for process capabilities (adapted from Ravi [2005]).

- $L_{min-abs}$ absolute minimum value
- L_{min} typical minimum value
- L_{max} typical maximum value
- $L_{max-abs}$ absolute maximum value

L_{req} is the requested value of product feature (e.g. required surface roughness). Compatibility assessment can be performed by mapping from qualitative description (low, low to medium, medium, medium to high and high) to numerical values. As in Ravi [2005] and later in Daws et al. [2008], compatibility is defined by the required value and the defined four values of the fuzzy set. If the required value is outside the set (Equation 2.4), compatibility is considered null. If it is in normal range, then the request is fully compatible (Equation 2.1). If the value falls between normal and extreme ranges, then the value is intermediate between 0 and 1, defined by a linear behaviour (Equation 2.2,2.3).

$$P_{L_{req}} = 1, if L_{min} < L_{req} < L_{max} \tag{2.1}$$

$$P_{L_{req}} = \frac{L_{req}L_{min-abs}}{L_{min}L_{min-abs}}, if L_{min-abs} < L_{req} < L_{min} \tag{2.2}$$

$$P_{L_{req}} = \frac{L_{max-abs}L_{req}}{L_{max-abs} - L_{max}}, if L_{max} < L_{req} < L_{max-abs} \tag{2.3}$$

$$P_{L_{req}} = 0, if L_{req} < L_{min-abs}, or L_{req} > L_{max-abs} \tag{2.4}$$

The approach of Giachetti [1998] defines two different cases that occur in compatibility evaluation. Using Dubois and Prade [2012] possibility theory, possibility and necessity are defined for every feature. Possibility assesses to what extent a feature satisfies the request (optimistic selection strategy), on the other hand, necessity expresses to what extent a features certainly satisfies the query. It is measured through a pessimistic selection strategy by measuring the impossibility of the opposite event. This opposite event is determined using the complement of the event. Figure 2.7 shows how to perform the calculations, in agreement with previous definition (Equations (2.1), (2.2), (2.3) and (2.4)), although it refers to a variable request. In order to evaluate possibility and necessity a unique compatibility number in required, Giachetti [1998] use a factor called β that represent the level of optimisms or pessimism of the decision maker. Factor β is 1 for an optimist decision maker and 0 for a negative one, but always included in the interval $\beta \in (0, 1)$. For manufacturing processes, Giachetti [1998] set the β to be 0.5.

A weighted average is calculated for each requirement between possibility and necessity values, mediated by factor β (possibility) and $1 - \beta$ (necessity). Using this methodology, a compatibility measure is assigned by Giachetti [1998] to every process/product selection features. A geometric weighted mean is used for aggregating all the compatibilities values (Equation 2.5). Weight (w) is assigned to every feature using linguistic values. Each of them is calculated as

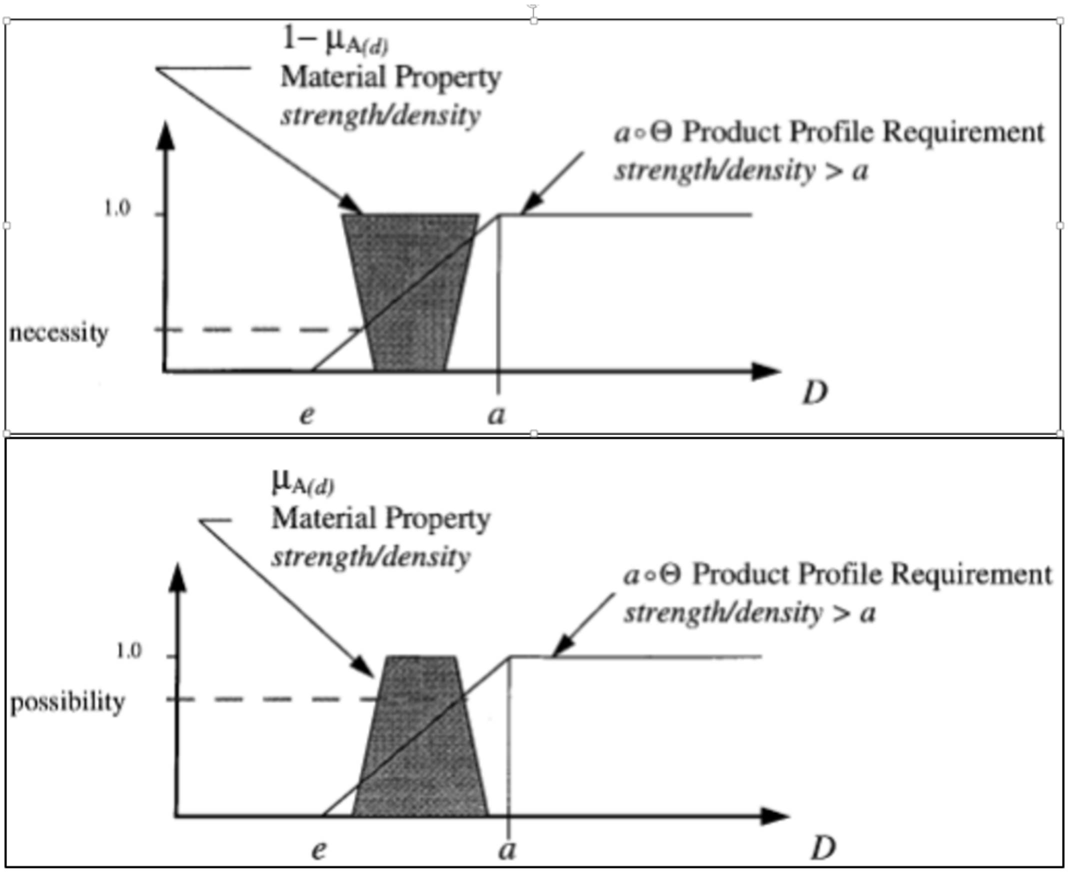


Figure 2.7: Possibility measure (left) and Necessity measure (right) under a variable requirement [Giachetti, 1998].

in Equation 2.6.

$$P_{L_{req_1},L_{req_2},,,L_{req_n}} = \prod_{i=1}^{N} P_{L_r eq_i}^{r^i} \tag{2.5}$$

$$r = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{2.6}$$

In conclusion, fuzzy logic is capable of ranking the candidate processes by their compatibility with target features. Usually these features include technological and other quantifiable requirements (e.g. tolerances, surface roughness), although it can be easily extended to every required feature (e.g. material usage, labour cost). The compatibilities values are sorted into an ordered list and a threshold applied for assessing the most compatible processes and discarding the others. Giachetti [1998] apply this theory to the first stages of product design and process selection, including a broad range of processes and material as possible candidates. Perzyk and Meftah [1998] use fuzzy logic for developing design for manufacturability of a single component. Functional requirements, manufacturing rules and material processability are evaluated for a single component through a process index, taking into consideration evaluating production volume, appearance, surface properties, dimensional tolerances, and material structure. The index is a triplet-type fuzzy number, which is combined with the ideal process (depending on the product requirements). Daws et al. [2008] limited the search to casting processes, including investment, mould (permanent, ceramic and full), shell, sand, die and squeeze casting. Similarly, Sáenz et al. [2015] apply a fuzzy logic approach to the selection of cutting process selection that considers the material-thickness relation, cutting speed, piece complexity and process tolerance capabilities.

Knowledge based systems use empirical data (usually collected in databases) in order to support selection process. These systems are usually flexible and leave to final selection to the user, by giving them all the information required to make a decision. For example, a knowledge base system developed by Sirilertworakul et al. [1993] aided designers in choosing the best alloy and casting process for a particular set of specifications. The database display both numerical and linguistic description of the processes, suitable for a certain material. The database includes a list of available material, although the material selection is prior to the process one (i.e. first list of processes are the material compatible ones). The designer has to select the best processes from its description, having excluded the unsuitable ones (i.e. relating to material and product specifications). Yu et al. [1993] develop a computer based routine which connects the geometrical factors, material and production attributes to identify the most suitable process (i.e. selecting from casting, hot and cold forging processes). The algorithm uses a developed design analysis which quantifies the compatibility of every target category. The methodology compares the required qualitative features (e.g. cold forging compatibility with aluminium tubes) by converting them to values. These values are compared datasets for every considered process, ranking them accordingly. Darwish and El-Tamimi [1996] propose a knowledge base algorithm for casting process selection, basing their decision criteria on design, production and manufacturing attributes. The author compare the process' manufacturing attributes quantitatively (minimum thickness, tolerances, mass range, surface roughness, economic lot size), qualitatively (porosity, dimensional accuracy, mechanical properties) and economically (tooling, labour, finishing and scrap costs). The available range of materials is used as a screening criteria for the processes. Similarly, Er and Dias [2000] develop a system for casting process selection including a comparative cost routine (Figure 2.8). Their methodology screens the processes on different levels, by determining the process compatibility with the target casting alloy, geometric complexity, casting accuracy and production quantity. This steps reduce the compatible processes and they are followed by a comparative cost analysis that ranks the remaining processes. Differently form the other authors, geometric complexity has been qualitatively assessed through questions regarding the product (e.g. undercuts or internal holes presence). The selected material has been used as screening factor, taking into consideration the resulting and required mechanical properties. Xu et al. [2001b] develop a knowledge base system for additive layer manufacturing, including the process cost as a decision criterion.

Manufacturing and product complexity measurement is another tool adopted by researchers for understanding the validity of a process selection. The process chain with the lowest complexity is the easiest to manufacture. Product complexity influences directly the manufacturing complexity, so an effective understanding of complexity nature and its relative measure can directly connect them. Product complexity increases with the number and diversity of features to be manufactured, as well as the nature and difficulty of the tasks required to produce the features. Cooper et al. [1992] have measured product complexity as a volume weighted average, meanwhile Guenov [2002] used the physical concept of entropy for

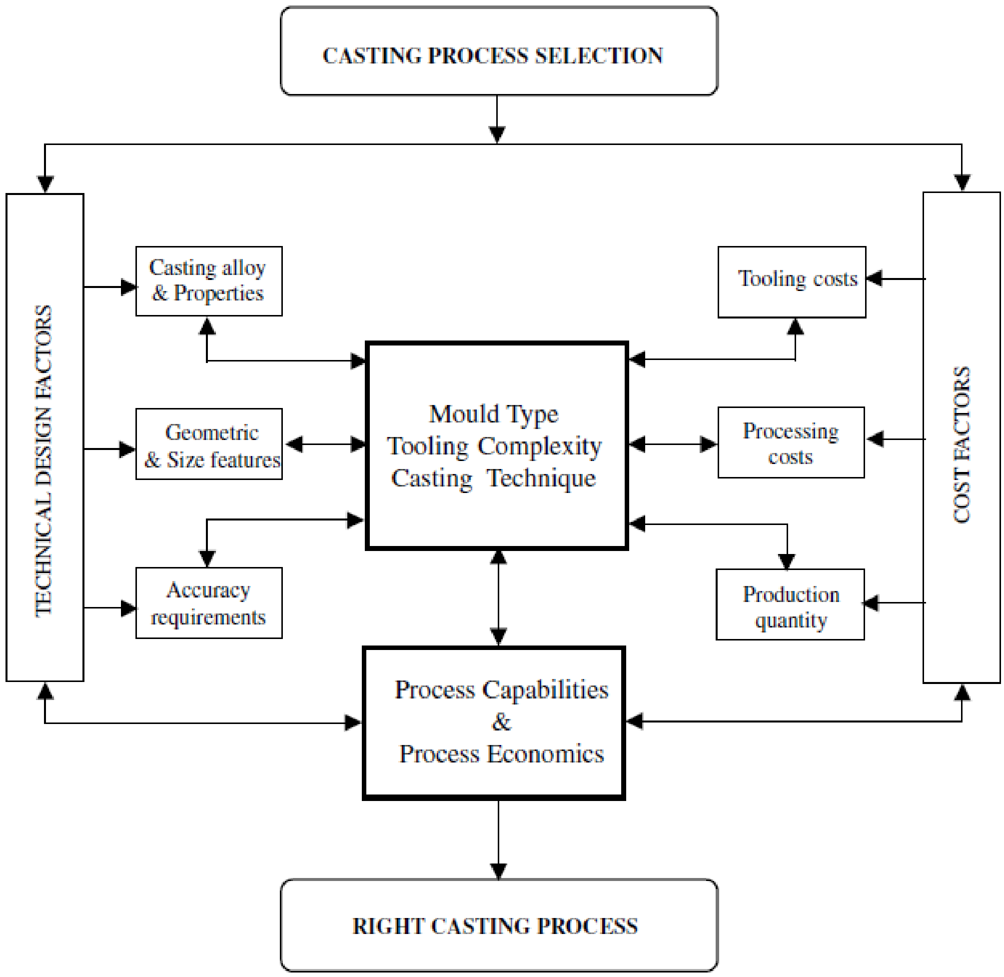


Figure 2.8: Casting process selection parameters and their interactions [Er and Dias, 2000].

evaluating the amount of information required for producing a component. Using the same concept, El Maraghy and Urbanic [2003] developed a complete formula for evaluating the product complexity (Equation 2.7).

$$CI_{product} = (D_{R_product} + c_{f_product})H_{product} \tag{2.7}$$

Where, $H_{product}$ is the information entropy measure (Equation 2.8), $D_{R_{product}}$ is uniqueness/diversity information measure (Equation 2.9) and $c_{f_{product}}$ is the relative complexity coefficient. The following equations define the three contributors to product complexity used in this paper.

$$H_{product} = log_2(N + 1) \tag{2.8}$$

$$D_{R_{product}} = \frac{n}{N} \tag{2.9}$$

$$c_{f_{product}} = \sum_{f=1}^{F} x_f c_{f,feature} \tag{2.10}$$

Where: N, total quantity of information; n, quantity of unique information; c_f, feature complexity coefficient (Equation 2.10); x_f, percentage of dissimilar features.
A matrix methodology is used to determine the relative complexity coefficient [El Maraghy and Urbanic, 2003]. Essentially the complexity matrix describes all product characteristics and specifications. A numerical value indicates the relative effort to produce each of them or to perform the related task. Features (J) and specification (K) are defined and evaluated for every characteristic, assigning them a factor (0 low effort, 0.5 medium effort, 1 high effort). All the factors are incorporated in the feature complexity coefficient (Equation 2.11)

and weighted by their percentage of presence in the component (Equations 2.12,2.13).

$$c_{f,feature} = \frac{F_N F_C F + S_N S_C F}{F_N + S_N} \tag{2.11}$$

Where, F_N, is the quantity of features; F_{CF}, is the feature complexity factor; S_N, is the quantity of specifications; S_{CF}, is the specification complexity factor.

$$F_{CF} = \frac{\sum_{j=1}^{J} factor - level_j)}{J} \tag{2.12}$$

$$S_{CF} = \frac{\sum_{k=1}^{K} factor - level_k)}{K} \tag{2.13}$$

The complexity index (obtained from the corresponding matrix) represents the difficulty of producing the component. A complexity index number does not have any meaning by itself. The comparison of process complexity indexes defines the closest one to the final shape, in terms of least needed manufacturing effort. Therefore, selecting the process with lowest complexity index, from a list of candidate processes, means to adhere to NNS approach (i.e. reduction in manufacturing effort). In this sense, the previous thresholds application to fuzzy sets (which reduces the process candidates number where complexity methodology is applied) is a further step in resources saving direction (limiting it to the most compatibles processes). Wiendahl and Scholtissek [1994] expand the complexity concept to the whole manufacturing process, including product design, operation (process equipment, tools and labour) and structure. Similarly to the previous authors, Kuzgunkaya and El Maraghy [2006] quantity the manufacturing complexity using an entropic approach. Their model evaluates both the various component types and technologies used in a manufacturing system on the systems structural complexity. The authors apply their model by selecting the lowest complex manufacturing system configuration of an engine cylinder head. Kerbrat et al. [2008] use the manufacturing complexity for evaluating how to combine subtractive and additive layer process for producing a mould. A modular CAD tool has been developed for comparing every single features of the mould, selecting the less complex one to produce. Guenov [2002] identify two measuring systems for high level decision makers. The aim is to compare alternatives during pre-competitive studies or during the architectural design process of composite systems. Similarly the to previous authors, the first measures complexity by estimating the Boltzmanns entropy, meanwhile the second measure is intended to estimate the costs and benefits related to systems performance.

Methodological investigations use a qualitative approach to determine the best process selection. The outputs of these papers is usually a framework or flowchart. Albiñana and Vila [2012] develop a complex framework for material and process selection, taking into consideration the whole product life-cycle. The framework analyse the product life-cycle, dividing it into three main phases: manufacturing, service and design/development. A dedicated part of the framework tries to rationalise the activities of requirements definition (design) and satisfaction (process). Xu et al. [2001a] develop a system for estimating the impact of different application of rapid prototyping processes. Using product requirements and process cost, the methodology is able to quantify the process characteristics and compare different processes. Shercliff and Lovatt [2001] define the interaction of process, material and design as peculiar to every category of processes (e.g. differences between casting and welding of an aluminium alloy). For the authors, the product requirements need to be matched one to one with the process attributes: these requirements can be design-related (e.g. mechanical properties or dimensional characteristics), production related (e.g. production volume and production rate) or processing-related. A pair matching is evaluated on technical feasibility, avoid in-process defects, product performance (i.e. final product characteristics) and economic bases. Differently from all the other authors, Lovatt and Shercliff [1998b,a] try to develop a connection between process modelling and process selection. They define the cost models and technical models most used in process selection, in order to validate the process candidate. Chakraborty and Dey [2007] use the Quality Function Development (QFD) chart, usually called house of quality, for matching the technical and design requirements as well as connecting them with the customer requirements. The authors developed a total score from this well-known quality enhancement instrument, using a score matrix.

Some authors have been able to implement process selection into **Optimization Algorithms**. In order to apply these, the investigators need to develop complex models for assessing the process application. Working on reconfigurable manufacturing systems, Bensmaine et al. [2013] use genetic algorithms (i.e. optimizing product design and machines data) and a simulation based optimization for process planning (i.e. providing the most economic chain configuration) for a single product type, taking into consideration market demand fluctuation and minimum production volume (i.e. for making the production feasible). The functions to optimize have been defined as machine usage and change costs, configuration change cost, tool usage and change costs. Vinodh et al. [2011] apply a fuzzy analytic network, using different criteria for evaluating the best process and the best supplier to select. Qualitative scores have been assigned to different criteria for evaluating the process/supplier. A matrix assigns a value to the process for every criteria and the algorithm ranks the different possible combinations. The selected criteria are coefficients that belong to business improvement, product quality, supplier service and risk.

Topological models describe how elements (Finite Element Analysis) are bounded and connected for classifying CAD models into shapes by detecting automatically (via algorithms) their geometrical characteristics. These numerical analyses are used for describing numerically the product features (e.g. using rules of proximity, the FEM elements identify an undercut). In this way, algorithms can assess all features of a component and assess the best process for realizing them. Holland et al. [2002] develop a CAD based algorithm that can identify cost effective manufacturing options for metal forming. The algorithm matches the

CAD features with a database of shapes and features, basing the matching on the critical features similarity (e.g. undercuts, external fillets, through holes). The optimal and economic processes to associate with every feature are also stored in a database. The orientation of the feature is determined by the algorithm. This determines the most suitable process, defining the forming direction and the realizable features. A similar approach has been used by Long et al. [2002], developing process-oriented forming features in cold extrusion to develop a process selection module (Computer-aided process planning, CAPP). The module is able to detect feature shape, main dimensions, and volumes, connecting them with the best suitable cold extrusion process option (i.e. giving also an indication of the stage numbers).

Material selection investigations can be taxonomized using the same categories of the process selection. In the context of process selection, the vast majority of authors use the workable material as screening for the available processes. However, some of the authors include material selection in their process selection method:Albiñana and Vila [2012] include a material selection in its methodology approach. Giachetti [1998] also uses fuzzy logic also for material selection, using a variable request for predicting the different final properties. This allows the author to extend their probabilistic approach to the material selection. Brechet et al. [2001] review the material selection methodology, pointing out the efficacy of the multi-objective criteria selection. Ashby has pioneered this field with several works (some of them extended to material selection). Ashby M. F. [1993] identify firstly some material performance index for materials. The author develop instruments for material selection, by plotting, for example, the Young modulus against the density of different materials or the linear expansion against the thermal conductivity. The nature of the mapping used is dependent on the final product requirements (thermal distortion): dedicated procedures need to be developed in order to measure the material attributes for the particular product design. Ashby [2000] uses single and multi-criteria optimization to the material selection problem. The authors derive, from the objective function, some differential equations, using multiple input variables and boundary conditions as constraints. In the multi-criteria selection, the solution of the equations are trade-off Pareto surfaces. As single target, the author use the minimization of the component mass. In their applications, the author uses the multi criteria for minimizing mass and cost (determining a Pareto trade-off solution) or using combined parameters to minimize (depending on the component requirements and functionality). For example, the author uses product cost and ratio of density ratio to elastic limit (i.e. measure of mechanical properties), forming another trade off Pareto selection. Kutz [2002] review some quantitative methods for material selection, pointing out the fundamental role of expert systems and numerical assistance (databases and knowledge base selection). Lately, the application of stochastic and heuristic algorithms to material selection has rapidly increased. For example, Milani et al. [2013] uses an Analytic Network Process (ANP) for multi-criteria selection: the material characteristics taken under consideration are density, thermal attributes (operating temperature, conductivity), physical properties, fatigue and mechanical characteristic. The network is able to establish a ranking of different materials for single product requirements.

2.2.2 Feasibility and Optimization of Manufacturing Process and Design

The process feasibility investigations are carried out by the researchers using three different approaches.

- **Analytical**: the feasibility is investigated using physical and mathematical models at a high level of abstraction. The models are often simplified approach, that only consider the essential system behaviour.
- **Numerical**: when an exact analytical solution is not often possible to obtain. So an heuristic (i.e. usually related to machine control, logistics and supply chain modelling), direct or iterative solutions (time-related mathematical model) are used for approximat-

ing the solution.

- **Experimental**: involve a testing design (e.g. Design of —Experiments), where variables are actively manipulated, controlled, and measured in an effort to gather evidence to support or refute a causal relationship. Models of these relationships can be derived from the experimental results.

These three approaches can be found in the feasibility and optimization investigations reported of every single process. For example Music et al. [2010] work on spinning has been adapted to review analytical, numerical and experiment papers related to flow forming (Section 5.2), in Case Study IA and IB

The connection between manufacturing process and product design has rarely been approached in a general way.

An example of this is the work of Wang and Shan [2007] that review the metamodels (developed from many different disciplines including statistics, mathematics, computer science, and various engineering disciplines) for supporting engineering design optimization.

Optimization of process and design has been approached by researchers using several methods:

- Optimization Algorithms
  - Analytical Models
  - Numerical Models
- Knowledge based
  - Expert Systems
    - Rule Based Optimization
    - Case-based Reasoning
  - Neural Networks

- Experimental Optimization (Design of Experiments)

The following paragrpahs consider each of these approaches in turn.

Optimization algorithms are often used for optimizing analytical and numerical models of processes. Depending on the model nature, the applied algorithm adapts to the optimization targets. The analytical models can be solved in closed form (giving an exact solution) or in a heuristic or stochastic form. The first is more rarely adopted, due to the difficulty of solving complex functions with a high number of variables. The second is more often used by researchers for both single and multi-objective optimizations. Similarly, the optimization algorithm for a numerical model is selected depending on the mathematical model applied. Many applications of analytical these methodologies can be found in literature [Hayama and Kudo, 1979a,b, Takemasu et al., 1996, Singhal et al., 1990, Tomov and Gagov, 1999] and numerical investigations [Zhao et al., 1997, Chen and Jung, 2008, Jalali Aghchai et al., 2012, Sanjari et al., 2008, Picart et al., 1998, Equbal et al., 2014, Castro et al., 2004, Zhang et al., 2014]. Some authors extend the analytical investigations to the complete manufacturing chain, instead of focusing on a single process. For example, Denkena et al. [2011] use a genetic algorithm for optimizing the lead time and quality of a forging line. The analytical models take into consideration production of both the workpiece and component. The algorithm optimizes simultaneously forging, turning (roughing and finishing), sawing and heating process (thermal treatment time). Graves et al. [1998] develop a cost model for optimising a manufacturing chain, developing the model for a single production stage as a building block for modeling a network of stages. Similarly to the analytical case, the numerical optimization can take into consideration the complete manufacturing chain. For example, Duggirala et al. [1994] optimize the whole cold forging process chain, applying micro Genetic Algorithms to a FEM.

Knowledge based expert systems attempt to represent initiate human knowledge as relationship between symbols (i.e. words). Sevenler et al. [1987] elaborate a CAD system for optimization the multi-stage cold forging process, based on die design rules. The rules set has been collected from experts in the field, which defined the rules for forward and backward extrusion (dimensional and die design instructions) as wells as the forging sequence. Similarly, Osakada et al. [1990] collect expert knowledge for building a set of design rules to apply to a FEM system, in order to minimize the cold forging defects by maximising the die filling (i.e. acting on die design).

Expert system (ES) optimization is one the most popular approach in manufacturing. The basic idea behind ES is simply that expertise, which is the vast body of task-specific knowledge, is transferred from a human to a computer, then like a human consultant, it gives advices and explains and if necessary, the logic behind the advice [Liao, 2005]. Expert systems are flexible and able to operate complex and various tasks. Their capability of operating on a variety of problems have made them spread along many fields of application. Liao [2005] identified the expert systems used in manufacturing, classifying them into different categories: dividing them into knowledge based, ruled based and cased-based systems. *Ruled Based Systems* are a subset of expert systems that contains information obtained from a human expert represented in the form of rules, such as IF - THEN. The rule can then be used to perform operations on data to infer appropriate conclusion. Kim and Im [1999] develop a multi-stage process optimization for forward and backward extrusion. A series of search trees, determined by pre-determined optimal operation, permit the artificial intelligence to select the most convenient forging path, using the required design characteristics as evaluation parameters.

The *Cased-based Reasoning* is a sub-category of expert system which adapts to solutions that were used to solve previous problems and for use in new problems. Kim and Im [1995] combine a material and design rule database with a CAD system. The aim is twofold: firstly, to design the forgeable geometry and also identify the basic sequence (based on the billet size and material), and, secondly, to minimize the level of the required forming loads at the last forging step by controlling the forming ratios. Caporalli et al. [1998] (described in the NNS literature review chapter) develop an expert system for hot forging optimization, based on

FEM, CAD and a priori optimal forging sequences to compare with.

Neural Networks. Osakada and Yang [1991] apply the neural networks to a previous model. As results, the system generates prediction of the most probable number of forming steps (using information about the complexity of the product shape and the materials of the die and billet) and a set of rules from FEM simulations. Similarly, Masood and Soo [2002] build a neural network for selecting parts suitable for additive layer manufacturing based on feature recognition.

Experimental optimization is carried out using statistical optimization tools. Several examples in the literature report experimental optimization application: particularly, Design of Experiments (for example, [Davidson et al., 2008, Kumar et al., 2011, Nahrekhalaji, 2010, Srinivasulu et al., 2012a]) and sensitivity analysis (for example, Jalali Aghchai et al. [2012]) are frequently used for optimizing casting and forging processes.

2.2.3 Process and Product Costs Analysis

Depending on nature of the process, the information available, the required level of accuracy and the cost variables used, Layer et al. [2002] classify cost models in three categories:

- **Statistical Models**: historic data and empirical examinations are evaluated with the objective of gaining information about the causal link between product characteristics and costs. The complexity of the result depends on the number of cost-relevant product characteristics. After modelling and training the neural network with adequate, historic data, it can be applied for cost calculation. The input parameters of the neural network are shape-describing and semantic product characteristics; the product costs are the output parameters

- **Analogous models**: cost estimation using analogy to reason from functional or geometrical similarity to a similar cost structure with the term similarity describing the level of correspondence of the relevant characteristics.

- **Generative-analytical models**: analytical approaches depict the relevant processes of product creation in detail and derive the costs incurred, aggregating them to provide an overall total. The result of the analytical approach based on a generative process plan is a detailed and differentiated cost estimation that enables specific conclusions about the cost drivers to be drawn and alternatives for adjusting product costs to be derived. Changes in boundary conditions, e.g. new manufacturing technology, new machines, etc, can more easily be considered, as the model used for calculation is dynamically generated.

In addition to the above dedicated cost models (for example, Park and Simpson [2005], Bariani et al. [1993], Nagahanumaiah et al. [2005], Jung [2002], Choudhury and Blum [1996], Knight [1992], Matwick [2003]) and general cost models (for example, [Allen and Swift, 1990, Esawi and Ashby, 2003, Niazi et al., 2006, Weustink et al., 2000, Yang and Lin, 1997, Chougule and Ravi, 2006, Jönsson et al., 2008]) can be found in the literature.

2.2.4 Closing Remarks

The literature related to manufacturing process selection, feasibility and optimization is clearly both broad and deep but in the context of this work the following observations can be made: fuzzy logic is capable of ranking the candidate processes in order of their features' compatibility with required ones. Usually these features include technological and other quantifiable requirements (e.g. tolerances, surface roughness), although it can be easily extended to other parameters (e.g. material usage, labour cost). The compatibilities values are able to rank the processes and materials for the given requirements. Fuzzy logic is also able to quantify the compatibility qualitative features compatibility and deal with uncertainty.

Complexity approaches have similar potential, although their application appear to be ori-

ented to product redesign and supply chain simplification. Similarly, topological optimization merges CAD and features identification, and is currently available in many commercial software packages. However, it fails to analyse complex problems, where uncertainty is present. Analytical models are less subjective and achieved the highest precision in quantification of process/material compatibly, particularly when few features are considered. However they are limited in dealing with uncertainty and complex connections between options. Further, analytical papers are limited to the consideration of only a few selection criteria into their selections: optimization papers overcome this problem by relying on probabilistic and analytical models, merging them with numerical capabilities and iteration.
Qualitative, methodological and knowledge based approaches are very flexible and in principle capable of dealing with complex interactions between material, design nd manufacturing process. However, the inability of quantifying feature's compatibility and generally low levels of subjectivity limit them to the selection of relatively restricted categories of process and materials.

2.3 Conclusions

The NNS review has identified and categorized the reported work on NNS manufacturing over the last thirty years. The process of creating a structured summary of the field has resulting in the identification of knowledge gaps and trends in the academic literature. NNS approach has evolved from being a generic term to a specific family of processes and technologies. The survey identifies the common approaches and the generic NNS research opportunities and limitations. These are:

1. The lack of a structured and systematic approached to NNS limits and confines researchers into the solution of problems that are limited to specific domains of manufacturing technology.

2. None of the reported investigations take into account both the economic and technological aspects of these relationships.

3. None of the reported investigations have examined a systematic link between process technological/economical investigation and process optimization.

4. No systematic link between product design and process optimization has been reported.

The literature review identifies that the process feasibility (both technological and economic) and the process/production optimization formulation varies based on the analysed process and manufacturing chains. On the other hand, the process/material selection formulation can be adapted to different processes, product designs and materials. The literature suggests that it is feasible to:

1. Select the manufacturing process based on material, production volume, component shape, technological and other requirements comparable with process attributes.

2. Carry out the technological feasibility study, connecting systematically the selected approach with a process optimization function.

3. Select correctly the cost model, considering the investigated process and the available data.

For process selection, fuzzy logic appears to be most flexible of the quantitative approaches, able to rank the processes for their compatibility with the target production. This dynamic approach is able ot also deal with a wide range of processes and uncertainty in process capabilities and multiple target requirements (qualitative and quantitative). However, the large amount of data necessary for using fuzzy logic makes it necessary to reduce the field of application. A static approach (e.g. PRIMA matrix of Swift and Booker [2013]) can reduce the number of processes involvd in the selection of the NNS candidate. Regarding the process feasibility and optimization, general patterns can be found for connecting the two approaches, although dedicated models need to be acquired (from the literature) or developed for every different NNS process. Particularly, the economic models and process models can be used for both establishing both the NNS process feasibility and also optimize its application.

In conclusion, NNS researchers have reported no quantitative methodology for guiding the manufacturing process and material selection. Similarly, systematic approaches for selecting the methodologies to apply NNS processes and determine their feasibility are not reported in the literature. Process parameters and product design optimization is not structured in the NNS literature using systematic approaches, with no available connections between feasibility models and optimization (e.g. developed in Denkena et al. [2011], Graves et al. [1998]).

In this sense, the aim of the research is to partially fill this gap by developing a quantitative methodology dedicated to the NNS manufacturing approach.

Chapter 3

The Near Net Shape Operative Protocol

This chapter proposes a systematic methodology for NNS process selection, feasibility analysis, and optimization. The methodology (known as the Near Net Shape Operative (NeNeShO) Protocol) is presented has three main phases, known as:

1. Phase I - Product Geometry, Manufacturing and Material Matching (ProGeMa3) is presented in Sub-section 3.1.1: as a methodology for primary shaping process selection, using a Process Selection Matrix (ProSMa) and fuzzy sets.

2. Phase II - Differential Cost and Feasibility Analysis (DCFA) presented in Sub-section 3.1.2: as a systematic approach for technological and economic feasibility analysis and modeling, based on a selected investigational approach (analytical, numerical or experimental) and specific production requirements.

3. Phase III - Conditional Design Optimization (CoDeO) is presented in Sub-section 3.1.3: (based on the previous phase models and investigational approach) this systematic approach selects the single or multi criteria optimization (i.e. including cost minimiza-

tion and technological constraints) method for product and process designs. A general model for approaching NNS optimization problem is also presented.

The phases are now described in detail.

3.1 Near Net Shape Operative Protocol: Framework Description

The research hypothesis (Section 1.2.8) and the limitation assumptions (Section 1.2.7) reduce the NeNeShO application to the discrete (i.e. not continuous) production of solid, metal and alloy components. A schematic overview of the framework is shown in Figure 3.1.

The NeNeShO Protocol is composed of three Phases with three different objectives:

- **Phase I - ProGeMa3** Methodology. The first step of ProGeMa3 is focused on the economic screening of existing opportunities for cost saving and execution of a first material selection phase (using Ashby [2000]). The components current shape, production volume and pre-selected material are subsequently used by a Process Screening Matrix (ProSMA) for selecting a cluster of compatible processes. This cluster (or list) of processes is used as input for the evaluation of the Process Compatibility. Using fuzzy logic, the process compatibility can rank the processes, and give as output the most suitable one, taking into consideration a series of features (e.g. tolerances or surface roughness).

- **Phase II - DFCA**. This methodology systematically combines the process investigation with a differential cost analysis. The technological feasibility study performed in this phase aims to establish if the process parameters require to form the component (i.e. forces, volumes, etc.) are within the range of reported investigations and equipment. After scoping literature and industrial practice, *Route 1, 2 or 3* can be selected depending on the type of investigation: analytical, numerical, or experimental respectively. Depending on the selection made, theoretical cost models (Route 1 or 2) or derived cost models (Route 3) needs to be developed. The differential cost analysis methodology is developed for comparing the existing and new NNS process chains, estimating the machining cost through a machining removal rate approximation

- **Phase III - CoDeO**. This phase systematically varies product design and process parameters in order to optimize the manufacturing cost, taking into account the NNS process and the remaining processes of the chain (e.g. machining) process mechanics and methods. The methodology is able to select the optimization methodology needed, depending on the route selected. A general formulation for NNS chain modelling is also introduced. The model identify the key variables and objective functions.

The following sections detail the processes required to implement each of the above phases.

3.1.1 Product Geometry, Manufacturing and Material Matching (ProGeMa3) Methodology - Phase I

Phase I of the operative protocol is devoted to finding opportunities for NNS applications. The proposed NNS selection methodology aims to extend the capabilities of reported systems and is known as Product, Geometry, Manufacturing, and Material Matching (ProGeMa3). The methodology is illustrated schematically in Figure 3.2. The aim of the methodology is to match an existent product design with a combination of material and process in order to create a NNS manufacturing operation.

The methodology is composed of four main steps:

1. Economic opportunities screening: identifies opportunities for NNS applications

2. Material Selection: selects the material in relationship to its functional requirements

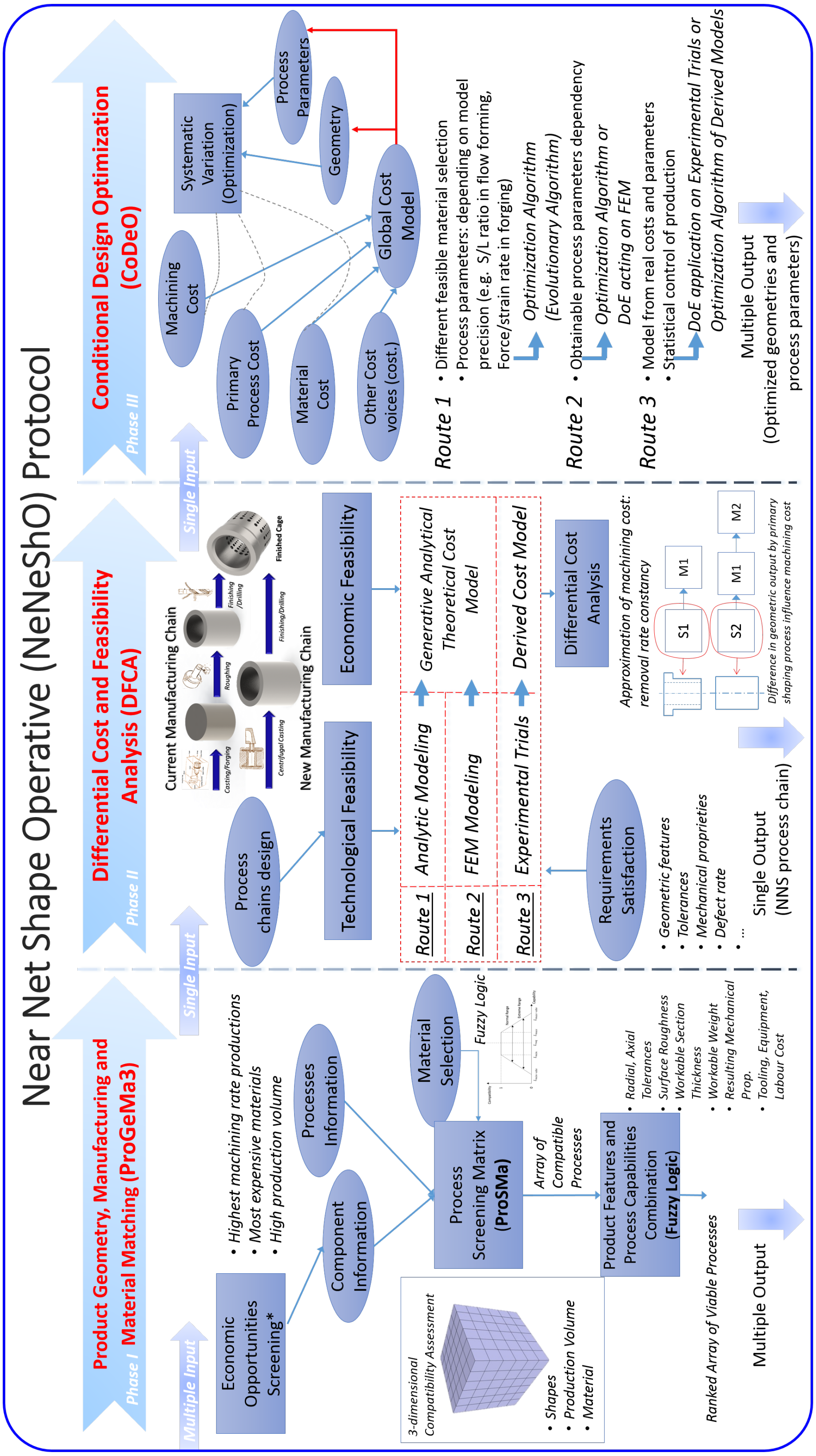


Figure 3.1: The Near Net Shape Operative (NeNeShO) Protocol.

3. Process Screening Matrix (ProSMa): acting as a filter, sets viable processes for the combination of shape, material and production volume.

4. Process Compatibility Evaluation (Fuzzy logic): is used to identify the best NNS process from the candidates selected in the previous steps.

Each of the elements of Phase I are described in detail.

Economic Opportunities Screening - Step 1

Economic opportunities screening *(Step 1)* is mainly devoted to screening and identify components whose manufacturing costs could potentially be improved by application of alternative NNS processes. Each the component's manufacturing chain need to be examined with aim of identifying production processes with the following features:

- High machining rate
- High raw material cost impact
- High production volume
- High lead time

The high complexity of the product design and manufacturing chain could be other factors in the identification of NNS opportunities. However, quantifying process chain complexity is difficult and consequently approximate evaluations have to be made in order to identify candidate components to target for NNS application. After this phase, information about the component's design and production needs to be obtained to enable the next step.

Material Selection - Step 2

The *Material Selection* has been done subsequent to the components selected in Step 1, using the method proposed by Ashby M. F. [1993] (reviewed in section 2.2.1). By using fuzzy

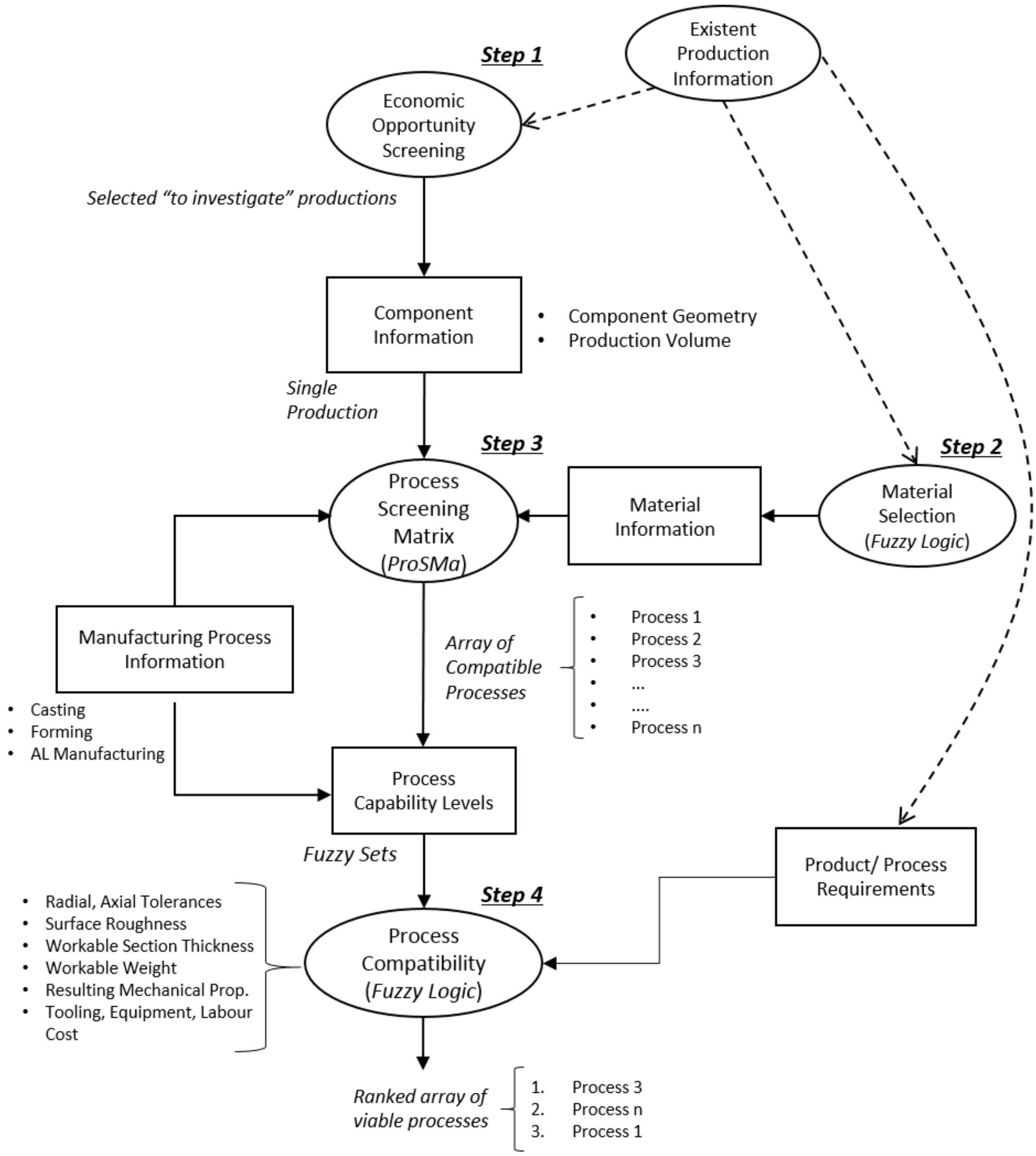


Figure 3.2: Product Geometry, Manufacturing and Material Matching (ProGeMa3) Methodology schematic.

logic, it is possible to select an optimal material based on the component requirements and usage conditions. In choosing this order of operations (i.e. material prior to process selection) ProGeMa3 is similar to the approaches of Darwish and El-Tamimi [1996], Er and Dias [2000], Swift and Booker [2013]. This order of operations effectively limits the resulting number of potential combinations and interactions between material and process selections.

Process Screening Matrix (ProSMA) - Step 3

The *Process Screening Matrix (ProSMA)* examines the technical feasibility of candidate processes and effectively reduce the number of possible manufacturing processes to investigate. Central to this step is a selection matrix (ProSMa), whose output is a list of viable processes given inputs of production volume, material and shape to investigate.

ProSMa's rows and columns are selected based on the component's geometry, production volume and the material.

Production volume, material and shape are classified in categories as follows:

- Material:
  - Irons
  - Steel (Carbon)
  - Steel (Alloy, Tool)
  - Stainless Steel
  - Copper & Alloys
  - Aluminium & Alloys
  - Magnesium & Alloys
  - Zinc & Alloys
  - Tin & Alloys
  - Lead &Alloys
  - Nickel & Alloys
  - Titanium & Alloys
- Production volume:
  - Very low (1 to 100)

  - Low (100 to 1,000)
  - Low to Medium (1,000 to 10,000)
  - Medium to High (10,000 to 100,000)
  - High (100,000+)
  - All quantities

- Component shape: 12 different component shapes can be selected, as shown in Table 3.1. The categories include three general geometric form (i.e. round, bar, tube) and five possible shapes derived from them (i.e. uniform cross section, change at the end, change at the centre, transverse element, and irregular).

The material and production volumes categories are adapted from Schey [1999], Kalpakjian and Schimd [2009] and Swift and Booker [2013].

The identification of the component's geometric shape is a qualitative judgment done manually by assessing the overall similarity to exemplars shown in Table 3.1.

The ProSMa matrix is presented in Tables 3.2, 3.3, 3.4 and 3.5. The matrix extended the work of Swift and Booker [2013], whose PRIMA matrix (Figure 2.5) only used the production volume and material as input. The number of casting and forming processes defined in Swift and Booker [2013] matrix do not take into consideration more recent manufacturing technologies, whereas ProSMa include novel process such as Semi Solid Metal Casting and additive layer manufacturing technologies. The ProSMa construction is based on the process literature review presented in Appendix B and on Schey [1999], Edwards et al. [2013], Ford and Despeisse [2016], Booth [2016], Swift and Booker [2013].

The manufacturing processes in the cells of the ProSMa have been indexed and divided into three broad categories as follows:

- Casting:
  - Sand Casting (C.1)

Increasing Spatial Complexity ⟶

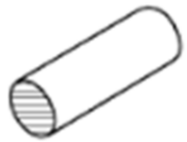
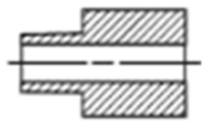
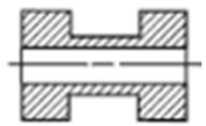
Abbreviation	0 Uniform Cross Section	1 Change at the end	2 Change at the centre	3 Transverse element	4 Irregular (Complex)
R(ound)					
B(ar)					
T(ube)					

Table 3.1: Component shape categories and nomenclature, adapted from Schey [1999].

Production Volume	Geometry	Irons			Steel (Carbon)			Steel (Alloy, Tool)			Stainless Steel			Copper & Alloys			Aluminium & Alloys		
		Round	Bar	Tube	Round	Bar	Tube	Round	Bar	Tube	Round	Bar	Tube	Round	Bar	Tube	Round	Bar	Tube
Very low (1 to 100)	0	C.4 C.5 C.6			C.6 C.11 F.1	C.6 C.11 F.1	C.6 C.10 F.1 F.7 F.8 F.9 F.10	C.6 C.11 F.1	C.1 C.6 C.11 F.1	C.1 C.6 C.10 F.1 F.7 F.8 F.9 F.10	C.6 C.11 F.1	C.6 C.11 F.1	C.6 C.10 F.1 F.8 F.9	C.6 C.11 F.1	C.6 C.11 F.1	C.6 C.10 F.1 F.7 F.8 F.9 F.10	C.6 C.11 F.1	C.6 C.11 F.1	C.6 C.10 F.1 F.7 F.8 F.9 F.10
	1				C.6 C.11 F.1 F.7			C.1 C.6 C.11 F.1 F.7						C.6 C.11 F.1 F.7			C.6 C.11 F.1 F.7		C.6 C.10 F.1 F.7 F.8 F.9 F.10
	2				C.6 C.11 F.1		C.6 C.10 F.8 F.9 F.10	C.1 C.6 C.11 F.1		C.1 C.6 C.10 F.8 F.9 F.10			C.6 C.10 F.8 F.9	C.11 C.6 F.1		C.6 C.10 F.8 F.9 F.10	C.6 C.11 F.1		C.6 C.10 F.8 F.9 F.10
	3				C.6 C.11	C.6 F.1	C.6 F.7 F.10	C.1 C.6 C.11 C.12	C.1 C.6 C.11 F.1	C.1 C.6 F.7 F.10	C.11 C.12 C.6	C.6 F.1	C.6	C.11 C.6	C.6 F.1	C.6 F.10	C.11 C.12 C.6	C.6 C.11 F.1	C.6 F.10
	4				C.6 C.11 C.12 F.7 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7	C.6 C.12 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7	C.6 C.10 F.7 F.8 F.10 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7	C.1 C.6 C.11 C.12 F.1 F.7 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7	C.1 C.6 C.11 C.12 F.1 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7	C.1 C.6 C.10 F.7 F.8 F.10 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7	C.6 C.11 C.12 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7	C.6 C.11 C.12 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7	C.6 C.10 F.8 AM.4 AM.5 AM.6 AM.7	C.10 C.11 C.12 C.6 F.1 F.7 F.8 F.9 F.10 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7	C.11 C.12 C.6 F.1 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7	C.6 C.10 F.7 F.8 F.10 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7	C.6 C.11 C.12 F.1 F.7 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7	C.6 C.11 C.12 F.1 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7	C.6 C.10 F.7 F.8 F.10 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7
Low (100 to 1,000)	0	C.2 C.4 C.5 C.6 C.8			C.6 C.11 F.1 F.2	C.6 C.11 F.1 F.2	C.6 C.10 F.1 F.2 F.8 F.9 F.10	C.1 C.2 C.6 F.1 F.2	C.1 C.2 C.6 F.1 F.2	C.1 C.2 C.6 F.1 F.7 F.8 F.9 F.10	C.2 C.6 F.1 F.2	C.2 C.6 F.1 F.2	C.2 C.6 F.1 F.8 F.9	C.2 C.6 F.1 F.2	C.2 C.6 F.1 F.2	C.2 C.6 F.1 F.7 F.8 F.9 F.10	C.2 C.3 C.6 C.11 F.1 F.2	C.2 C.3 C.6 C.11 F.1 F.2	C.2 C.3 C.6 C.10 F.1 F.7 F.8 F.9 F.10
	1				C.6 C.11 F.1 F.2 F.7			C.1 C.2 C.6 F.1 F.2 F.7		C.1 C.2 C.6 F.1 F.2 F.7 F.8 F.9 F.10			C.2 C.6 F.1 F.2 F.8 F.9	C.2 C.6 F.1 F.2 F.7		C.2 C.6 F.1 F.2 F.7 F.8 F.9 F.10	C.2 C.6 C.11 C.3 F.1 F.2 F.7		C.2 C.3 C.6 C.10 F.1 F.2 F.7 F.8 F.9 F.10
	2				C.6 C.11 F.1 F.2		C.6 F.2 F.8 F.9 F.10	C.1 C.2 C.6 F.1 F.2		C.1 C.2 C.6 F.2 F.8 F.9 F.10			C.2 C.6 F.2 F.8 F.9	C.2 C.6 F.1 F.2		C.2 C.6 F.2 F.8 F.9 F.10	C.2 C.6 C.11 C.3 F.1 F.2		C.2 C.3 C.6 C.10 F.2 F.8 F.9 F.10
	3				C.6 C11 F.2	C.6 F.1 F.2	C.6 F.2 F.10	C.1 C.2 C.6 F.2		C.1 C.2 C.6 F.2 F.10	C.2 C.6 F.2		C.2 C.6 F.2	C.2 C.6 F.1 F.2		C.2 C.6 F.2 F.10	C.2 C.6 C.11 C.12 C.3 F.2		C.2 C.3 C.6 F.2 F.10
	4				C.6 C.11 C.12 F.2 F.7 AM.5 AM.6 AM.7	C.6 C.12 F.2 AM.5 AM.6 AM.7	C.6 C.10 F.2 F.8 F.10 AM.5 AM.6 AM.7	C.1 C.2 C.6 F.2 F.7 AM.5 AM.6 AM.7	C.1 C.2 C.6 F.2 AM.5 AM.6 AM.7	C.1 C.2 C.6 F.2 F.7 F.8 F.10 AM.5 AM.6 AM.7	C.2 C.6 F.2 AM.5 AM.6 AM.7	C.2 C.6 F.2 AM.5 AM.6 AM.7	C.2 C.6 F.2 F.8 AM.5 AM.6 AM.7	C.2 C.6 F.2 AM.5 AM.6 AM.7	C.2 C.6 F.1 F.2 AM.5 AM.6 AM.7	C.2 C.6 F.2 F.7 F.8 F.10 AM.5 AM.6 AM.7	C.2 C.6 C.10 C.11 C.12 C.3 F.2 F.7 F.10 AM.5 AM.6 AM.7	C.2 C.3 C.6 C.11 C.12 F.2 AM.5 AM.6 AM.7	C.2 C.3 C.6 C.10 F.2 F.7 F.8 F.10 AM.5 AM.6 AM.7
Low to Medium (1,000 to 10,000)	0	C.2 C.4 C.5 C.6 C.7 C.8 C.11 F.3 F.11 F.12	C.2 C.4 C.5 C.6 C.7 C.8 F.3 F.11 F.12	C.2 C.4 C.5 C.6 C.7 C.8 C.10 F.3 F.11	C.2 C.5 C.6 C.7 C.8 C.11 F.1	C.2 C.5 C.6 C.7 C.8 C.11 F.1 F.2 F.3 F.12	C.2 C.5 C.6 C.7 C.8 C.10 F.1 F.3 F.8 F.9 F.10	C.2 F.1 F.2 F.3 F.4 F.5 F.10	C.2 F.1 F.2 F.3 F.4 F.5 F.10 F.11 F.12	C.2 F.1 F.3 F.4 F.5 F.10	C.2 C.6 C.11 F.1 F.2 F.3 F.11 F.12	C.2 C.6 C.11 F.1 F.2 F.3 F.11	C.2 C.6 C.10 F.1 F.3 F.8 F.9 F.10 F.11	C.2 C.3 C.5 C.7 C.11 C.15 F.1 F.2	C.2 C.3 C.5 C.7 C.11 C.15 F.1 F.2 F.11 F.12	C.2 C.3 C.5 C.7 C.10 C.15 F.1 F.8 F.9 F.11	C.2 C.3 C.7 C.8 C.11 C.14 C.15 F.1 F.2 F.11 F.12	C.2 C.3 C.7 C.8 C.11 C.14 C.15 F.1 F.2 F.11 F.12	C.2 C.3 C.7 C.8 C.10 C.14 C.15 F.1 F.10 F.11
	1				C.2 C.5 C.6 C.7 C.8 C.11 F.2 F.3 F.11 F.12		C.2 C.5 C.6 C.7 C.8 C.10 F.1 F.2 F.3 F.8 F.9 F.10	C.2 F.1 F.2 F.3 F.4 F.5 F.6 F.11 F.12	C.2 F.1 F.2 F.3 F.4 F.5 F.6 F.10 F.11 F.12	C.2 F.1 F.2 F.3 F.4 F.5 F.6 F.10 F.11		C.2 C.6 C.11 F.1 F.2 F.3 F.6 F.11 F.12	C.2 C.6 C.10 F.1 F.2 F.3 F.8 F.9 F.10 F.11	C.2 C.3 C.5 C.7 C.11 C.15 F.1 F.2 F.11 F.12		C.2 C.3 C.5 C.7 C.10 C.15 F.1 F.2 F.8 F.9 F.11			C.2 C.3 C.7 C.8 C.10 C.14 C.15 F.1 F.2 F.10 F.11
	2						C.2 C.5 C.6 C.7 C.8 C.10 F.2 F.8 F.9 F.10	C.2 F.1 F.2 F.3 F.4 F.6 F.11 F.12		C.2 F.2 F.5 F.6 F.10 F.11			C.2 C.6 C.10 F.2 F.8 F.9 F.10 F.11			C.2 C.3 C.5 C.7 C.10 C.15 F.2 F.8 F.9 F.11			C.2 C.3 C.7 C.8 C.10 C.14 C.15 F.2 F.10 F.11
	3	C.2 C.4 C.5 C.6 C.7 C.8 C.11 F.3 F.11	C.2 C.4 C.5 C.6 C.7 C.8	C.2 C.4 C.5 C.6 C.7 C.8	C.2 C.5 C.6 C.7 C.8 C.11 F.2 F.3 F.11	C.2 C.5 C.6 C.7 C.8 F.1 F.2 F.3	C.2 C.5 C.6 C.7 C.8 F.2 F.10	C.2 F.2 F.3 F.4 F.5 F.6 F.11	C.2 F.1 F.2 F.3 F.4 F.5 F.6	C.2 F.2 F.6 F.10	C.2 C.6 C.11 C.12 F.2 F.3 F.11	C.2 C.6 F.1 F.2 F.3 F.8	C.2 C.6 F.2 F.10	C.2 C.3 C.5 C.7 C.10 C.11 C.15 F.2 F.11	C.2 C.3 C.5 C.7 C.11 C.12 C.15 F.1 F.2	C.2 C.3 C.5 C.7 C.15 F.2	C.2 C.3 C.7 C.8 C.10 C.11 C.12 C.14 C.15 F.2 F.11	C.2 C.3 C.7 C.8 C.10 C.11 C.14 C.15 F.1 F.2 F.10	C.2 C.3 C.7 C.8 C.14 C.15 F.2 F.10
	4			C.2 C.4 C.5 C.6 C.7 C.8 C.10 F.11	C.2 C.5 C.6 C.7 C.8 C.11 C.12 F.2 F.3 F.11	C.2 C.5 C.6 C.7 C.8 C.11 F.2 F.3	C.2 C.5 C.6 C.7 C.8 C.10 F.2 F.8 F.10	C.2 F.2 F.3 F.4 F.5 F.6 F.11 F.12	C.2 F.1 F.2 F.3 F.4 F.5	C.2 F.2 F.3 F.6 F.10 F.11		C.2 C.6 C.11 C.12 F.2 F.3 F.8 F.9 F.10	C.2 C.6 C.10 F.2 F.8 F.10 F.11	C.2 C.3 C.5 C.7 C.11 C.12 C.15 F.2 F.11 F.12	C.2 C.3 C.5 C.7 C.11 C.12 C.15 F.2	C.2 C.3 C.5 C.7 C.10 C.15 F.2 F.8 F.11	C.2 C.3 C.7 C.8 C.11 C.12 C.14 C.15 F.2 F.11 F.12	C.2 C.3 C.7 C.8 C.11 C.12 C.14 C.15 F.2 F.10	C.2 C.3 C.7 C.8 C.10 C.14 C.1+C3:T175 F.2 F.10 F.11

Casting Processes

Sand Casting	C.1	Pressure Die Casting	C.9
Shell Moulding	C.2	True-Centrifugal Casting	C.10
Plaster Moulding	C.3	Semi-Centrifugal Casting	C.11
Lost Foam	C.4	Centrifuge Casting	C.12
Investment Casting	C.5	Squeeze	C.13
Ceramic Mould	C.6	Thixocasting Rheocasting	C.14
Gravity-Die Casting	C.7	Thixoforming	C.15
Vacuum-Die Casting	C.8		

Forming Processes

Open-Die Forging	F.1	Shear Forming	F.8
Closed-Die Forging	F.2	Flow Forming	F.9
Isothermal Forging	F.3	Hydroforming	F.10
Precision Forging	F.4	Powder Forging	F.11
Cold Forming	F.5	Isostatic Pressing	F.12
Injection Forging	F.6	Metal Injection Moulding	F.13
Rotary Forging	F.7		

Additive Layer Manufacturing

Selective Laser Syntering (SLS)	AM.1
Selective Laser Melting (SLM)	AM.2
Direct Metal Laser Sinering (DMLS)	AM.3
Electron Beam Melting (EBM)	AM.4
Laser Based Metal Deposition (LBDM)	AM.5
Electron Beam Based Metal Deposition (EBMD)	AM.6
Plasma Deposition Manufacturing (PDM)	AM.7

Table 3.2: Process Selection Matrix (ProSMa) - Part I (available at https://doi.org/10.15129/30a94e8d-cfc8-424f-9046-1e814ee0c0cbE).

Production Volume \ Material	Geometry	Irons			Steel (Carbon)			Steel (Alloy, Tool)			Stainless Steel			Copper & Alloys			Aluminium & Alloys			
		Round	Bar	Tube	Round	Bar	Tube	Round	Bar	Tube	Round	Bar	Tube	Round	Bar	Tube	Round	Bar	Tube	
Medium to High (10,000 to 100,000)	0	C.2 C.7 C.8 F.3 F.11 F.12	C.2 C.7 C.8 F.3 F.11 F.12	C.2 C.7 C.8 F.3 F.11	C.13 F.1 F.2 F.3 F.4 F.5	C.13 F.1 F.2 F.3 F.4 F.13	C.13 F.1 F.3 F.4 F.5 F.6 F.13	F.1 F.2 F.3 F.4 F.5	F.1 F.2 F.3 F.4 F.5 F.11 F.12	F.1 F.3 F.4 F.5 F.11	C.13 F.1 F.2 F.3 F.4 F.5 F.11	C.13 F.1 F.2 F.3 F.4 F.5 F.11 F.12 F.13	C.13 F.1 F.3 F.4 F.5 F.6 F.11 F.13	C.2 C.9 C.15 C.13 F.1 F.2 F.4 F.5 F.11 F.12 F.13	C.2 C.9 C.13 F.1 F.2 F.4 F.5 F.11 F.12 C.15 F.13	C.2 C.9 C.13 C.15 F.1 F.4 F.5 F.11 F.13	C.2 C.7 C.8 C.9 C.13 C.14 C.15 F.1 F.2 F.4 F.5 F.11 F.12	C.2 C.7 C.8 C.9 C.13 C.14 C.15 F.1 F.2 F.4 F.5 F.11 F.12	C.2 C.7 C.8 C.9 C.13 C.14 C.15 F.1 F.4 F.5 F.11	0
	1				C.13 F.13 F.1 F.2 F.3 F.4 F.5 F.6	C.13 F.1 F.2 F.3 F.4 F.5 F.6 F.12 F.13	C.13 F.2 F.3 F.4 F.5 F.6 F.11 F.13	F.1 F.2 F.3 F.4 F.5 F.6 F.11 F.12	F.1 F.2 F.3 F.4 F.5 F.6 F.11 F.12	F.1 F.2 F.3 F.4 F.5 F.6 F.11	C.13 F.1 F.2 F.1 F.2 F.3 F.4 F.5 F.6 F.11 F.12 F.13	C.13 F.1 F.2 F.3 F.4 F.5 F.6 F.11 F.12 F.13	C.13 F.1 F.2 F.3 F.4 F.5 F.6 F.11 F.13	C.2 C.9 C.13 F.1 F.2 F.4 F.5 F.6 F.11 F.12 C.15 F.13	C.2 C.9 C.13 F.1 F.2 F.4 F.5 F.6 F.11 F.12 C.15 F.13	C.2 C.9 C.13 C.15 F.1 F.2 F.4 F.5 F.6 F.11 F.13	C.2 C.7 C.8 C.9 C.13 C.14 C.15 F.1 F.2 F.4 F.5 F.6 F.11 F.12	C.2 C.7 C.8 C.9 C.13 C.14 C.15 F.1 F.2 F.4 F.5 F.6 F.11 F.12	C.2 C.7 C.8 C.9 C.13 C.14 C.15 F.1 F.2 F.4 F.5 F.6 F.11	1
	2				C.13 F.1 F.2 F.3 F.4 F.5 F.6 F.11 F.12 F.13	C.13 F.1 F.2 F.3 F.4 F.5 F.6 F.11 F.12 F.13	C.13 F.2 F.5 F.6 F.11 F.13	F.1 F.2 F.3 F.4 F.5 F.11 F.12		F.1 F.2 F.5 F.6 F.11	C.13 F.1 F.2 F.3 F.4 F.5 F.6 F.11 F.12 F.13		C.13 F.2 F.5 F.6 F.11 F.13	C.2 C.9 C.13 C.15 F.1 F.2 F.4 F.5 F.6 F.11 F.12 F.13		C.2 C.9 C.13 C.15 F.1 F.2 F.5 F.6 F.11 F.13	C.2 C.7 C.8 C.9 C.13 C.14 C.15 F.1 F.2 F.4 F.5 F.6 F.11 F.12		C.2 C.7 C.8 C.9 C.13 C.14 C.15 F.2 F.5 F.6 F.11	2
	3	C.2 C.7 C.8 F.3 F.11	C.2 C.7 C.8	C.2 C.7 C.8 F.11	C.13 F.2 F.3 F.4 F.6 F.11 F.13	C.13 F.1 F.2 F.3 F.4 F.5 F.6 F.13	C.13 F.1 F.2 F.5 F.6 F.11 F.13	F.2 F.3 F.4 F.6 F.11	F.1 F.2 F.3 F.4 F.5 F.6	F.2 F.5 F.6	C.13 F.2 F.3 F.4 F.6 F.11 F.13	C.13 F.1 F.2 F.3 F.4 F.5 F.13	C.13 F.2 F.6 F.13	C.2 C.9 C.13 F.2 F.4 F.6 F.11 C.15 F.13	C.2 C.9 C.13 F.1 F.2 F.4 F.5 F.6 C.15 F.13	C.2 C.9 C.13 C.15 F.2 F.6 F.13	C.2 C.7 C.8 C.9 C.13 C.14 C.15 F.2 F.4 F.6 F.11	C.2 C.7 C.8 C.9 C.13 C.14 C.15 F.1 F.2 F.4 F.5 F.6	C.2 C.7 C.8 C.9 C.13 C.14 C.15 F.2 F.6	3
	4			C.2 C.7 C.8 F.3 F.11	C.13 F.2 F.3 F.4 F.13	C.13 F.2 F.3 F.4 F.13	C.13 F.13 F.1 F.2 F.3 F.4 F.5 F.6 F.11	F.2 F.3 F.4 F.6 F.11	F.1 F.2 F.3 F.4 F.5	F.2 F.4 F.6 F.11	C.13 F.2 F.3 F.4 F.6 F.11 F.13	C.13 F.2 F.3 F.4 F.5 F.6 F.13	C.13 F.2 F.6 F.11 F.13	C.2 C.9 C.13 C.15 F.2 F.4 F.6 F.11 F.13	C.2 C.9 C.13 F.2 F.4 F.5 C.15 F.13	C.2 C.9 C.13 C.15 F.2F.6 F.11 F.13	C.2 C.7 C.8 C.9 C.13 C.14 C.15 F.2 F.4 F.6 F.11	C.2 C.7 C.8 C.9 C.13 C.14 C.15 F.2 F.4 F.5	C.2 C.7 C.8 C.9 C.13 C.14 C.15 F.2 F.6 F.11	4
High (100,000+)	0	C.2 C.7 C.8 F.11 F.12	C.2 C.7 C.8 F.11 F.12	C.2 C.7 C.8 F.11	C.13 F.1 F.2 F.3 F.4 F.5 F.13	C.13 F.1 F.2 F.3 F.4 F.5 F.13	C.13 F.1 F.3 F.4 F.5 F.13	F.13			C.13 F.13			C.2 C.13 C.15 F.1 F.2 F.4 F.5 F.11 F.12 F.13	C.2 C.13 C.15 F.1 F.2 F.4 F.5 F.11 F.12 F.13	C.2 C.13 C.15 F.1 F.4 F.5 F.11 F.13	C.2 C.7 C.8 C.9 C.13 C.14 F.1 F.2 F.4 F.5 F.11 F.12	C.2 C.7 C.8 C.9 C.13 C.14 F.1 F.2 F.4 F.5 F.11 F.12	C.2 C.7 C.8 C.9 C.13 C.14 F.1 F.4 F.5 F.11	0
	1				C.13 F.1 F.2 F.3 F.4 F.5 F.6 F.13	C.13 F.1 F.2 F.3 F.4 F.5 F.6 F.13	C.13 F.1 F.2 F.3 F.4 F.5 F.6 F.13							C.2 C.13 C.15 F.1 F.2 F.4 F.5 F.6 F.11 F.12 F.13	C.2 C.13 C.15 F.1 F.2 F.4 F.5 F.6 F.11 F.13	C.2 C.13 C.15 F.1 F.2 F.4 F.5 F.6 F.11 F.13	C.2 C.7 C.8 C.9 C.13 C.14 F.1 F.2 F.4 F.5 F.6 F.11 F.12	C.2 C.7 C.8 C.9 C.13 C.14 F.1 F.2 F.4 F.5 F.6 F.11 F.12	C.2 C.7 C.8 C.9 C.13 C.14 F.1 F.2 F.4 F.5 F.6 F.11	1
	2				C.13 F.1 F.2 F.3 F.4 F.5 F.6 F.13		C.13 F.2 F.5 F.6 F.13							C.2 C.13 C.15 F.1 F.2 F.4 F.5 F.6 F.11 F.12 F.13		C.2 C.13 C.15 F.2 F.5 F.6 F.11 F.13	C.2 C.7 C.8 C.9 C.13 C.14 F.1 F.2 F.4 F.5 F.6 F.11 F.12		C.2 C.7 C.8 C.9 C.13 C.14 F.2 F.5 F.6 F.11	2
	3	C.2 C.7 C.8 F.11	C.2 C.7 C.8	C.2 C.7 C.8	C.13 F.2 F.3 F.4 F.6 F.13		C.13 F.2 F.6 F.13							C.2 C.13 C.15 F.2 F.4 F.6 F.11 F.13		C.2 C.13 C.15 F.2 F.6 F.13	C.2 C.7 C.8 C.9 C.13 C.14 F.2 F.4 F.6 F.11	C.2 C.7 C.8 C.9 C.13 C.14 F.1 F.2 F.4 F.5 F.6	C.2 C.7 C.8 C.9 C.13 C.14 F.2 F.6	3
	4			C.2 C.7 C.8 F.11	C.13 F.2 F.3 F.4 F.6 F.13	C.13 F.1 F.2 F.3 F.4 F.5 F.13	C.13 F.2 F.6 F.13							C.2 C.13 C.15 F.2 F.4 F.6 F.11 F.13	C.2 C.13 C.15 F.2 F.4 F.5 F.13	C.2 C.13 C.15 F.2 F.5 F.6 F.11 F.13	C.2 C.7 C.8 C.9 C.13 C.14 F.2 F.4 F.6 F.11	C.2 C.7 C.8 C.9 C.13 C.14 F.2 F.4 F.5	C.2 C.7 C.8 C.9 C.13 C.14 F.2 F.6 F.11	4
All quantities	0	C.1			C.1 C.4 C.5			C.1 C.4 C.5			C.1 C.4 C.5			C.1 C.4 C.5			C.1 C.4 C.5			0
	1																			1
	2																			2
	3																			3
	4																			4

Casting Processes

Sand Casting	C.1	Pressure Die Casting	C.9
Shell Moulding	C.2	True-Centrifugal Casting	C.10
Plaster Moulding	C.3	Semi-Centrifugal Casting	C.11
Lost Foam	C.4	Centrifuge Casting	C.12
Investment Casting	C.5	Squeeze	C.13
Ceramic Mould	C.6	Thixocasting Rheocasting	C.14
Gravity-Die Casting	C.7	Thixoforming	C.15
Vacuum-Die Casting	C.8		

Forming Processes

Open-Die Forging	F.1	Shear Forming	F.8
Closed-Die Forging	F.2	Flow Forming	F.9
Isothermal Forging	F.3	Hydroforming	F.10
Precision Forging	F.4	Powder Forging	F.11
Cold Forming	F.5	Isostatic Pressing	F.12
Injection Forging	F.6	Metal Injection Moulding	F.13
Rotary Forging	F.7		

Additive Layer Manufacturing

Selective Laser Syntering (SLS)	AM.1
Selective Laser Melting (SLM)	AM.2
Direct Metal Laser Sinering (DMLS)	AM.3
Electron Beam Melting (EBM)	AM.4
Laser Based Metal Deposition (LBDM)	AM.5
Electron Beam Based Metal Deposition (EBMD)	AM.6
Plasma Deposition Manufacturing (PDM)	AM.7

Table 3.3: Process Selection Matrix (ProSMa) - Part II (available at `https://doi.org/10.15129/30a94e8d-cfc8-424f-9046-1e814ee0c0cbE`).

<table>
<tr><th rowspan="2">Production Volume</th><th rowspan="2">Material / Geometry</th><th colspan="3">Magnesium & Alloys</th><th colspan="3">Zinc & Alloys</th><th colspan="3">Tin & Alloys</th><th colspan="3">Lead & Alloys</th><th colspan="3">Nickel & Alloys</th><th colspan="3">Titanium& Alloys</th></tr>
<tr><th>Round</th><th>Bar</th><th>Tube</th><th>Round</th><th>Bar</th><th>Tube</th><th>Round</th><th>Bar</th><th>Tube</th><th>Round</th><th>Bar</th><th>Tube</th><th>Round</th><th>Bar</th><th>Tube</th><th>Round</th><th>Bar</th><th>Tube</th></tr>
<tr><td rowspan="5">Very low (1 to 100)</td><td>0</td><td>C.4 C.6 C.11 F.1</td><td rowspan="3">C.4 C.11 C.6 F.1</td><td>C.4 C.6 C.10F.1 F.7 F.8 F.9 F.10</td><td>C.4 C.6 C.11 F.1</td><td rowspan="5">C.1 C.4 C.6</td><td rowspan="2">C.1 C.4 C.6 F.7 F.8 F.9 F.10</td><td>C.1 C.4 C.6 C.11 F.1</td><td rowspan="5">C.1 C.4 C.6</td><td rowspan="3">C.1 C.4 C.6 F.7 F.8 F.9 F.10</td><td>C.1 C.4 C.6</td><td rowspan="5">C.1 C.4 C.6</td><td rowspan="2">C.1 C.4 C.6 F.7 F.8 F.9 F.10</td><td>C.4 C.6 C.11 F.1</td><td rowspan="3">C.4 C.6 C.11 F.1</td><td>C.4 C.6 C.10 F.1 F.7 F.8 F.9 F.10</td><td>C.1 C.4 C.5 F.1</td><td>C.1 C.4 F.1</td><td rowspan="2">C.1 C.4 C.5 F.1 F.7 F.8 F.9 F.10</td></tr>
<tr><td>1</td><td>C.4 C.11 C.6 F.1 F.7</td><td>C.4 C.6 C.10 F.1 F.7 F.8 F.9 F.10</td><td>C.1 C.4 C.6 C.11 F.7</td><td>C.1 C.4 C.6 F.7 C.11</td><td>C.1 C.4 C.6 F.7</td><td>C.4 C.6 C.11 F.1 F.7</td><td>C.4 C.6 C.10 F.1 F.7 F.8 F.9 F.10</td><td>C.1 C.4 C.5 F.1 F.7</td><td>C.1 C.4 F.1</td></tr>
<tr><td>2</td><td>C.4 C.6 C.11 F.1</td><td>C.4 C.6 C.10 F.8 F.9 F.10</td><td>C.1 C.4 C.6 C.11</td><td>C.1 C.4 C.6 F.8 F.9 F.10</td><td>C.1 C.4 C.6 C.11</td><td>C.1 C.4 C.6</td><td>C.1 C.4 C.6 F.8 F.9 F.10</td><td>C.4 C.6 C.11 F.1</td><td>C.4 C.6 C.10 F.8 F.9 F.10</td><td>C.1 C.4 C.5 F.1</td><td>C.1 C.4 F.1</td><td>C.1 C.4 C.5 F.8 F.9 F.10</td></tr>
<tr><td>3</td><td>C.4 C.10 C.11 C.12 C.6</td><td>C.4 C.11 C.12 C.6 F.1</td><td>C.4 C.6 F.10</td><td>C.1 C.4 C.6</td><td>C.1 C.4 C.6 F.10</td><td>C.1 C.4 C.6</td><td>C.1 C.4 C.6 F.10</td><td>C.1 C.4 C.6</td><td>C.1 C.4 C.6 F.8 F.10</td><td>C.4 C.6 C.11 F.1</td><td>C.4 C.6 F.1</td><td>C.4 C.6 C.10 F.10</td><td>C.1 C.4 C.5 F.1</td><td>C.1 C.4 F.1</td><td>C.1 C.4 C.5 F.10</td></tr>
<tr><td>4</td><td>C.4 C.6 C.11 C.12 F.7</td><td>C.4 C.11 C.12 C.6</td><td>C.4 C.6 C.10 F.7 F.8 F.10</td><td>C.1 C.4 C.6 F.7</td><td>C.1 C.4 C.6 F.7 F.8 F.10</td><td>C.1 C.4 C.6 F.7</td><td>C.1 C.4 C.6 F.7 F.8 F.10</td><td>C.1 C.4 C.6 F.7</td><td>C.1 C.4 C.6 F.7 F.8 F.10</td><td>C.4 C.6 C.11 C.12 F.7 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7</td><td>C.4 C.6 C.11 C.12 F.1 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7</td><td>C.4 C.6 C.10 F.7 F.8 F.10 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7</td><td>C.1 C.4 C.5 F.1 F.7 F.8 F.9 F.10 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7</td><td>C.1 C.4 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7</td><td>C.1 C.4 C.5 F.7 F.8 F.10 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7</td></tr>
<tr><td rowspan="5">Low (100 to 1,000)</td><td>0</td><td rowspan="3">C.3 C.4 C.5 C.6 F.1 F.2</td><td rowspan="4">C.3 C.4 C.5 C.6 F.1 F.2</td><td>C.3 C.4 C.5 C.6 F.1 F.8 F.9 F.10</td><td rowspan="5">C.1 C.3 C.4 C.6</td><td rowspan="5">C.1 C.3 C.4 C.6</td><td rowspan="3">C.1 C.3 C.4 C.6 F.8 F.9 F.10</td><td rowspan="5">C.1 C.3 C.4 C.6</td><td rowspan="5">C.1 C.3 C.4 C.6</td><td rowspan="3">C.1 C.3 C.4 C.6 F.8 F.9 F.10</td><td rowspan="5">C.1 C.3 C.4</td><td rowspan="5">C.1 C.3 C.4 C.6</td><td rowspan="3">C.1 C.3 C.4 F.8 F.9 F.10</td><td rowspan="3">C.2 C.4 C.6 C.11 F.1 F.2</td><td rowspan="3">C.2 C.4 C.6 C.11 F.1 F.2</td><td>C.2 C.4 C.6 C.10 F.1 F.8 F.9 F.10</td><td rowspan="3">C.1 C.4 C.5 F.1 F.2 F.11</td><td rowspan="3">C.1 C.4 C.5 F.1 F.2 F.11</td><td>C.1 C.4 C.5 F.1 F.8 F.9</td></tr>
<tr><td>1</td><td>C.3 C.4 C.5 C.6 F.1 F.2 F.8 F.9 F.10</td><td>C.2 C.4 C.6 C.10 F.1 F.2 F.8 F.9 F.10</td><td>C.1 C.4 C.5 F.1 F.2 F.8 F.9</td></tr>
<tr><td>2</td><td>C.3 C.4 C.5 C.6 F.2 F.8 F.9 F.10</td><td>C.2 C.4 C.6 C.10 F.2 F.8 F.9 F.10</td><td>C.1 C.4 C.5 F.1 F.2 F.8 F.9</td></tr>
<tr><td>3</td><td rowspan="2">C.3 C.4 C.5 C.6 F.2</td><td>C.3 C.4 C.5 C.6 F.2 F.10</td><td>C.1 C.3 C.4 C.6 F.10</td><td>C.1 C.3 C.4 C.6 F.10</td><td rowspan="2">C.1 C.3 C.4 F.8 F.10</td><td>C.2 C.4 C.6 C.11 F.2</td><td>C.2 C.4 C.6 F.1 F.2</td><td>C.2 C.4 C.6 F.2 F.10</td><td>C.1 C.4 C.5 F.1 F.2 F.8 F.9 F.11</td><td>C.1 C.4 C.5 C.6 F.1 F.2</td><td>C.1 C.4 C.5</td></tr>
<tr><td>4</td><td>C.3 C.4 C.5 C.6 F.2</td><td>C.3 C.4 C.5 C.6 F.2 F.8 F.10</td><td>C.1 C.3 C.4 C.6 F.8 F.10</td><td>C.1 C.3 C.4 C.6 F.8 F.10</td><td>C.2 C.4 C.6 C.11 C.12 F.2 AM.5 AM.6 AM.7</td><td>C.2 C.4 C.6 C.11 C.12 F.1 F.2 AM.5 AM.6 AM.7</td><td>C.2 C.4 C.6 C.10 F.2 F.8 F.10</td><td>C.2 C.4 C.6 C.11 C.12 F.2 AM.5 AM.6 AM.7</td><td>C.2 C.4 C.6 C.11 C.12 F.2 F.8 F.9 F.10 AM.5 AM.6 AM.7</td><td>C.2 C.4 C.6 C.10 F.2 F.8 F.10 AM.5 AM.6 AM.7</td></tr>
<tr><td rowspan="5">Low to Medium (1,000 to 10,000)</td><td>0</td><td>C.3 C.4 C.5 C.7 C.14 C.15 F.1 F.2 F.4 F.5</td><td>C.3 C.4 C.5 C.7 C.14 C.15 F.1 F.2 F.4 F.5</td><td>C.3 C.4 C.5 C.7 C.14 C.15 F.1 F.4 F.5 F.8 F.9 F.10</td><td rowspan="5">C.3 C.7 C.8 C.15</td><td rowspan="5">C.3 C.7 C.8 C.15</td><td rowspan="3">C.3 C.7 C.8 C.15 F.8 F.9 F.10</td><td rowspan="5">C.3 C.7 C.8 C.15</td><td rowspan="5">C.3 C.7 C.8 C.15</td><td rowspan="3">C.3 C.7 C.8 C.15 F.8 F.9 F.10</td><td rowspan="5">C.3 C.7 C.15</td><td rowspan="5">C.3 C.7 C.8 C.15</td><td rowspan="3">C.3 C.7 C.15 F.8 F.9 F.10</td><td rowspan="3">C.2 C.4 C.7 C.6 C.11 C.15 F.1 F.2 F.3 F.11 F.12</td><td rowspan="3">C.2 C.4 C.6 C.7 C.11 C.12 C.15 F.1 F.2 F.3 F.11 F.12</td><td>C.2 C.4 C.7 C.6 C.10 C.15 F.1 F.3 F.8 F.9 F.10 F.11</td><td rowspan="3">C.8 C.15 F.1 F.2 F.11 F.12</td><td rowspan="3">C.8 C.15 F.1 F.2 F.11 F.12</td><td>C.8 C.15 F.1 F.8 F.9 F.10 F.11</td></tr>
<tr><td>1</td><td rowspan="2">C.3 C.4 C.5 C.7 C.14 C.15 F.1 F.2 F.4 F.5 F.6</td><td rowspan="4">C.3 C.4 C.5 C.7 C.14 C.15 F.1 F.2 F.4 F.5 F.6</td><td>C.3 C.4 C.5 C.7 C.14 C.15 F.1 F.2 F.4 F.5 F.6 F.8 F.9 F.10</td><td>C.2 C.4 C.7 C.6 C.10 C.15 F.1 F.2 F.3 F.8 F.9 F.10 F.11</td><td>C.8 C.15 F.1 F.2 F.8 F.9 F.10 F.11</td></tr>
<tr><td>2</td><td>C.3 C.4 C.5 C.7 C.14 C.15 F.2 F.5 F.6 F.8 F.9 F.10</td><td>C.2 C.4 C.7 C.6 C.10 C.15 F.2 F.3 F.8 F.9 F.10 F.11</td><td>C.8 C.15 F.2 F.10 F.11</td></tr>
<tr><td>3</td><td>C.3 C.4 C.5 C.7 C.14 C.15 F.2 F.4 F.6</td><td>C.3 C.4 C.5 C.7 C.14 C.15 F.1 F.2 F.6 F.10</td><td>C.3 C.7 C.8 C.15 F.10</td><td>C.3 C.7 C.8 C.15 F.10</td><td rowspan="2">C.3 C.7 C.15 F.8 F.10</td><td>C.2 C.4 C.7 C.6 C.11 C.15 F.2 F.3</td><td>C.2 C.4 C.7 C.6 C.15 F.1 F.2</td><td>C.2 C.4 C.7 C.6 C.15 F.2 F.10</td><td>C.8 C.15 F.2 F.9 F.11</td><td>C.8 C.15 F.1 F.2 F.11</td><td>C.8 C.15 F.2 F.10</td></tr>
<tr><td>4</td><td>C.3 C.4 C.5 C.7 C.14 C.15 F.2 F.4 F.6</td><td>C.3 C.4 C.5 C.7 C.14 C.15 F.2 F.5 F.6 F.8 F.10</td><td>C.3 C.7 C.8 C.15 F.8 F.10</td><td>C.3 C.7 C.8 C.15 F.8 F.10</td><td>C.2 C.4 C.7 C.6 C.11 C.12 C.15 F.2 F.3</td><td>C.2 C.4 C.7 C.6 C.11 C.12 C.15 F.2</td><td>C.2 C.4 C.7 C.6 C.10 C.15 F.2 F.8 F.10 F.11</td><td>C.8 C.15 F.2 F.11</td><td>C.8 C.15 F.2 F.11</td><td>C.8 C.15 F.2 F.8 F.10 F.11</td></tr>
</table>

Casting Processes				Forming Processes				Additive Layer Manufacturing	
Sand Casting	C.1	Pressure Die Casting	C.9	Open-Die Forging	F.1	Shear Forming	F.8	Selective Laser Syntering (SLS)	AM.1
Shell Moulding	C.2	True-Centrifugal Casting	C.10	Closed-Die Forging	F.2	Flow Forming	F.9	Selective Laser Melting (SLM)	AM.2
Plaster Moulding	C.3	Semi-Centrifugal Casting	C.11	Isothermal Forging	F.3	Hydroforming	F.10	Direct Metal Laser Sinering (DMLS)	AM.3
Lost Foam	C.4	Centrifuge Casting	C.12	Precision Forging	F.4	Powder Forging	F.11	Electron Beam Melting (EBM)	AM.4
Investment Casting	C.5	Squeeze	C.13	Cold Forming	F.5	Isostatic Pressing	F.12	Laser Based Metal Deposition (LBDM)	AM.5
Ceramic Mould	C.6	Thixocasting Rheocasting	C.14	Injection Forging	F.6	Metal Injection Moulding	F.13	Electron Beam Based Metal Deposition (EBMD)	AM.6
Gravity-Die Casting	C.7	Thixoforming	C.15	Rotary Forging	F.7			Plasma Deposition Manufacturing (PDM)	AM.7
Vacuum-Die Casting	C.8								

Table 3.4: Process Selection Matrix (ProSMa) - Part III (available at `https://doi.org/10.15129/30a94e8d-cfc8-424f-9046-1e814ee0c0cbE`).

<table>
<tr><th rowspan="2" colspan="2">Material
Production Volume / Geometry</th><th colspan="3">Magnesium & Alloys</th><th colspan="3">Zinc & Alloys</th><th colspan="3">Tin & Alloys</th><th colspan="3">Lead & Alloys</th><th colspan="3">Nickel & Alloys</th><th colspan="3">Titanium& Alloys</th><th rowspan="2"></th></tr>
<tr><th>Round</th><th>Bar</th><th>Tube</th><th>Round</th><th>Bar</th><th>Tube</th><th>Round</th><th>Bar</th><th>Tube</th><th>Round</th><th>Bar</th><th>Tube</th><th>Round</th><th>Bar</th><th>Tube</th><th>Round</th><th>Bar</th><th>Tube</th></tr>
<tr><td rowspan="5">Medium to High (10,000 to 100,000)</td><td>0</td><td rowspan="2">C.7 C.9 C.14 C.15 F.1 F.2 F.4 F.5</td><td>C.7 C.9 C.14 C.15 F.1 F.2 F.4 F.5</td><td>C.7 C.9 C.14 C.15 F.1 F.4 F.5</td><td rowspan="2">C.7 C.8 C.9 C.15 F.4 F.5</td><td>C.7 C.8 C.9 C.15 F.4 F.5</td><td>C.7 C.8 C.9 C.15 F.4 F.5</td><td>C.7 C.8 C.9 C.15 F.4 F.5</td><td>C.7 C.8 C.9 C.15 F.4 F.5</td><td>C.7 C.8 C.9 C.15 F.4 F.5</td><td>C.7 C.9 C.15 F.4 F.5</td><td>C.7 C.8 C.9 C.15 F.4 F.5</td><td rowspan="3">C.7 C.9 C.15 F.4 F.5 F.6</td><td rowspan="3">C.1 C.7 C.9 C.11 C.15 F.3 F.11 F.12 F.13</td><td rowspan="3">C.1 C.7 C.9 C.11 C.15 F.3 F.11 F.12 F.13</td><td rowspan="2">C.1 C.7 C.9 C.10 C.15 F.3 F.11 F.13</td><td>C.8 C.15 F.1 F.2 F.3 F.4 F.5 F.11 F.12 F.13</td><td rowspan="3">C.8 C.15 F.1 F.2 F.3 F.11 F.12</td><td>C.8 C.15 F.1 F.2 F.3 F.4 F.5 F.11 F.13</td><td>0</td></tr>
<tr><td>1</td><td rowspan="3">C.7 C.9 C.14 C.15 F.1 F.2 F.4 F.5 F.6</td><td>C.7 C.9 C.14 C.15 F.1 F.2 F.4 F.5 F.6</td><td rowspan="3">C.7 C.8 C.9 C.15 F.4 F.5 F.6</td><td>C.7 C.8 C.9 C.15 F.4 F.5 F.6</td><td>C.7 C.8 C.9 C.15 F.4 F.5 F.6</td><td rowspan="3">C.7 C.8 C.9 C.15 F.4 F.5 F.6</td><td>C.7 C.8 C.9 C.15 F.4 F.5 F.6</td><td>C.7 C.9 C.15 F.4 F.5 F.6</td><td rowspan="3">C.7 C.8 C.9 C.15 F.4 F.5 F.6</td><td>C.8 C.15 F.13 F.1 F.2 F.3 F.4 F.5 F.6 F.11 F.12</td><td>C.8 C.15 F.1 F.2 F.5 F.6 F.11 F.13</td><td>1</td></tr>
<tr><td>2</td><td>C.7 C.9 C.14 C.15 F.1 F.2 F.4 F.5 F.6</td><td>C.7 C.9 C.14 C.15 F.2 F.5 F.6</td><td>C.7 C.8 C.9 C.15 F.4 F.5 F.6</td><td>C.7 C.8 C.9 C.15 F.5 F.6</td><td>C.7 C.8 C.9 C.15 F.4 F.5 F.6</td><td>C.7 C.8 C.9 C.15 F.5 F.6</td><td>C.7 C.9 C.15 F.4 F.5 F.6</td><td>C.1 C.7 C.9 C.10 C.15 F.11 F.13</td><td>C.8 C.15 F.13 F.1 F.2 F.3 F.4 F.5 F.6 F.11 F.12</td><td>C.8 C.15 F.2 F.3 F.5 F.6 F.11 F.13</td><td>2</td></tr>
<tr><td>3</td><td>C.7 C.9 C.14 C.15 F.2 F.4 F.6</td><td>C.7 C.9 C.14 C.15 F.2 F.6</td><td>C.7 C.8 C.9 C.15 F.4 F.6</td><td rowspan="2">C.7 C.8 C.9 C.15 F.6</td><td>C.7 C.8 C.9 C.15 F.4 F.6</td><td rowspan="2">C.7 C.8 C.9 C.15 F.6</td><td>C.7 C.9 C.15 F.4 F.6</td><td rowspan="2">C.7 C.9 C.15 F.4 F.6</td><td rowspan="2">C.1 C.7 C.9 C.15 F.3 F.11 F.13</td><td>C.1 C.7 C.9 C.15 F.13</td><td>C.1 C.7 C.9 C.15 F.13</td><td>C.8 C.15 F.13 F.2 F.3 F.4 F.6 F.11</td><td>C.8 C.15 F.1 F.2 F.3</td><td>C.8 C.15 F.2 F.6 F.13</td><td>3</td></tr>
<tr><td>4</td><td>C.7 C.9 C.14 C.15 F.2 F.4 F.6</td><td>C.7 C.9 C.14 C.15 F.2 F.4 F.5</td><td>C.7 C.9 C.14 C.15 F.1 F.2 F.4 F.6</td><td>C.7 C.8 C.9 C.15 F.4 F.6</td><td>C.7 C.8 C.9 C.15 F.4 F.5</td><td>C.7 C.8 C.9 C.15 F.4 F.6</td><td>C.7 C.8 C.9 C.15 F.4 F.5</td><td>C.7 C.9 C.15 F.4 F.6</td><td>C.7 C.8 C.9 C.15 F.4 F.5</td><td>C.1 C.7 C.9 C.11 C.12 C.15 F.13</td><td>C.1 C.7 C.9 C.10 C.15 F.11 F.13</td><td>C.8 C.15 F.13 F.2 F.3 F.4 F.6 F.11</td><td>C.8 C.15 F.2 F.3</td><td>C.8 C.15 F.2 F.3 F.6 F.11 F.13</td><td>4</td></tr>
<tr><td rowspan="5">High (100,000+)</td><td>0</td><td>C.7 C.9 C.14 C.15 F.1 F.2 F.4 F.5</td><td>C.7 C.9 C.14 C.15 F.1 F.2 F.4 F.5</td><td>C.7 C.9 C.14 C.15 F.1 F.4 F.5</td><td>C.8 C.9 C.15 F.4 F.5</td><td>C.8 C.9 C.15 F.4 F.5</td><td>C.8 C.9 C.15 F.4 F.5</td><td>C.8 C.9 C.15 F.4 F.5</td><td>C.8 C.9 C.15 F.4 F.5</td><td>C.8 C.9 C.15 F.4 F.5</td><td>C.9 C.15 F.4 F.5</td><td>C.8 C.9 C.15 F.4 F.5</td><td rowspan="3">C.9 C.15 F.4 F.5 F.6</td><td rowspan="5" colspan="3">C.15 F.13</td><td rowspan="5" colspan="3">C.15 F.13</td><td>0</td></tr>
<tr><td>1</td><td>C.7 C.9 C.14 C.15 F.1 F.2 F.4 F.5 F.6</td><td rowspan="3">C.7 C.9 C.14 C.15 F.1 F.2 F.4 F.5 F.6</td><td>C.7 C.9 C.14 C.15 F.1 F.2 F.4 F.5 F.6</td><td>C.8 C.9 C.15 F.4 F.5 F.6</td><td rowspan="3">C.8 C.9 C.15 F.4 F.5 F.6</td><td>C.8 C.9 C.15 F.4 F.5 F.6</td><td>C.8 C.9 C.15 F.4 F.5 F.6</td><td rowspan="3">C.8 C.9 C.15 F.4 F.5 F.6</td><td>C.8 C.9 C.15 F.4 F.5 F.6</td><td>C.9 C.15 F.4 F.5 F.6</td><td rowspan="3">C.8 C.9 C.15 F.4 F.5 F.6</td><td>1</td></tr>
<tr><td>2</td><td>C.7 C.9 C.14 C.15 F.1 F.2 F.4 F.5 F.6</td><td>C.7 C.9 C.14 C.15 F.2 F.5 F.6</td><td>C.8 C.9 C.15 F.4 F.5 F.6</td><td>C.8 C.9 C.15 F.5 F.6</td><td>C.8 C.9 C.15 F.4 F.5 F.6</td><td>C.8 C.9 C.15 F.5 F.6</td><td>C.9 C.15 F.4 F.5 F.6</td><td>2</td></tr>
<tr><td>3</td><td>C.7 C.9 C.14 C.15 F.2 F.4 F.6</td><td>C.7 C.9 C.14 C.15 F.2 F.6</td><td>C.8 C.9 C.15 F.4 F.6</td><td rowspan="2">C.8 C.9 C.15 F.6</td><td>C.8 C.9 C.15 F.4 F.6</td><td>C.8 C.9 C.15 F.6</td><td>C.9 C.15 F.4 F.6</td><td rowspan="2">C.9 C.15 F.4 F.6</td><td>3</td></tr>
<tr><td>4</td><td>C.7 C.9 C.14 C.15 F.2 F.4 F.6</td><td>C.7 C.9 C.14 C.15 F.2 F.4</td><td>C.7 C.9 C.14 C.15 F.2 F.6</td><td>C.8 C.9 C.15 F.4 F.6</td><td>C.8 C.9 C.15 F.4 F.5</td><td>C.8 C.9 C.15 F.4 F.6</td><td>C.8 C.9 C.15 F.4</td><td>C.8 C.9 C.15 F.4 F.6</td><td>C.9 C.15 F.4 F.6</td><td>C.8 C.9 C.15 F.4</td><td>4</td></tr>
<tr><td rowspan="5">All quantities</td><td>0</td><td rowspan="5" colspan="3">C.1</td><td rowspan="5" colspan="3">none</td><td rowspan="5" colspan="3">none</td><td rowspan="5" colspan="3">none</td><td rowspan="5" colspan="3">C.1 C.5</td><td rowspan="5" colspan="3">none</td><td>0</td></tr>
<tr><td>1</td><td>1</td></tr>
<tr><td>2</td><td>2</td></tr>
<tr><td>3</td><td>3</td></tr>
<tr><td>4</td><td>4</td></tr>
</table>

Casting Processes

Sand Casting	C.1	Pressure Die Casting	C.9
Shell Moulding	C.2	True-Centrifugal Casting	C.10
Plaster Moulding	C.3	Semi-Centrifugal Casting	C.11
Lost Foam	C.4	Centrifuge Casting	C.12
Investment Casting	C.5	Squeeze	C.13
Ceramic Mould	C.6	Thixocasting Rheocasting	C.14
Gravity-Die Casting	C.7	Thixoforming	C.15
Vacuum-Die Casting	C.8		

Forming Processes

Open-Die Forging	F.1	Shear Forming	F.8
Closed-Die Forging	F.2	Flow Forming	F.9
Isothermal Forging	F.3	Hydroforming	F.10
Precision Forging	F.4	Powder Forging	F.11
Cold Forming	F.5	Isostatic Pressing	F.12
Injection Forging	F.6	Metal Injection Moulding	F.13
Rotary Forging	F.7		

Additive Layer Manufacturing

Selective Laser Syntering (SLS)	AM.1
Selective Laser Melting (SLM)	AM.2
Direct Metal Laser Sinering (DMLS)	AM.3
Electron Beam Melting (EBM)	AM.4
Laser Based Metal Deposition (LBDM)	AM.5
Electron Beam Based Metal Deposition (EBMD)	AM.6
Plasma Deposition Manufacturing (PDM)	AM.7

Table 3.5: Process Selection Matrix (ProSMa) - Part IV (available at `https://doi.org/10.15129/30a94e8d-cfc8-424f-9046-1e814ee0c0cbE`).

- Shell Moulding (C.2)
- Plaster Moulding (C.3)
- Lost Foam Casting (C.4)
- Investment Casting (C.5
- Ceramic Mould Casting (C.6)
- Gravity-Die Casting (C.7)
- Gravity-Die Casting (C.8)
- Vacuum-Die Casting (C.9)
- Pressure Die Casting (C.10)
- True-Centrifugal Casting (C.11)
- Semi-Centrifugal Casting (C.12)
- Centrifuge Casting (C.13)
- Squeeze Casting (C.14)
- Thixocasting Rheocasting (C.15)
- Thixoforming (C.16)

- Forming:
  - Open-Die Forging (F.1)
  - Closed-Die Forging (F.2)
  - Isothermal Forging (F.3)
  - Precision Forging (F.4)
  - Cold Forming (F.5)
  - Injection Forging (F.6)

  - Rotary Forging (F.7)
  - Shear Forming (F.8)
  - Flow Forming (F.9)
  - Hydroforming (F.10)
  - Powder Forging (F.11)
  - Isostatic Pressing (F.12)
  - Metal Injection Moulding (F.13)

- Additive Layer Manufacturing:
  - Selective Laser Sintering (SLS) (AM.1)
  - Selective Laser Melting (SLM) (AM.2)
  - Direct Metal Laser Sintering (DMLS) (AM.3)
  - Electron Beam Melting (EBM) (AM.4)
  - Laser Based Metal Deposition (LBDM) (AM.5)
  - Electron Beam Based Metal Deposition (EBMD) (AM.6)
  - Plasma Deposition Manufacturing (PDM) (AM.7)

The ProSMa is intended to be used for single components. Referring to Table 3.1, for all Round (R), Barr (B) and Tubular (T) basic geometries, the irregular (complex) shape (classified as 4) is effectively a " catch all" that matches all the cases that are not included in the other categories (i.e. uniform cross section, change at the end, change at the centre, transverse element). If the shape cannot be identified from its spatial complexity (i.e. it si not associable with any of the categories form 0 to 4), all the process for the identified basic geometry (Round, Barr or Tube) should be taken into consideration for the considered material and production volume.

The ProSMa can also be used as guidance for mapping the manufacturing implications of design changes (e.g. movement from a geometric category to another). However ProSMa is not meant to be a tool for generating new product designs (given the difficulty of representing all the possible functional features). Although, it can provide guidance for the manufacturing of merged geometries (e.g. redesign of two distinct components to a single one).

Process Compatibility Evaluation - Step 4

The *Process Compatibility Evaluation* uses fuzzy logic to enable identification of the most suitable manufacturing processes from the viable ones, selected in Step 3. This stage has a dual function:

- Final screening: the processes that cannot form particular features of components are excluded at this stage (e.g. unfeasible thickness section).
- Process ranking: all the viable processes are ranked in order of their compatibility (i.e. between product requirements and process capabilities).

The fuzzy logic approach allows these two objectives to be achieved by associating the request with a four level fuzzy description of the process capabilities (an approach firstly proposed by Giachetti [1998] and presented in Section 2.2.1). The process capabilities are described by four levels and trapezoidal probabilistic behaviour: the medium levels (2 and 3) are associated with the normal process capabilities, so the assigned probability to be achieved is 1. The extreme ranges (1 and 4) are the maximum and minimum capabilities reachable by the process. Between these values and the normal operative ranges (i.e. between 1 and 2 and between 3 and 4), the fuzzy probability needs to be taken into consideration, by assuming a linear behaviour between the two points. Using the Equations (2.1), (2.2), (2.3), (2.4), (2.5) and (2.6), it is possible to determine the process compatibility by assessing the required levels, for a number of product attributes, and comparing them with four capabilities levels

Linguistic evaluation	Value
High	5
Moderate to High	4
Moderate	3
Low to Moderate	2
Low	1

Table 3.6: Linguistic evaluation scale used in fuzzy logic.

(fuzzy trapezoidal shape) of the processes. The following four characteristics are taken into consideration:

- Technological Attributes (tolerances and surface roughness)
- Feasibility attributes (minimum section and weight)
- Resulting mechanical properties
- Process Costs (tooling, equipment and labour)

The first two categories are numerical, while the last two can be evaluated only on a qualitative scale. The linguistic evaluation scale employed is shown in Table 3.6: it allows the translation of qualitative evaluation into a numerical one (that can be used for probability calculation). The calculated compatibility for each characteristic are combined to a single compatibility value using the Equations 2.5 and 2.6. The compatibility values are ranked using a weighting scale shown in Table 3.7. As mentioned previously, Giachetti [1998] introduced a

Features Importance Category	Weight
Very Important	5
Important	4
Medium Important	3
Low Important	2
Almost negligible	1

Table 3.7: Weighting Scale used in fuzzy logic.

method of combining measures of possibility and necessity presented here as Equation 3.1.

$$C_i = P_i(\beta)N_i(1-\beta) \tag{3.1}$$

Where: *i-th* is the index of the attribute; C_i is the compatibility for the single attribute; P_i is the possibility (based on the probabilistic evaluation of the request); N_i is the necessity probabilistic evaluation; β is the 'optimism' level. As mentioned, the latter is selected according to Giachetti [1998] as 0.5. The Equations 2.1, 2.2, 2.3 and 2.4, for calculating the single feature probability, need to be modified depending on the required value form (e.g. constant value, linear, quadratic, ext.). If the request is a single value (R_{eq}), the possibility and necessity values are calculated as in Tables 3.8 and 3.9, using the four capabilities levels ($Lev_1, Lev_2, Lev_3, Lev_4$). Similarly if the request is smaller or bigger than certain values, the possibility and necessity formulas need to be modified accordingly, as displayed in Tables 3.10, 3.11 and Tables 3.12, 3.13 respectively.

$Request = Valuey$	Possibility
If $Level1 \leq Request < Level2$	$(Req - Lev_1)/(Lev_2 - Lev_1)$
If $Level2 \leq Request \leq Level3$	1
If $Level3 < Request \leq Level4$	1-$(Req - Lev_3)/(Lev_4 - Lev_3)$
If $Request < Level1$	0
If $Request > Level4$	0

Table 3.8: Possibility probability calculation for $Request = Value$.

$Request = Value$	Necessity
If $Level1 \leq Request < Level2$	1-$(Req - Lev_1)/(Lev_2 - Lev_1)$
If $Level2 \leq Request \leq Level3$	1
If $Level3 < Request \leq Level4$	1-$(Req - Lev_3)/(Lev_4 - Lev_3))$
If $Request < Level1$	0
If $Request > Level4$	0

Table 3.9: Necessity probability calculation for $Request = Value$.

$Request < Value$	Possibility
If $Level1 \leq Request < Level2$	$(Req - Lev_1)/(Lev_2 - Lev_1)$
If $Level2 \leq Request \leq Level3$	1
If $Level3 < Request \leq Level4$	1
If $Request < Level1$	0
If $Request > Level4$	1

Table 3.10: Possibility probability calculation for $Request < Value$.

$Request < Value$	Necessity
If $Level1 \leq Request < Level2$	1-$(Req - Lev_1)/(Lev_2 - Lev_1)$
If $Level2 \leq Request \leq Level3$	0
If $Level3 < Request \leq Level4$	0
If $Request < Level1$	1
If $Request > Level4$	0

Table 3.11: Necessity probability calculation for $Request < Value$.

$Request > Value$	Possibility
If $Level1 \leq Request < Level2$	1-$(Req - Lev_3)/(Lev_4 - Lev_3)$
If $Level2 \leq Request \leq Level3$	1
If $Level3 < Request \leq Level4$	1
If $Request < Level1$	0
If $Request > Level4$	1

Table 3.12: Possibility probability calculation for $Request > Value$.

3.1.2 Differential Cost and Feasibility Analysis (DCFA) - Phase II

Phase II assesses systematically the potential benefit and feasibility of a new NNS manufacturing process replacing an existing process. Because the proposed methodology considers both technological and economic feasibility (shown schematically in 3.3) it is referred to a 'Differential Cost and Feasibility Analysis' (DCFA). The first step assesses the technical ability of the new process chain to produce a component that satisfies the specifications (i.e. geometric features, tolerances, mechanical properties, defect rates). Whereas, the economic feasibility describes the efficiency of the new manufacturing chain by measuring the resources used for producing the component (i.e. cost) and comparing them to the current method of production.

Requirements and Process Chain Definition

Although NNS processes can vary in their nature (e.g. casting, forging, additive layer manufacturing) they are always primary shaping processes (i.e. one that facilitates the transition from raw material to a semi-finished product). Therefore the choice of NNS operation inevitably impacts on the supply chain design (e.g. required machining steps, heat treatment,

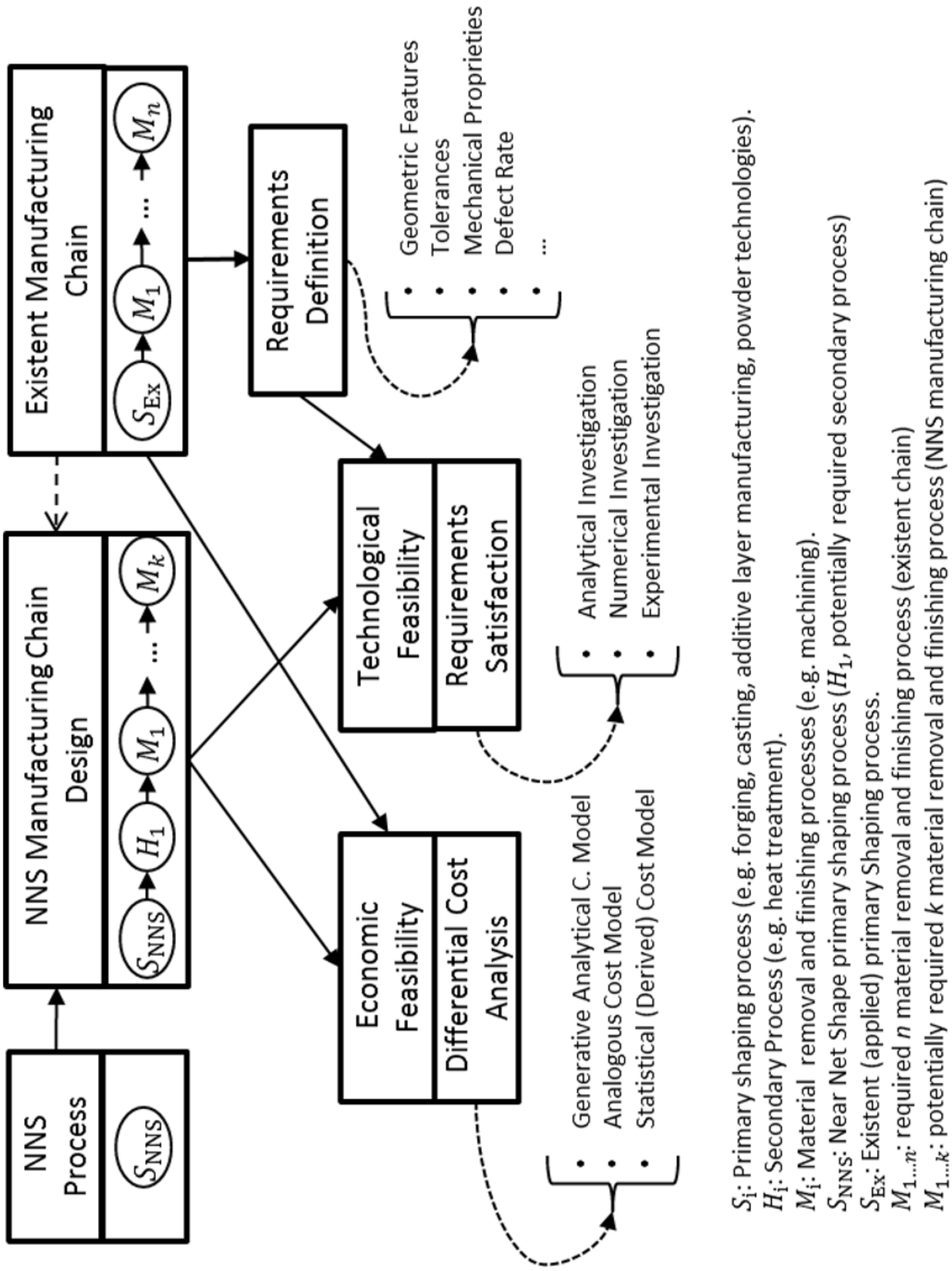


Figure 3.3: Differential Cost and Feasibility Analysis (DCFA) methodology schematic.

$Request > Value$	Necessity
If $Level1 \leq Request < Level2$	1
If $Level2 \leq Request \leq Level3$	$(Req - Lev3)/(Lev4 - Lev3)$
If $Level3 < Request \leq Level4$	1
If $Request < Level1$	1
If $Request > Level4$	0

Table 3.13: Necessity probability calculation for $Request > Value$.

etc.) and its overall efficiency (i.e. amount of resources employed to reach the required final production quality). The adoption of a new NNS process is motivated by opportunities to reduce machining (less material waste) and increase raw material usage with a new primary shaping process that maintains at least the current product quality as requirements (i.e. quality improvement and collateral advantages can be achieved). In this investigation, the functional and production requirements are directly acquired from the existing product and process chain. The product (e.g. mechanical tolerance) and production (e.g. defect rate) requirements definition and, in general, any issues related to quality management are not within the scope of this investigation. Similarly, the sensitivity analysis is limited only to the optimization phase, excluding the possibility of moving qualitative targets (i.e. in relationship with different primary shaping process).

Given the necessity of using various process designs (different trials configuration and process parameters) for evaluating a viable configurations, different process chains need to be configured to firstly identify the technological feasibility, and, subsequently, to be compared with the current process chain's economics. In other words, the alternative process designs need to be developed to give a breadth to the cost analysis (i.e. if only the extreme values of parameters are used the process may appear unfeasible when in fact it can be economic for different parameters combinations) and allow more options to be tested in the technological feasibility assessment stage.

Systematic Literature Review and Route Selection

The first step towards the feasibility evaluation of the NNS approach is to develop a "Systematic Literature Review" (e.g. Music et al. [2010] for spinning) for the investigated NNS process. A systematic review is necessary to identify the current investigation methodologies for a certain process, considering both shape and material to be produced. The identification of the most effective feasibility assessment approach needs to be linked with the overall requirements. With this aim, the existing investigations should be classified into:

- Analytical (Theoretical)
- Numerical (Theoretical)
- Experimental (Empirical)

The aim of the investigation is to identify, or develop (i.e. if an experimental model is selected), prediction models able to determine if the NNS process can accomplish the requirements in a reliable way, given the input material and shape, between the existing models. Following the prediction model selection, this choice of feasibility assessment method the route to select in the NeNeShO 3.1:

- **Route 1**: analytical investigation of technological feasibility and theoretical cost model for assessment of economic feasibility (i.e. generative analytical models).
- **Route 2**: numerical investigation of technological feasibility and theoretical cost model for assessment of economic feasibility (i.e. generative analytical models and analogous models).
- **Route 3**: experimental investigation of technological feasibility and derived cost model for assessment of economic feasibility (i.e. statistical models).

In case where more than one approach can be used priority is given in this order: analytical approach followed by numerical followed by experimental. This is because the analytical and numerical approaches will allow different process designs to be tested in a quick and economic way, before the experimental process is used for final validation. As mentioned, for assessing the feasibility, different process chain designs may need to be created, allow testing of different process parameters, other steps could include adapting possible unfeasible features (e.g. undercuts) or eliminating operations from the process chain (e.g. welding) to the process. These modifications will impact on both the technological and economic feasibility investigations, as they affect both the primary shaping process and the following machining operations.

Differential Analysis: Technological and Economic Feasibility

The application of the selected prediction model (theoretical or experimental) to the NNS process and aims to effectively evaluate the NNS technological feasibility.
In this case, the experimental investigation can be used for both assessing technological feasibility and developing process models.
The technological feasibility assessment of adopting a NNS process (including its post process operation such as thermal treatments) can initially be done analytically (e.g. upper-bound model for hot forging process) or numerically (e.g. viscoplastic model applied for simulating a flow forming process) and then experimentally validated (i.e. by prototypes and/or experimental testing). Analytical, or numerical, feasibility studies have to be connected to theoretical models that define the engineering science of the process: however, other factors (e.g. reliability, accuracy and cost) also need to be taken into consideration before simulating the process. Consequently, the final geometry produced by the NNS process and its raw material usage are defined during this phase.
The economic feasibility is conducted as a differential cost analysis, so, in contrast to the technological feasibility, which aims to ensure equal quality (in process and product requirements) between NNS and existing process chain, the economic feasibility evaluates the eco-

nomic difference between them in order to assess the potential competitive advantage (or disadvantage) of NNS usage.

In other words, its main target is to compare the cost differences between the old and new manufacturing process chain from a holistic view. Such a cost model can be statistical or generative-analytical [Layer et al., 2002] depending on nature of the process, the information available, the required level of accuracy and cost variables. Many dedicated cost models [Park and Simpson, 2005, Bariani et al., 1993, Nagahanumaiah et al., 2005, Jung, 2002] and general cost models [Allen and Swift, 1990, Esawi and Ashby, 2003, Niazi et al., 2006, Weustink et al., 2000, Yang and Natarajan, 2010] can be found in literature.

The route selection defines the cost model to be applied:

- If one between **Route 1 or 2** is selected, a theoretical cost model needs to be taken from literature or developed in parallel to the analytical or numerical model.
- If **Route 3** is selected a statical cost model needs to be derived from the experimental data.

Figure 3.4 illustrates the differential cost analysis schematic used in DFCA.

The process chains need to be schematized in terms of generic manufacturing processes inn order to be comparable. This allows the processes that act on the same features to be considered constants, for example the heat treatments or final polishing, can be exclude from the differential analysis. In other words, only the parts of a process chains that give different cost contributions need to be taken into account (e.g. a welding process used in the existing process chain, where the primary shaping process is an open die forging process, on the other hand, the NNS process chain, using an additive layer manufacturing processes, does not require it) in evaluating the impact of the new primary shaping process.

Essential for the differential cost analysis are the evaluation of:

- Primary shaping process cost (i.e. including raw material and operational cost)

- Machining cost

Where the primary shaping process cost of the NNS process is evaluated using the cost models identified by the route selection and the cost of machining operations are evaluated approximately using the machining removal rate. To do this, the geometrical output of the new primary shaping process (V_{NNS}) needs to be evaluated. The difference between this volume and the final component volume (V_F) (i.e. or the volume of the considered final operation) can be used for estimating the machining process time through the Machining removal rate (MRR). Using the machining cost per minute (c_{Mach}) it is possible to estimate the machining cost (C_{Mach}) as in 3.2

$$C_{Mach} = \frac{V_{NNS} - V_F}{MRR} C_{Mach} \tag{3.2}$$

This rough measure is able to give an estimation of the machining process costs that might be saved by the application of a new NNS process chain.

The existing process chain can be modelled economically in the same way (if no other models have previously been developed for evaluating the current costs) to be compared to the NNS one. The primary shaping cost does not need to be precisely modelled, but can be estimated by using the cost from current industrial data associated with similar parts. For calculating the machining cost, the same machining removal rate approximation can be used, by estimating the component volume output from the existent primary shaping process (V_{Ex}). In case this is not possible, the final component cost can be used as comparison parameter.

The output of the DFCA phase is the evaluation of the NNS process chain feasibility as well as the models for investigating the process feasibility and the cost models, which are used in the optmization phase (Phase III).

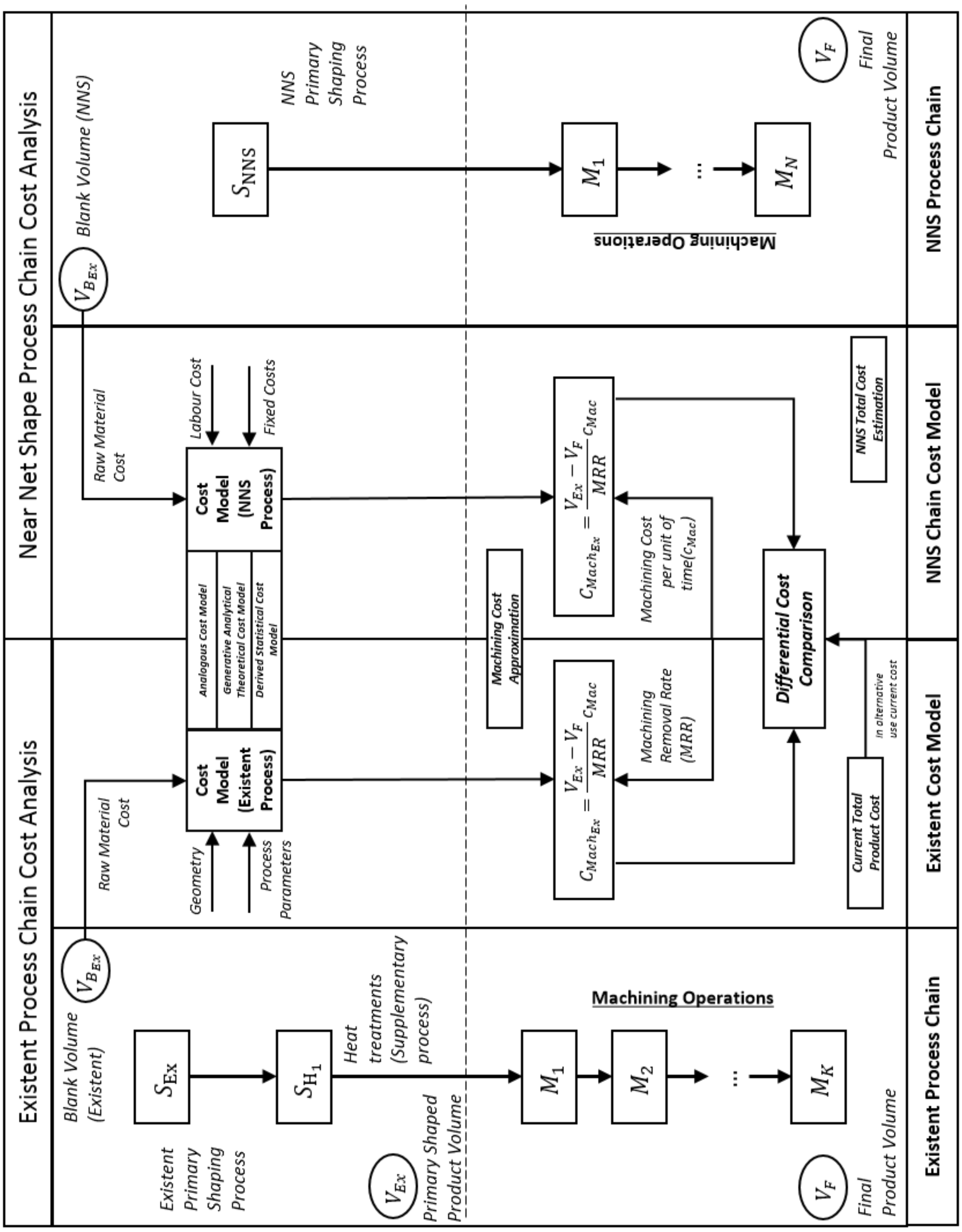


Figure 3.4: Differential Cost Analysis methodology general scheme.

3.1.3 Conditional Design Optimization (CoDeO) - Phase III

The models generated in the Phase II (DFCA) can be used in the phase for modelling the optimization of design and process parameters. In general, for optimizing the product design and process parameters, it is necessary to have a cost model which is function of both. The models needed for this optimization are:

1. Cost model of the primary shaping process, dependent on process parameters (e.g. forging force or intermediate geometry) and/or product design variables (e.g. diameter)

2. Cost model of the machining process dependent on process parameters and/or product design variables

3. Support models (i.e. linear or non-linear) for the primary shaping or machining processes (e.g. production rate target or turning force constraint)

The first and the second models depends on the optimization algorithm to be selected. This selection is influenced by the investigation mode selected and the models generated in the previous phase.

The presence of support models is dependent on the nature of the processes, production targets and product requirements. A model can investigate the product quality (i.e. if it can be formalized by a function) or represent the technological aspect (e.g. forging force) to optimize or keeping into feasible boundaries. By adding these as objectives function, the optimization changes from a single to a multi-criteria process. If these criteria can be added into other forms (e.g. non-linear constraints), the optimization can retain its single scope and optimising the cost by giving boundaries to the variable optimization.

These models allow the exploration of iterative systematic product and process design variation that can be optimized concurrently by minimizing the process cost (as main target), process technological features and product/production targets.

The optimization method is associated with the choice made in the Phase I (i.e. material and process selections) and Phase II (i.e. the investigation approach selected for technological assessment and the cost models generated) as follows:

- If **Route 1** (*analytical approach*) is selected, the analytical process and cost models can be optimized by using differential (i.e. closed solution) or stochastic algorithm (i.e. iterative solution), depending on the number of variables to be optimized. In this case, different feasible material (i.e. part of the process model) can be tested along with the process variables and design variables. Process parameters and design variable optimization depend on the model resolution achieved in the previous phase or in the literature

- If **Route 2** (*numerical approach*) is selected, it is possible to optimize the design variables and process parameters by the application of topological optimization or Design of Experiments applied to FEM. In this case, it is possible to correlate the whole product design to systematic variations of parameters, estimating the existing correlation and their influence on the costs

- If **Route 3** (*experimental approach*) is selected, the cost models have been derived from real data. Depending on the models' precision and experimental conditions, it is possible to use experimental methodologies for optimization (Design of Experiments) or using algorithm for optimizing the empirical formulas (stochastic optimization). In the first case, it is possible to achieve a statistical control of the process and have a statistical correlation between the product and process design variables and the manufacturing cost.

Figure 3.5 shows a schematic representation of the CoDeO. The selection of the optimization approach is followed by a systematic review of the existing optimization methods in the literature (i.e. which metaheuristic method is the most appropriate for the developed models?

Which DoE approach is more adapt to the NNS process?).

For guiding the optimization process, a NNS problem formulation and general model is developed in the next paragraph. The aim is to provide a guidance in the variable selection (both process parameters and product design variables) and the definition of their correlation (i.e. connection between intermediate geometries, machining parameters and final geometry). The models formalize the objective function in single-criteria optimization (i.e. minimization the global cost of the NNS chain), while aid the multi-criteria formulation of the additional objective functions (to add depending on NNS porcess models, functional product and production requirements) and the selection of optimization constraints.

NNS optimization: problem formulation and modelling

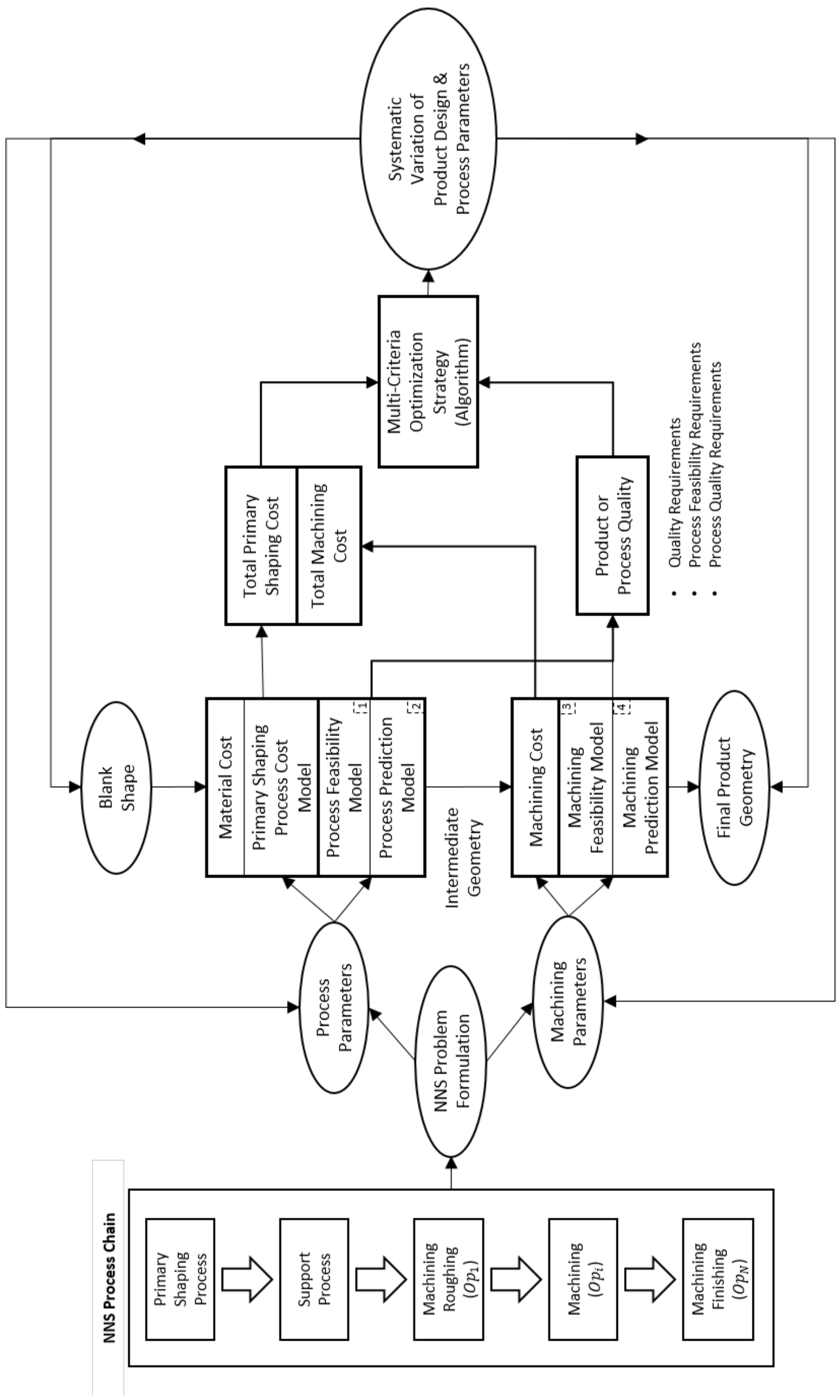
A generic NNS manufacturing chain can be modelled as a primary shaping process and subsequent limited number of machining steps as in Figure 3.6. The primary shaping component can be either a forming, casting or additive layer manufacturing process. The industrial need is to have a simultaneous optimization of design and process parameters, achieving:

- Product geometric requirements (e.g. assembly constraints)
- Quantitative product requirements (e.g. surface roughness, component weight)
- Process quality (e.g. defect rate, tool wear, forging force)
- Production targets (e.g. product cost, production rate, lead-time)

The process parameters to consider are:

- Primary shaping process variables $(v_1, v_2, .., v_n)$
- Machining process variables $(m_{11}, m_{12}, ..., m_{1k}\ m_{21}, m_{22}, ..., m_{2k}\ m_{N1}, m_{N2}, ..., m_{Nk})$

Where N is the number of machining operations required, n is the number of near net shape process variables, k is the number of machining variables. Referring to Figure 3.6, the design



1 – e.g. Forming Force Prediction Models
2 – e.g. Final Tolereance Precition Models
3 – e.g. Turning Force Prediction Models
4 – e.g. Surface Roughness Precition Models

Figure 3.5: Schematic of Conditional Design Optimization (CoDeO) methodology.

variables to consider are

- Billet, Preform or Raw Material Volume $(d_{b_1}, d_{b_2}...d_{b_V})$
- Near Net Shaped Component $(d_{s_1}, d_{s_2}...d_{s_V})$
- Intermediate machined geometries or Semi-finished component $(d_{i_{11}}, d_{i_{12}}...d_{i_{1V}}; d_{i_{21}}, d_{i_{22}}...d_{i_{2V}};$ $d_{i_{N1}}, d_{i_{N2}}...d_{i_{NV}})$
- Finished $(d_{f_1}, d_{f_2}...d_{f_V})$

Where V is the number of design variables. Referring to Figure 3.6(schematic of the general model), a machining process (milling or tuning) parameters can generally be synthesized in (3.3)

$$m_{11}, m_{12}, ..., m_{1k}; m_{21}, m_{22}, ..., m_{2k}; m_{N1}, m_{N2}, ..., m_{Nk} = a, v_c, F, N \quad (3.3)$$

Where, a is the cutting depth, v_c is the cutting speed, F is the feed rate and N is number of passes.

Using geometrical constrains and machining parameters some of the intermediate machining geometries can be written as function of final and primary shaped geometries, by the number of machining steps (3.4).

$$d_{i_{11}}, d_{i_{12}}...d_{i_{1N}}; d_{i_{21}}, d_{i_{22}}...d_{i_{2N}}; d_{i_{V1}}, d_{i_{V2}}...d_{i_{VN}} = f(d_{s_1}, d_{s_2}...d_{s_V}; d_{f_1}, d_{f_2}...d_{f_V}; a) = N \quad (3.4)$$

This allows the number of machining steps N to be expressed as a function of the design variables.

Expressing the machining steps number as in (3.4), the total machining time T_M, and consequently the total machining cost C_M, can be written as (3.5).

$$T_M = f(d_{s_1}, d_{s_2}...d_{s_V}; d_{f_1}, d_{f_2}...d_{f_V}; a, v_c, F) \quad (3.5)$$

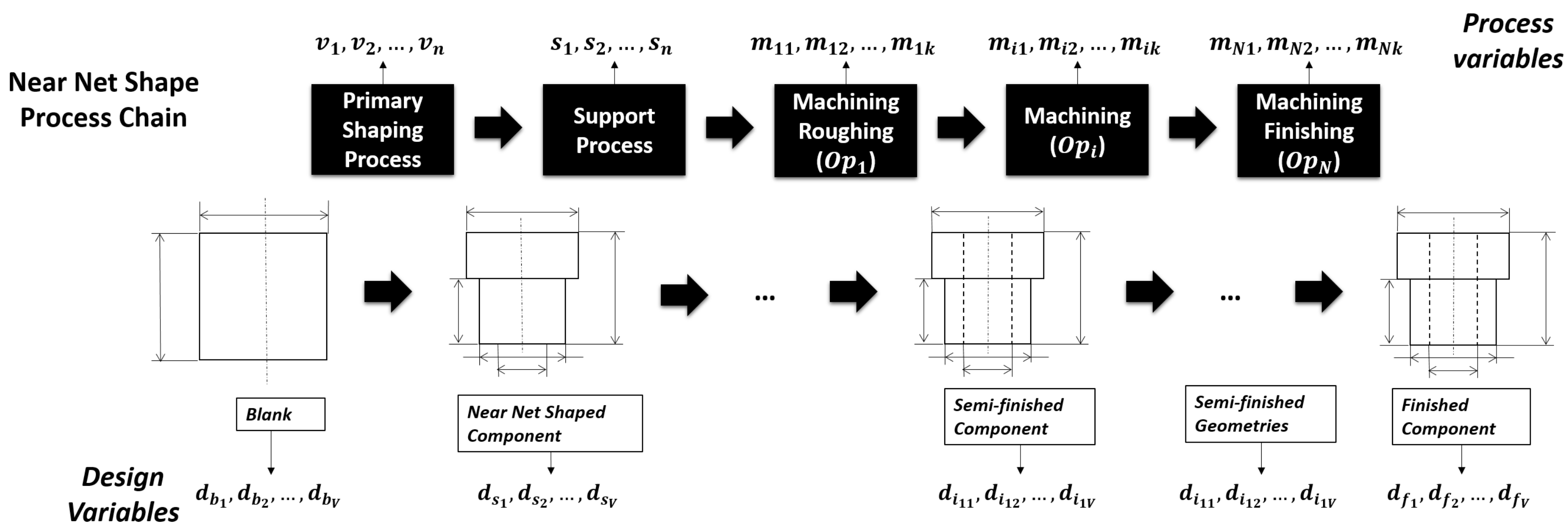


Figure 3.6: Near Net Shape process optimization: schematic of variables and problem formulation

In case of single criteria optimization, the objective function OBJ_i can be written as in (3.6)

$$\left\{ OBJ_1 = C_{NNS} + C_M = CNNS + T_M c_M \right. \tag{3.6}$$

Where, c_M is the hourly machining cost and C_NNS the cost model for the NNS process. In case of multi-criteria optimization, the objective functions can be formulated as in (3.7)

$$\begin{cases} OBJ_1 = C_{NNS} + C_M \\ OBJ_2 = T_{NNS} = f(v_1, v_2, .., v_n) \\ OBJ_3 = T_{Mach} = f(a, v_c, F) \end{cases} \tag{3.7}$$

The cost model for the NNS process C_NNS needs to be build individually, depending on the process nature and data available.This cost is function of input and output geometries and process parameters.

$$C_{NNS} = f(v_1, v_2, .., v_n; d_{b_1}, d_{b_2}...d_{b_V}; d_{s_1}, d_{s_2}...d_{s_V}) \tag{3.8}$$

Non-linear constrains can be added to the objective functions, limiting the feasible individuals in order to match process limit capabilities (e.g. turning power constraint), quality targets (e.g. surface roughness constrain) and production targets (e.g. machining removal rate).

NNS process variables and models are dependent on the process nature, which could be investigated in literature or experimentally.

The design variables selection is case dependant and can be influenced by several factors. The main constraints are usually geometrical or connected to key features for influencing component functionality or manufacturing costs. Their definition is difficult to standardize.

3.2 Discussion

A NNS process selection methodology has been proposed but it needs to be tested using case studies. The NNeShO Protocol could be unworkable because

1. Missing inputs: crucial information required in one stage is not supplied by a previous stage.
2. Some of the parameters cannot be quantified (particularly in the ProGeMa3 phase)
3. Creating an infinite loop: a recursive definition that prevents a conclusion from being reached (referring to the DFCA phase, particularly the possible NNS process chain design)
4. Impossibility of route definition: some processes may need concurrent investigations for establishing their feasibility (more than one feasibility approaches need to be used contemporarily)
5. Improper matching between the investigated approach and cost modelling (improper link between technological and economic feasibility, internal to Phase II DFCA)
6. Improper matching between the investigated approach and optimization model (i.e improper link between Phase II DFCA and Phase III CoDeO)
7. Improper matching between NNS variables (process, material and product design) and with product requirements, generating unfeasible NNS process chains.
8. Inappropriate choice of parameters and approximation of variables values.

The following chapters will investigate if the proposed methodology is workable.

Chapter 4

Validation: Product Geometry, Manufacturing and Material Matching (ProGeMa3) Methodology Application

4.1 Introduction

In this chapter, the ProGeMa3 (Phase I of the NeNeShO Protocol) has been applied to the case study company, Weir Group PLC, with the aim of selecting feasible NNS application. The Product Geometry, Manufacturing and Material Matching (ProGeMa3) Methodology (Section 3.1.1) has been applied to some of the components, produced in various divisions of the company. The procedure has been able to gather four case studies, following the production targets definition. A subsection has been dedicated to the process review and another to the application of the methodology.

The objectives of the validation case studies is to verify that the necessary and sufficient information is generated at each stage to enable a conclusion to be reached.

4.1.1 Manufacturing Process Review

Having limited the investigation to the discontinuous production of solid metal components, several corresponding manufacturing processes have been reviewed for both quantifying and investigating their capabilities. Some of the processes have been used for many years and their capabilities are quantified widely in the literature (e.g. sand casting, closed die forging). For innovative and niche processes, the geometrical capabilities and process parameters (e.g. producible thickness) need to be extracted from research papers (e.g. hydroforming, rotary forging, shear forming). The reviewed processes are introduced in Appendix B using the following scheme:

- Process Description
- Process variants
- Workable Materials
- Final Product Characteristics
- Typical Applications

The processes have been categorized into casting, forming and additive layer manufacturing (ALM). The information gathered in this section are used for mapping the process capabilities and quantifying their production features.

Appendix B details the summaries for the investigated processes, which are classified as follows:

- Casting:
  - Sand casting

  - Gravity die casting
  - Vacuum permanent mold casting
  - Pressure die casting
  - Shell mold casting
  - Plaster mold casting
  - Ceramic mold casting
  - Centrifugal casting: True centrifugal casting, Semi- centrifugal casting, Centrifuging casting
  - Lost-foam mold casting
  - Investment casting
  - Squeeze casting
  - Semi-solid Metal Casting (SSMC): Thixocasting, Rheocasting, Thixoforming

- Forming
  - Forging: Open die forging, Impression-die (closed-die) forging, Precision forging, Isothermal forging, Cold forming, Injection forging
  - Orbital (Rotary) forging
  - Spinning: Conventional spinning, Shear forming, Flow forming
  - Tube Hydroforming
  - Powder Metallurgy: Powder forging, Isostatic pressing
  - Metal injection moulding (MIM)

- Additive Layer Manufacturing
  - Metal powder beds: Selective Laser Sintering (SLS), Selective laser melting (SLM), Direct metal laser sintering (DMLS), Electron beam melting (EBM), Gas phase deposition (GPD), Tri-dimensional printing (3DP)

- Blown metal powder: Laser based metal deposition (LBDM). Electron beam metal deposition (EBDM), Plasma deposition manufacturing (PDM)
- Process involving solidification of molten metal: Fuse deposition modelling (FDM), Shape deposition manufacturing (SDM), Ballistic particle manufacturing (BPM), Spatial forming (SP)
- Process involving solid sheets: Laminated object manufacturing (LOM)

4.2 ProGeMa3 Application to the Case Study Company

The ProGeMa3 (Section 3.1.1) has been applied to the components of four main products (i.e. assemblies) of the company, doing an investigation conducted directly in the company's manufacturing facilities.

The considered components have been taken from the following products (Table 4.1):

- Wall stimulation pump (Oil&Gas, SPM Pumps) (Figure 4.1)
- Centrifugal Pumps (Oil&Gas, Gabbionetta Pumps) (Figure 4.2)
- Vertical Turbine Pump (Minerals, Floway Pumps) (Figure 4.3)
- Control Valves (Flow Control, Weir V&C Elland and Ipswich) (Figure 6.3)

The individual components (for these four assemblies) have been summarized in Table 4.1, including their material variants and production volumes. The application of ProGeMa3 can be summarized (as described in Section 3.1.1) in its main four stages:

1. Economic opportunities screening
2. Material Selection
3. Process Screening Matrix (ProSMA)
4. Process Compatibility Evaluation (Fuzzy logic)

Figure 4.1: Fracking pump.

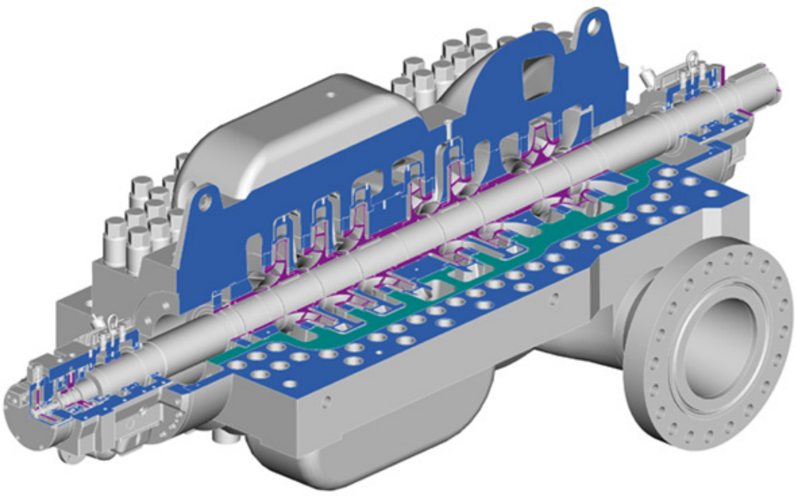


Figure 4.2: Centrifugal pump.

Figure 4.3: Vertical turbine pump.

Main Productions	Component	Production Volume	Material	Geometry	Feasible Processes (ProSMa)
Fracking Pumps (oil & Gas)	Crankshafts	100-1,000	Stainless Steel	R7	C.6 C.11 C.12 F.2 F.7 AM.5 AM.6 AM.7
	Suction/Discharge Nozzles	100-1,000	Cast Iron	T7	C.2 C.4 C.5 C.6 C.8
	Fluid Ends	100-1,000	Alloy Steel	B7	C.1 C.2 C.6 F.2 AM.5 AM.6 AM.7
	Riser Pipe	100-1,000	Carbon Steel	T2	C.1 C.2 C.6 F.2 F.8 F.9 F.10
	Plungers	100-1,000	Alloy Steel	R2	C.1 C.2 C.6 F.1 F.2 F.7
	Valve Seat	1,000-10,000	Alloy Steel	T2	C.2 F.1 F.2 F.3 F.4 F.5 F.6 F.10 F.11
Centrifugal Pumps (Oil &Gas), Vertical Turbine Pump (Minerals)	Shaft	100-1,000	Stainless Steel	T2	C.1 C.2 C.6 F.2 F.8 F.9 F.10
	Impeller	100-1,000	Cast Iron	T7	C.2 C.4 C.5 C.6 C.8
	Casing	100-1,000	Cast Iron	B7	C.2 C.4 C.5 C.6 C.8
	Riser Pipe	10 -100	Carbon Steel	T2	C.6 F.2 F.8 F.9 F.10
	Bearing Housing	100-1,000	Alloy Steel	B7	C.1 C.2 C.6 F.2 AM.5 AM.6 AM.7
	Wear Rings	1,000-10,000	Aluminum Bronze	T0	C.2 C.3 C.7 C.8 C.10 C.14 C.15 F.1 F.10 F.11
	Shaft Sleeves, Bushes	1,000-10,000	Stainless Steel	T1	C.2 C.6 C.10 F.1 F.2 F.3 F.8 F.9 F.10 F.11
Control Valves and Globe, Butterfly, Gate, Ball Valves) (Oil & Gas, Nuclear, POWER Generation)	Bonnet	10-100	Stainless Steel	T7	C.6 C.10 F.7 F.8 F.10 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7
	Body	10-100	Alloy Steel	T6	C.6 F.7 F.10
	Disc	10-100	Stainless Steel	T7	C.6 C.10 F.7 F.8 F.10 AM.1 AM.2 AM.3 AM.4 AM.5 AM.6 AM.7
	Seat	10-100	Stainless Steel	T1	C.6 C.10 F.1 F.7 F.8 F.9 F.10
	Plug Stem	10-100	Stainless Steel	R2	C.6 C.11 F.1
	Cage (Gasket)	10-100	Stainless Steel	T1	C.1 C.4 C.5 C.6 C.11 F.9

Table 4.1: Considered component description, production volume, material, geometry (using Table 3.1 nomenclature) and process screening matrix results

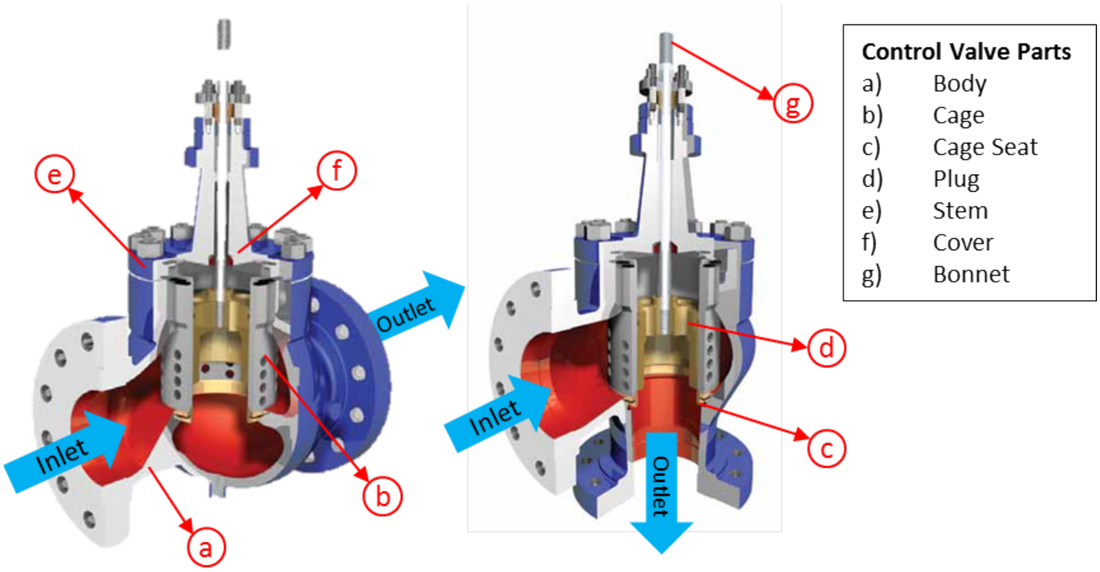


Figure 4.4: Control valve.

The following sections detail the ProGeMa3 stages and its application to the mentioned assemblies.

4.2.1 Economic Opportunities Screening - Step 1

The application of the economic screening could not be carried on, due to the low level of information maintained by the company on its own productions. At this stage, the relevant information that could not be accessed or formalized were:

- Precise production volume, product design and material variants: only an estimation of them could be made, due to the variability in customer demands and the difficulty of quantification (i.e. Weir company decentralization of activities)

- Required machining time for component production: only qualitative and not detailed indications on machining time could be gathered (i.e. lack of databases about machining). The data, regarding the machining process, have been gathered directly on site, using actual production processes (as explained in the next subsection)

- Process chain complexity: the major part of the primary shaping processes are conducted by suppliers. For this reason, the manufacturing chain of some productions (i.e. before machining steps) have not been defined, as some are partially unknown by the company (e.g. some components blanks have been made by casting, but it was not clear which process has been used).

For these reasons, the Process Screening Matrix (ProSMA) was applied to all the components.

4.2.2 Material Selection - Step 2

For all the components the material selection has been constrained by three factors

- Application environment: material is selected by the required erosion/corrosion resistance, particularly for fracking pumps, centrifugal and vertical pumps. Changing material requires extensive testing.
- Production variants: all the components already include different material variants, selected by specific customer requests.
- Industrial sector: material choice is dictated by the customer request for pumps/vales (i.e. Oil & Gas sector) and product standards for valves (i.e. Nuclear sector). Customer are unwilling to accept any new material for these components, without extensive validation.

In the considered components, the materials have been already optimized by extensive investigations and new materials require extensive testing to be considered as valid alternatives [The WEIR group PLC, 2016]. Consequently applying material changes in this context is out of the scope of this investigation. Therefore, the materials remains unchanged from the adopted ones.

4.2.3 Process Screening Matrix (ProSMA) - Step 3

Following the previous rationale, ProSMa (Tables 3.2, 3.3, 3.4 and 3.5) has been applied to the main components of the productions mentioned above. In Table 4.1, the application of the process selection matrix is also displayed: every component has been associated to a number of feasible processes, depending on its characteristics (i.e. process nomenclature is the same used in the process selection matrix(ProSMa), Table 3.1).

Tables 4.1 considered component description, production volume, material, geometry (using the nomenclature presented in Figure 3.1) and process screening matrix results.

Individual component's geometries have been classified referring to the geometry classification described in Figure 3.1). For all the analysed components, the classification's results are showed in the Geometry category in Table 4.1.

From the NNS processes identification, four productions have been selected (valve seat, riser pipe, valve cage and valve body). Accordingly to the economic selection criteria of ProGeMa3, manufacturing process characteristic are aligned with the NNS approach, as the machining and raw material costs have been the main drivers of cost for almost all the selected components.

The rationale for the components selection are explained as follows.

1. Valve seat (Case Study IA, Figure): the component has a high production volume and the main part of the costs are associated to the material cost. Possibility of increasing the component's tensile strength through the manufacturing process has been considered one of the main targets.

2. Riser pipe (Case Study IB, Figure): the long lead time due to the extensive machining and welding processes is the main reason for the investigation. The possibility of corrosion reduction by increasing of the mechanical characteristics is a potential target for a new process.

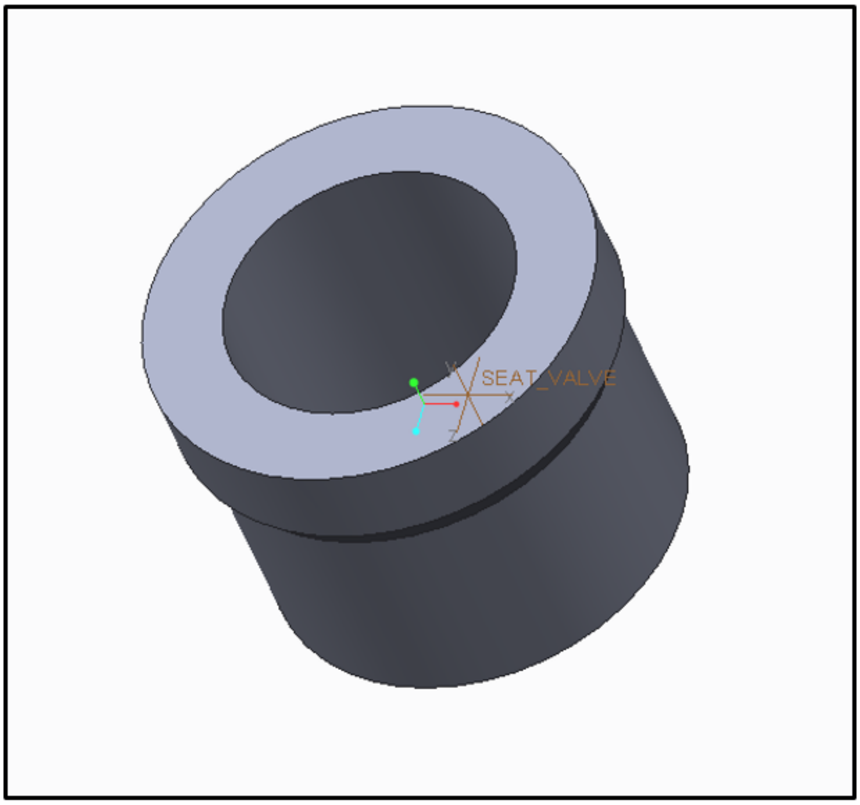


Figure 4.5: Case Study IA: valve seat.

3. Valve cage (Case Study II, Figure): the extensive machining and the very high material cost (i.e. stainless steel) are the main reasons for the selection of this component.

4. Valve body (Case Study III, Figure): the component has a high material cost. The opportunity of increasing the material strength though a different process selection was a primary target of the company.

Regarding the process selection, the components' qualitative targets have been considered by the next stage, the fuzzy logic selection, in form of required values (i.e. product requirements).

The ProSMa's application on the four case studies have selected the following process as NNS candidates:

- Case Study IA:

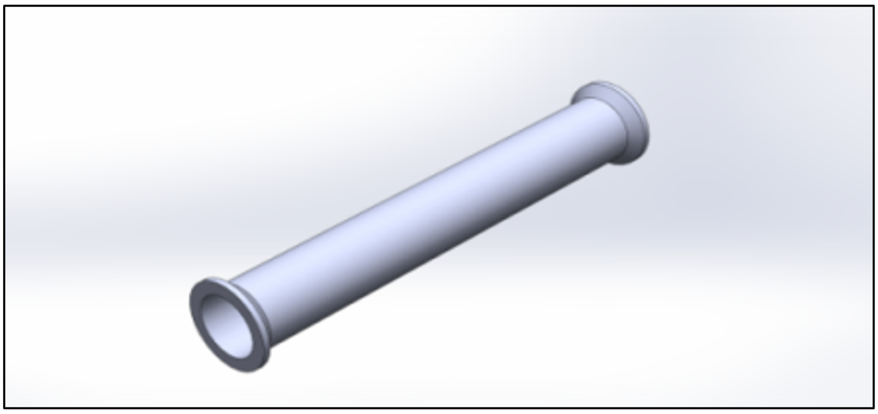


Figure 4.6: Case Study IA: riser pipe

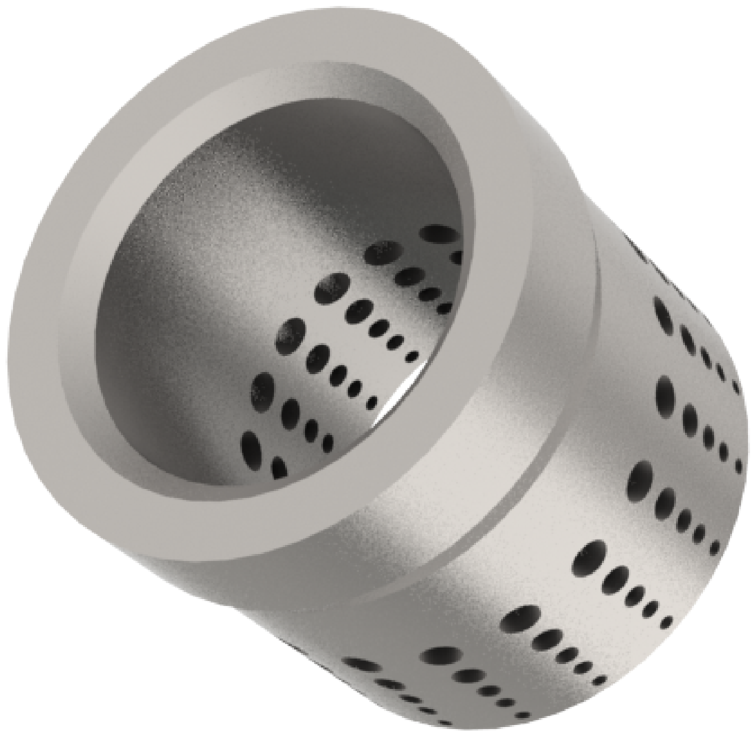


Figure 4.7: Case Study II: valve cage

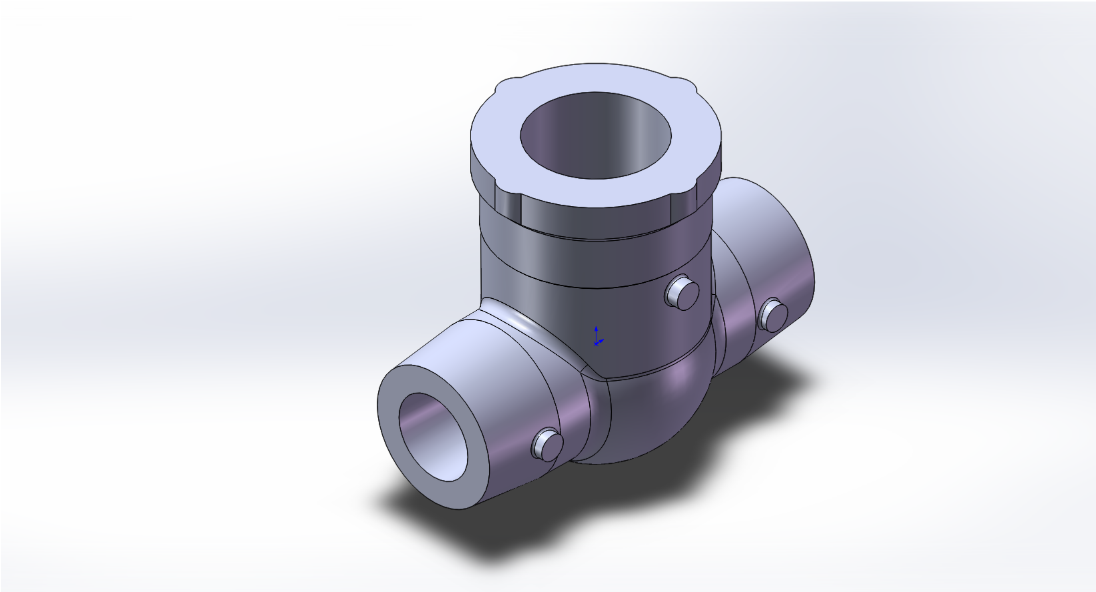


Figure 4.8: Case Study III: valve body.

  - Hot Closed-die Forging
  - Hot Precision Forging
  - Hot Injection Forging
  - Rotary Forging
  - Flow Forming
  - Centrifugal Casting
  - Sand Casting
  - Shell Moulding
  - Investment Casting
  - Lost Foam Casting

- Case Study IB:
  - Centrifugal Casting
  - Ceramic Moulding

  - Flow Forming
  - Sand Casting
  - Lost Foam Casting

- Case Study II:
  - Centrifugal Casting
  - Ceramic Moulding
  - Flow Forming
  - Sand Casting
  - Lost Foam Casting
  - Investment Casting

- Case Study III:
  - Hot Closed-die Forging
  - Hot Open-Die Forging
  - Centrifugal Casting
  - Ceramic Moulding
  - Sand Casting
  - Lost Foam Casting
  - Investment Casting

4.2.4 Process Compatibility Evaluation (Fuzzy logic) - Step 4

The fuzzy logic approach matches the product requirements and process characteristic by defining their compatibility. These features are evaluated and compared between the required characteristics (product functional requirements and quality targets) and the process working ranges. As mentioned, the process characteristic are defined by four levels: two variables define the typical range and two define the uncertain range (the absolute minimum and maximum values). Each characteristic gives (by the particular process levels and required values) a level of compatibility, which is influenced by weighted coefficients. All the compatibility levels, for the different processes (i.e. screened by the selection matrix) can be ranked, and so the most suitable one can be selected.

The following product features have been considers for evaluating the process' compatibility:

- Radial (or Planar) Tolerance [±mm] (numerical evaluation).
- Axial (or Vertical) Tolerance [±mm] (numerical evaluation).
- Surface Roughness [Ra] (numerical evaluation).
- Section Thickness [mm] (numerical evaluation).
- Weight [kg] (numerical evaluation).
- Resulting Mechanical Proprieties (linguistic evaluation).
- Tooling Cost (linguistic evaluation).
- Equipment Cost (linguistic evaluation).
- Labour Cost (linguistic evaluation).

For the investigated processes, the component's fuzzy sets (capabilities ranges) have been defined from the following sources:

- Tolerances and roughness ranges have been derived from Swift and Booker [2013], Schey [1999], Kalpakjian and Schimd [2009], Davidson et al. [2008], Schuler [1998], Takemasu et al. [1996], Plancak et al. [2012], Tomov and Gagov [1999], Campbell [2000].

- Workable weight and section thickness ranges have been defined as in Schey [1999], Kalpakjian and Schimd [2009], Swift and Booker [2013], Altan and Ngaile [2005], Srinivasulu et al. [2012a], Schuler [1998], Srinivasulu et al. [2012b], Chang et al. [1998], Sheljaskov [1994], Plancak et al. [2012], Tomov and Gagov [1999], Campbell [2000].

- Resulting mechanical properties capabilities have been qualitatively assessed from Wong et al. [2003], Podder et al. [2012], Bewlay et al. [2003], Altan and Ngaile [2005], Schey [1999], Kalpakjian and Schimd [2009], Allen and Swift [1990].

- Tooling, equipment and labour cost have been assessed using linguistic evaluation (Low, Moderate to Low, Moderate, Moderate to High, High) from Swift and Booker [2013], Schey [1999], Kalpakjian and Schimd [2009], Cominotti and Gentili [2008], Altan and Ngaile [2005], Bhatkal and Hannibal [1999].

The components' required values have been taken by the industrial documentation (tolerances, roughness, dimensions and weight) and the defined quality targets (mechanical properties).

For the four selected case studies, the required levels of the considered characteristics, are showed in Table 4.2. The tolerance, surface roughness, workable thickness and workable weight levels have been taken from the components drawings and technical data.

The tolerances and surface roughness levels have been taken as close as possible to the required ones. In the Cases IB, II and III, the tolerances and surface roughness have been taken as in the final requirements, meanwhile in the Case Study IA, the general tolerance has been used (because many surfaces require finishing machining, due to the level of tolerances and roughness required). The resulting mechanical proprieties has been selected by an estimation of the current and required mechanical proprieties, using the necessary quality improvements defined above. Similarly, the process costs requirements have been decided by taking into account the current manufacturing process, so using its tooling, equipment and labour cost as

Request (Fuzzy Logic)	Case Study IA	Case Study IB	Case Study II	Case Study III
Radial Tolerance [±mm]	0.3	0.25	0.25	0.25
Axial Tolerance [±mm]	0.3	0.25	0.25	0.25
Surface Roughness [Ra]	1.6	3.2	1.6	3.2
Workable Section Thickness [mm]	45	33.0	80	60
Workable Weight [kg]	2.7	1300	360	32
Resulting Mechanical Proprieties	≥4	≥4	≥2	≥4
Tooling Cost	≤3	≤3	≤3	≤4
Equipment Cost	≤4	≤4	≤3	≤4
Labour Cost	≤4	≤4	≤3	≤4

Table 4.2: Required levels for process compatibly evaluation through fuzzy logic.

references. Therefore, any costs need to be ”less than” the current ones, on the other hand, the material properties need to ”bigger than” the current ones.

In Table 4.3, all the weighting coefficients for the fuzzy calculation of compatibility have been listed. These coefficients have been selected in such a way as to determine the impact of a single feature on the whole process' compatibility as follows:

- The highest weight ($value = 5$) has been given to the workable weight and section thickness, as they determine objectively the component manufacturability.
- The tolerances and surface roughness have been assigned with a high relevance ($value = 4$), according to the NNS approach (Case Study III has a lower weight because of the lower tolerances and roughness in the non-machined zone).
- Despite measured linguistically, a high relevance ($value = 4$) has been given to the mechanical properties, according to product requirements and quality targets. Because of the lower mechanical properties required, the weight in Case Study II is lower than in other cases ($value = 3$).
- The compatibility weights for the labour, equipment and tooling costs have been set to medium ($value = 3$), due to the high level of approximation.

Weighting Factors (Fuzzy Logic)	Case Study IA	Case Study IB	Case Study II	Case Study III
Radial Tolerance [±mm]	4	4	4	3
Axial Tolerance [±mm]	4	4	4	3
Surface Roughness [Ra]	4	4	4	3
Workable Section Thickness [mm]	5	5	5	5
Workable Weight [kg]	5	5	5	5
Resulting Mechanical Proprieties	4	4	3	4
Tooling Cost	3	3	3	3
Equipment Cost	3	3	3	3
Labour Cost	3	3	3	3

Table 4.3: Required levels for process compatibly evaluation through fuzzy logic.

Appendix C shows the application of the fuzzy formulation to the considered process characteristics for the required levels (Table 4.2) and weight coefficients (Table 4.3). In Appendix C, the results of fuzzy formulation for compatibility between the single process features and product requirements (using Equations 2.1, 2.2, 2.3, 2.4, 2.5 and 2.6) as well as their corresponding possibility/necessity values (using Tables 3.8, 3.9, 3.10, 3.11, 3.12) are showed. Based on weights ranking (Equation (2.6)) the total compatibility (Equation (3.1)) are detailed in Appendix for every process of the four case studies.

The compatibility results are summarized and discussed in the next paragraphs for the four case studies.

Case Study IA

The application of fuzzy logic to the valve seat (Case study IA) is displayed in Appendix C and its compatible processes (compatibility calculation through fuzzy logic) are detailed in Tables C.1, C.2, C.3, C.4, C.5, C.6, C.7, C.8, C.9 and C.10.

In Table 4.4, the total compatibility values for the Case Study IA are summarized. Sand casting, investment casting and lost foam casting process result incompatible with the Case Study I's required levels. Figure 4.9 visualizes the total processes compatibilities ranking. The hot precision forging results the most compatible process (0.91), followed by flow form-

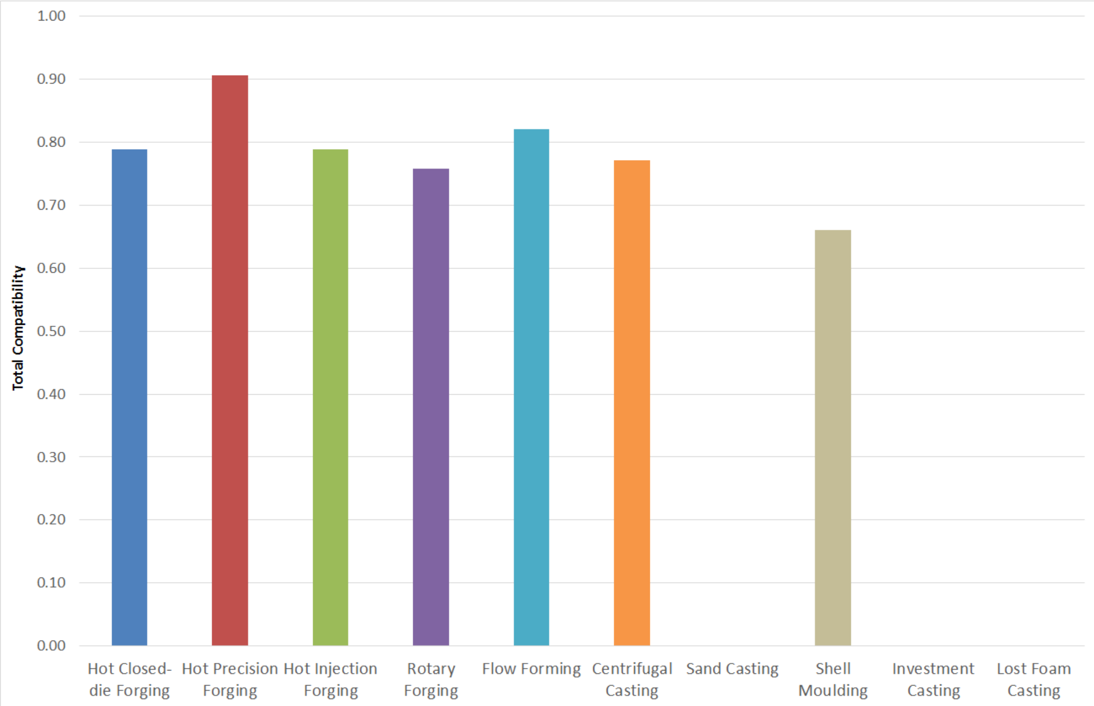


Figure 4.9: Process compatibilities ranking for the Case Study IA.

Manufacturing Process	Total Compatibility (Case IA)
Hot Closed-die Forging	0.79
Hot Precision Forging	0.91
Hot Injection Forging	0.79
Rotary Forging	0.76
Flow Forming	0.82
Centrifugal Casting	0.77
Sand Casting	0.00
Shell Moulding	0.66
Investment Casting	0.00
Lost Foam Casting	0.00

Table 4.4: Case Study IA: compatibility rankings of the processes by fuzzy logic.

ing (0.82), hot closed die forging (0.79) and rotary forging (0.76).

Displaying radar charts, the Figure 4.10 and Figure 4.11 display the detailed compatibility values of all the considered characteristics. The Figure 4.11 show the detailed compatibility levels for the forming processes. The high compatibility level of the tolerances, roughness and section thickness are the reasons for the high rating of precision's forming overall total com-

Figure 4.10: Process compatibilities breakdown for the Case Study IA (part I).

patibility.

As showed in Figure 4.9, the tolerances, roughness and mechanical properties compatibly values make the casting process less suitable for this application. For sand casting and lost foam casting, the tolerances, roughness and mechanical properties capabilities are not sufficient for allowing the process to be suitable for this application. Similarly, investment casting capabilities on mechanical properties are not sufficient for matching the requirements for the valve seat production. The only two casting processes that are able to partially satisfy the requirements are centrifugal casting and shell moulding. These forming processes are most suitable for the required levels of tolerances, roughness, and mechanical properties (Figure 4.10). The cold forming processes (i.e. rotary forging and flow forming) did not fully satisfy the required workable thickness and part weight levels, although they better fit with the resulting mechan-

Figure 4.11: Process compatibilities breakdown for the Case Study IA (part II).

ical properties and tolerances needed. On the other hand, the hot forming processes characteristics fully meet the first two requirements but fall into the fuzzy zone for the second ones (with the exception of the hot precision forging process).

Given that the currently applied process is hot precision forging and the increasing of resulting mechanical proprieties is one of the main targets, the second process in the ranking (flow forming) has been selected for this case study.

Case Study IB

The compatibility calculations for the Case study IB (riser pipe) are detailed in Tables C.12), C.13), C.11), C.14) and C.15.

Table 4.5 displays the total compatibility values of the Case study IB. Similarly to Case study

Manufacturing Process	Total Compatibility (Case Study IB)
Centrifugal Casting	0.85
Ceramic Moulding	0.73
Flow Forming	0.82
Sand Casting	0.00
Lost Foam Casting	0.00
Investment Casting	0.00

Table 4.5: Case Study IB: compatibility rankings of the processes by fuzzy logic.

IA, sand casting, investment casting and lost foam casting process result incompatible with the required levels. Only three processes results in are compatible: centrifugal casting, ceramic moulding and flow forming. Figure 4.12 displays the compatibly rankings for all the considered process. The centrifugal casting process results the most suitable (0.85), followed by flow forming (0.82) and ceramic moulding (0.82).

Figure 4.13 shows the individual compatibility values. As with the previous case, it is possible to notice that sand casting and lost foam casting are not able to satisfy the requirements in terms of tolerances, roughness and mechanical proprieties, except from the ceramic moulding and the centrifugal casting processes. The second process in the ranking (i.e. flow forming) has been associated with Case Study IB, because casting (first in the ranking) is the current process and mechanical properties increase is the main target production target.

Case Study II

The application of fuzzy logic to the valve cage manufacturing (Case study II) is showed in Tables C.18), C.19, C.17, C.20, C.21 and C.22.

Table 4.6 shows the total compatibility values of the Case study II. Similarly to the previous case studies, sand casting, investment casting and lost foam casting result not compatible using the applied methodology. Three processes (centrifugal casting, ceramic moulding and flow forming) have been considered compatible with the valve cage manufacturing. Figure 4.14 displays the compatibly rankings for all the considered process. As in Case Study II, The

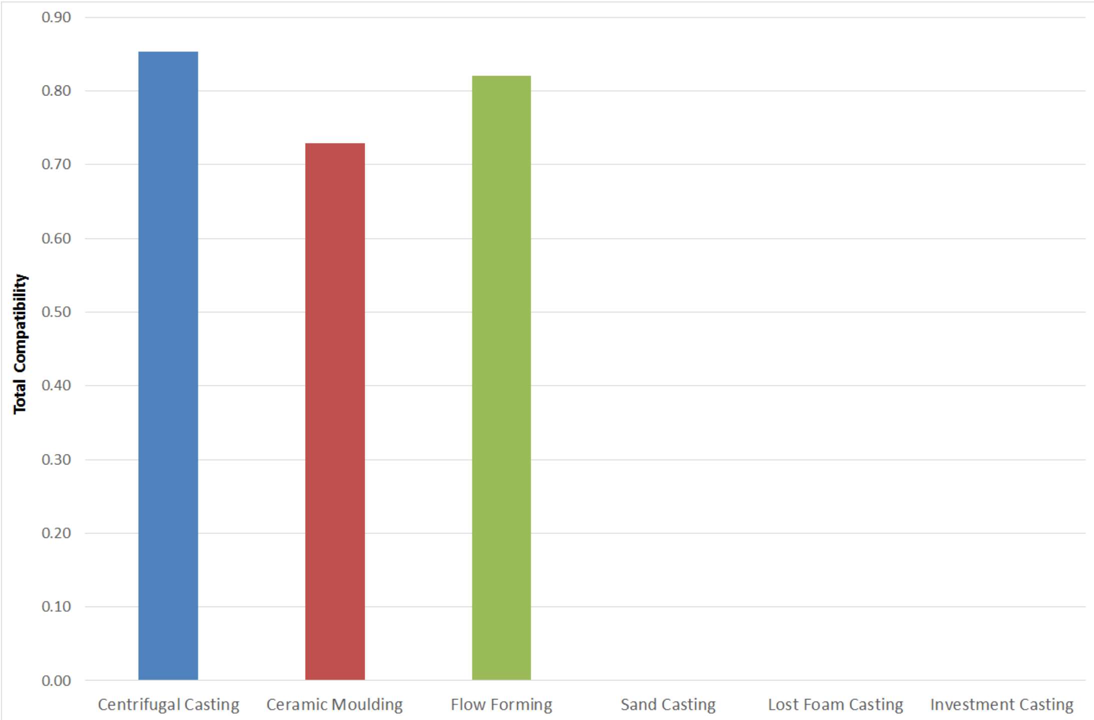


Figure 4.12: Process compatibilities ranking for the Case Study IA.

Manufacturing Process	Total Compatibility (Case Study II)
Centrifugal Casting	0.92
Ceramic Moulding	0.68
Flow Forming	0.77
Sand Casting	0.00
Lost Foam Casting	0.00
Investment Casting	0.00

Table 4.6: Case Study II: compatibility rankings of the processes by fuzzy logic.

centrifugal casting process is the most suitable (0.92), followed by flow forming (0.77) and ceramic moulding (0.68). As displayed in Figure 4.15, the centrifugal casting process satisfies almost completely the required levels because the required resulting mechanical properties are lower than in the previous cases. This results in the highest compatibility of the processes, compared with ceramic moulding and flow forming process. For this reason, centrifugal casting has been selected for the Case Study II.

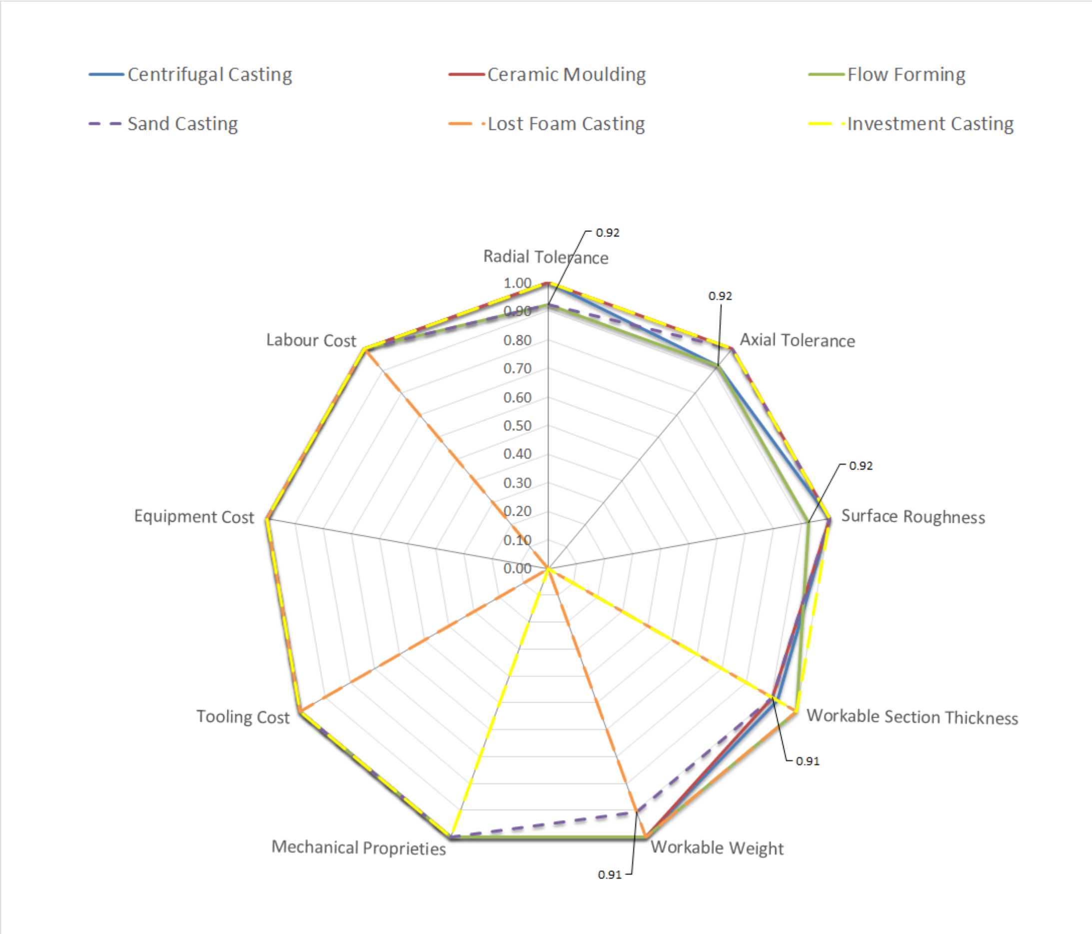


Figure 4.13: Process compatibilities ranking for the Case Study IB.

Case Study III

The compatible processes and compatibility calculation tables through fuzzy logic are showed in Tables C.23), C.24, C.25, C.26, C.27, C.28 and C.29).

In Table 4.6 are showed the total compatibility values of the Case study II. In this case, four processes have been considered feasible: two casting processes (centrifugal casting and ceramic moulding) and two forging processes (hot closed-die and open-die forging). The three remaining casting processes results are unfeasible as in the previous cases. Figure 4.16 rank the different processes compatibilities: hot open-die and closed-die forging result the most feasible (both with a score of 0.88), followed by centrifugal casting (0.81) and ceramic mould-

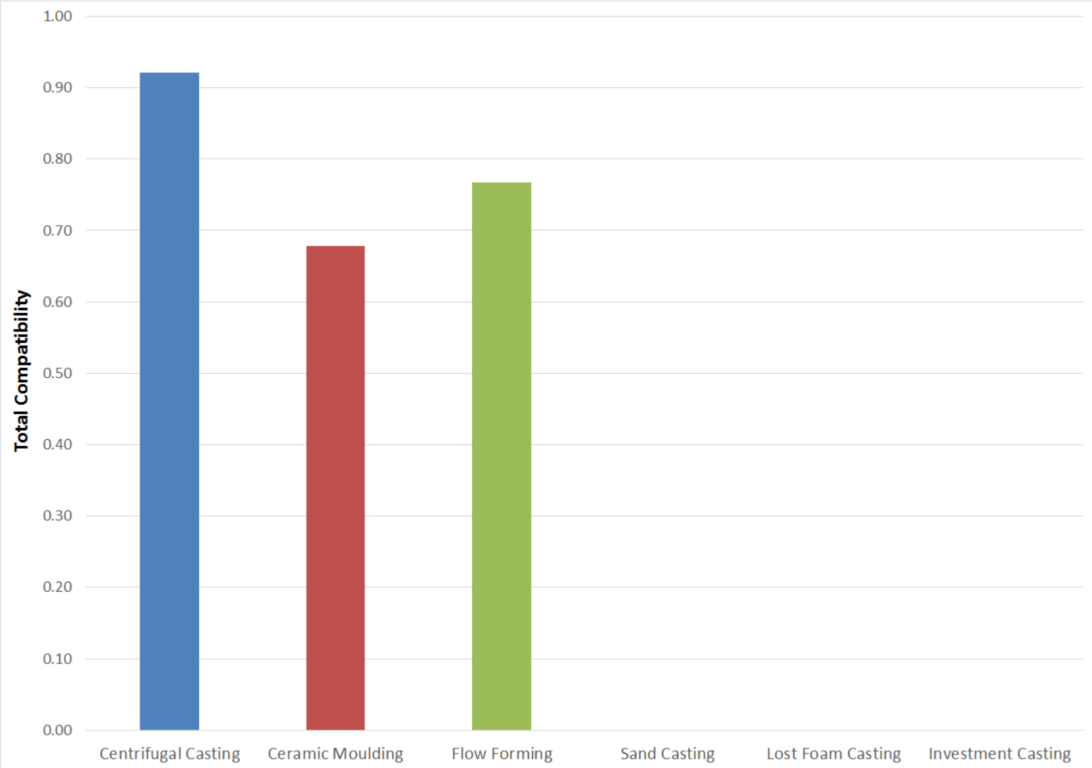


Figure 4.14: Process compatibilities ranking for the Case Study II.

Manufacturing Process	Total Compatibility (Case Study III)
Hot Closed-die Forging	0.88
Hot Open-Die Forging	0.88
Centrifugal Casting	0.79
Ceramic Moulding	0.72
Sand Casting	0.00
Lost Foam Casting	0.00
Investment Casting	0.00

Table 4.7: Case Study III: compatibility rankings of the processes by fuzzy logic.

ing (0.72).

In Figure 4.17, it is possible to see how the forging processes fully satisfy the all the requirements, except for the required tolerances, which result is still feasible (even if they fall in the fuzzy zone). The centrifugal casting process has lower compatibility on the resulting mechanical properties, meanwhile the ceramic moulding has higher capabilities in surface roughness but higher costs. The hot closed-die forging has been selected for this case study, due to the

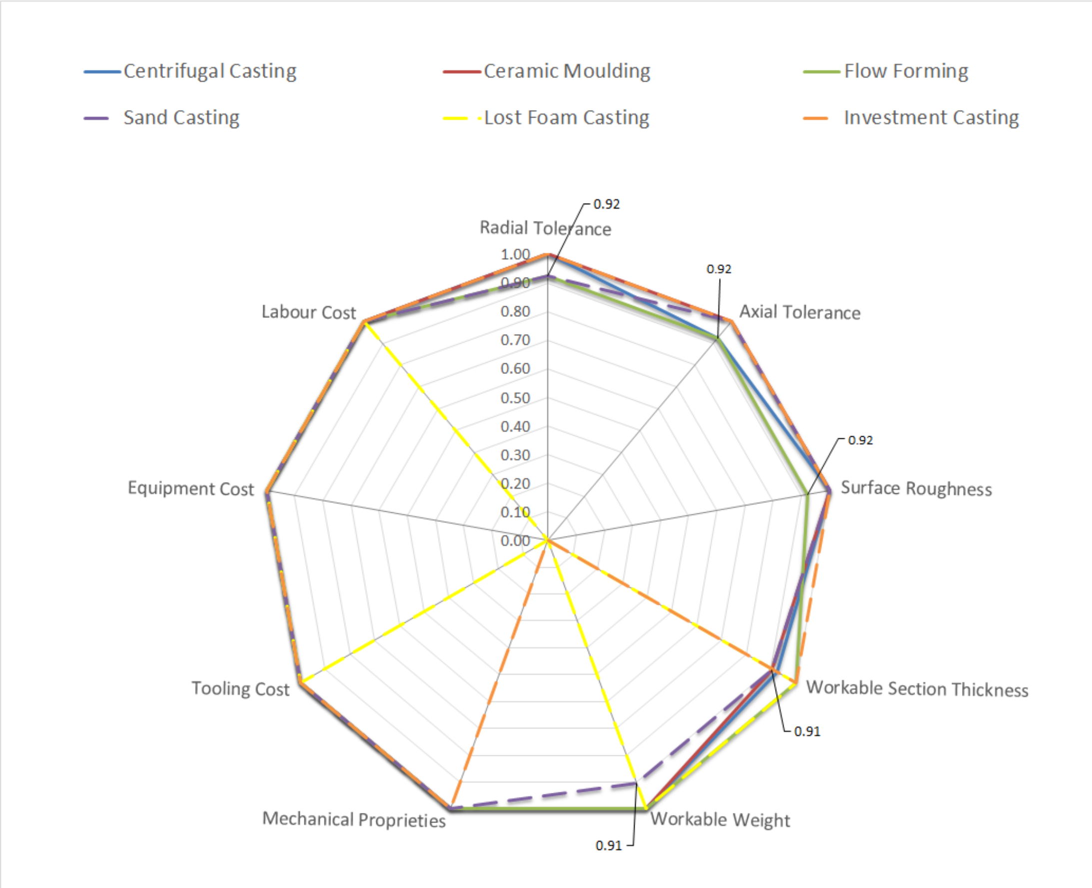


Figure 4.15: Process compatibilities breakdown for the Case Study II.

current application of open-die forging process (for small-medium sizes) as wells sand casting process (for big components).

4.3 Conclusion: Case Studies Definition and Acquisition

In summary the application on ProGeMa3 to the case study company can be summarized in:

1. Economic opportunities screening: this stage was not applicable before ProSMa, due to the lack of economic data about the components production.
2. Material Selection: materials have been kept constant due to required erosion/corrosion resistance and constraints given the by sector of application (i.e. material choice is dic-

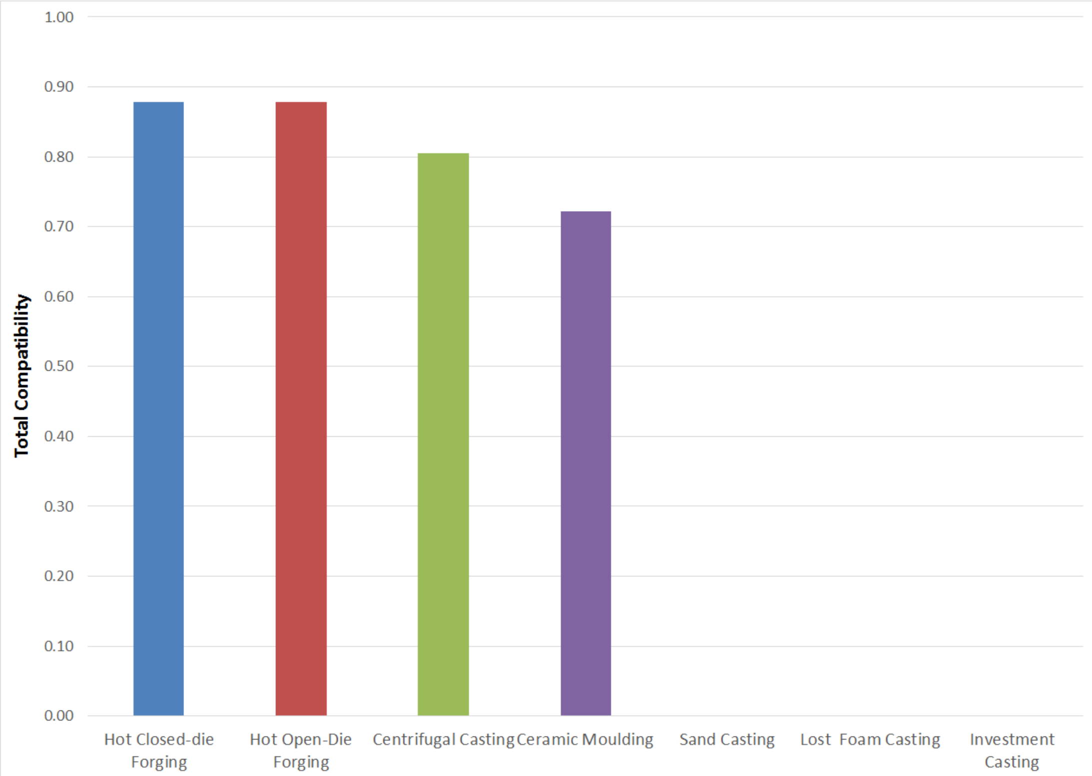


Figure 4.16: Process compatibilities ranking for the Case Study III.

tated by customers request and normative).

3. Process Screening Matrix (ProSMA): the ProSMa has been applied to all the components in the target assemblies, reducing the NNS process candidates (Table 4.1). Depending on qualitative economic considerations and technological targets, four case studies (Case Study IA, IB, II and III) have been selected among all others.

4. Process Compatibility Evaluation (Fuzzy logic): for the four case studies, target features of the component have been evaluated in comparison with processes' capabilities, using fuzzy sets. Fuzzy logic application defines the NNS process candidates to investigate for the four case studies.

The selected case studies and the relative NNS processes are as follows:

1. Case Study IA: flow forming of a valve seat

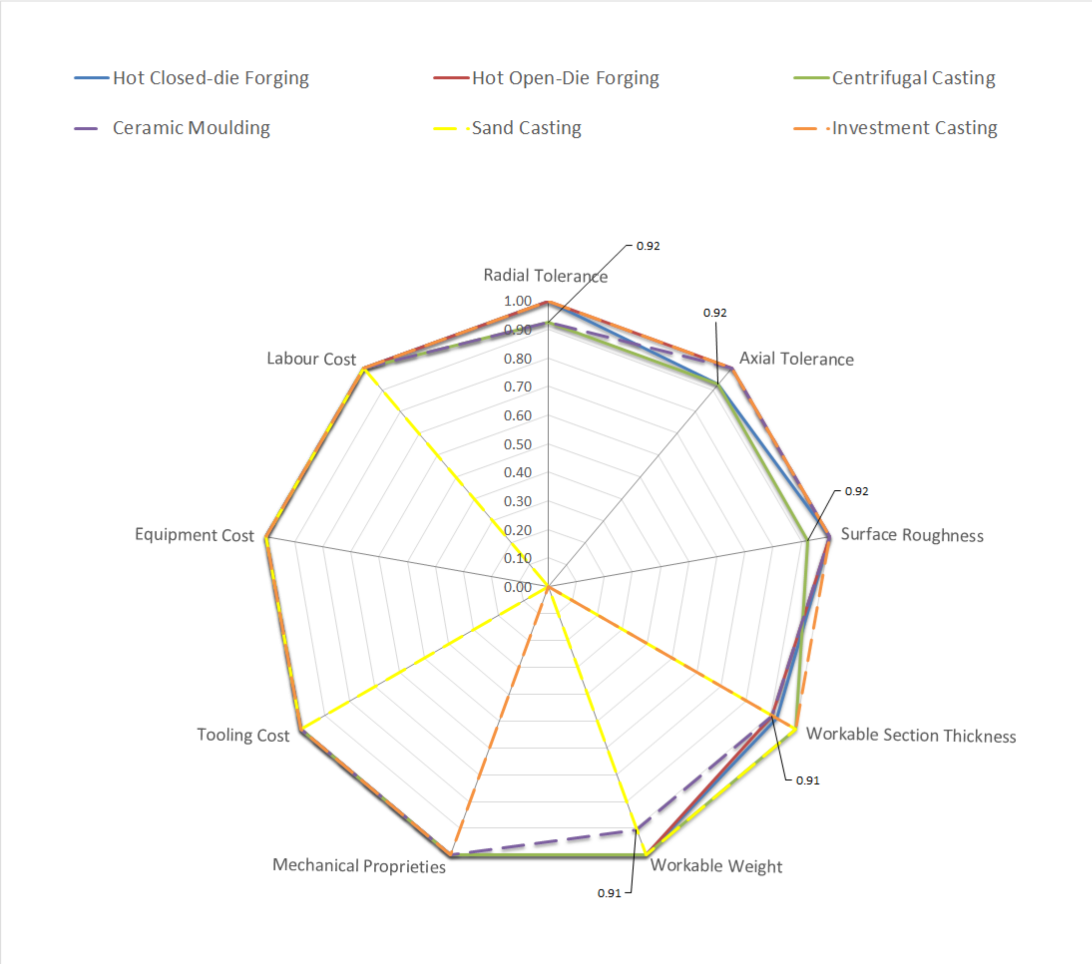


Figure 4.17: Process compatibilities breakdown for the Case Study III.

2. Case Study IB: flow forming of a riser pipe

3. Case Study II: centrifugal casting of a valve cage

4. Case Study III: hot closed-die forging of a valve body

The Case Study IA and IB has been acquired "off-line" by requesting detailed information from the component manufacturers regarding product design and requirements. Similarly, the manufacturing process chain details have been gathered from engineering managers and procurement. In contrast, Case Study II and III needed a more in depth investigation. For both cases, numerous product variants and requirements combinations generate a large amount manufacturing data. In Case Study II, some of the data were specifically gathered for this particular project: neither manufacturing parameters nor detailed cost data have ever been collected before, even for the current production process. The manufacturing chains and their cost needed to be investigated and formalized during this investigation. This lack of manufacturing knowledge and data made application of new manufacturing process and its analysis particularly challenging. In Case Study III, manufacturing data had already been gathered by the company, although they were not formalized. Both these case studies have been developed through industrial visits, which lasted two weeks (Case Study II) and ten days (Case Study III).

Chapter 5

Validation: Case Study IA and IB - Flow Forming of Valve Seat and Riser Pipe

5.1 Introduction

The previous chapter has identified two potential candidates for the flow forming process: riser pipe (Case Study IA) and valve seat (Case Study IB).

Phase II of the NeNeShO (i.e. DFCA) aims to assess technological and economic feasibility, so in the next section of this chapter, the literature is investigated to identify an approach for evaluating the technological feasibility of the flow forming process. This survey results in the selection of a NeNeShO Protocol route (i.e. Route 1) because of the high reliability of the analytical and empirical prediction models for flow forming.

The following section provides details of DFCA (Section 3.1.2) of both the components (i.e. riser pipe and valve seat). Different NNS process chains have been designed for producing the

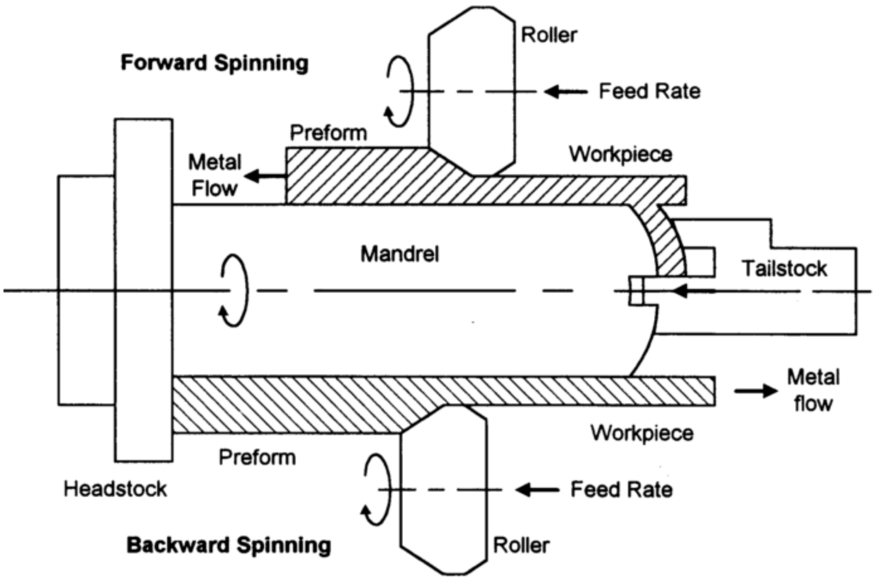


Figure 5.1: A schematic illustration of Flow forming [Chang et al., 1998].

two components by flow forming process. After the technological feasibility of their manufacture using a flow forming process has been assessed (i.e. energy based model), an analytical time/cost model is used to estimate the cost of their manufacture.

5.2 Systematic Literature Review - Flow Forming

The flow forming process manufactures rotational components using deformation forces generated by rotating rollers that compress and stretch a blank (called a preform) through consecutive stages. Flow forming plastically deforms a hollow metal blank on a rotating mandrel by means of forces generated by a number of moving rollers (Figure 5.1). The blank's material is constrained to flow in an axial direction by the movement (i.e. feed) of a number of rollers. Large thickness reductions of over 50% can be achieved with multiple passes of the rollers (i.e. several repetitions of the forming process) while the internal diameter remains almost constant.

Despite the limited commercial applications of the process a steady stream of research into its mechanics and characterization has been reported since its introduction in the 1950s (Figure 5.3). Today flow forming is of growing importance because it:

1. Produces components with good tolerance control and geometrical accuracy.

2. Allows precise control of a component's wall thicknesses and so enables the manufacture of optimized designs.

3. Supports a large range of workable materials (e.g. Steel, Alloy Steel, Titanium and Titanium Alloy, Brass, Copper, Aluminium, Nickel, Niobium).

4. Produces components with low surface roughness (compared with other plastic deformation processes).

5. Improves the mechanical properties of formed materials (through working hardening).

6. Reduces material waste (compared with traditional machining, forging and forming processes).

The economic advantages arise from the processes ability to form material into a complicate shape that allows the elimination of subsequent manufacturing or finishing steps. Thus a reduction of cost can be achieved while simultaneously enabling lightweight designs with good mechanical properties.

Any comprehensive literature review for flow-forming, must address both the physical mechanisms underlying the process and their application in the engineering of manufacturing procedures. To provide a framework for the review that effectively distinguished between these two interacting streams of work, the methodology proposed in Music et al. [2010] (for shear forming) has been adopted (Figure 5.2) with some small modifications.

This distinctive capability of the process is characterized by the reduction ratio (R_0) parameter:

$$R_0 = \frac{t_0 - t}{t_0} \tag{5.1}$$

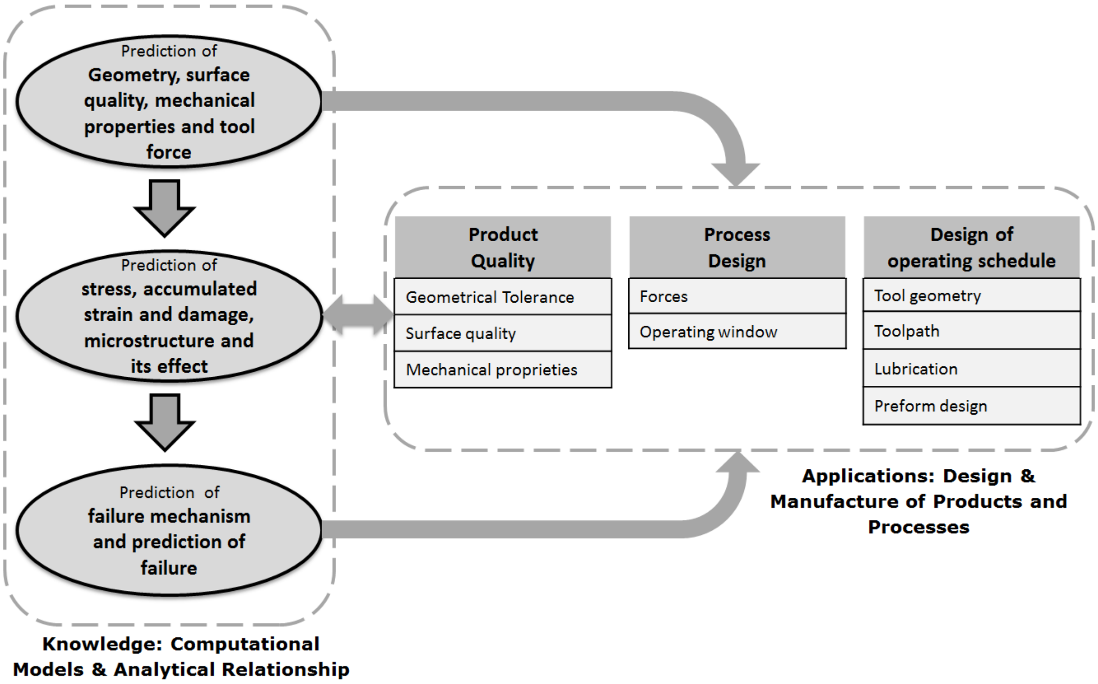


Figure 5.2: Review methodology developed from Music et al. [2010].

or

$$R_0 = ln\left(\frac{t_0}{t}\right) \tag{5.2}$$

Where, t_0 is the initial thickness of the blank and t is the final thickness of the workpiece [Hayama and Kudo, 1979b]. Limits of flow forming processes imposed by, say, material properties or machine power are frequently defined in terms of reduction ratio. For example tube "spinnability" is defined by Kalpakcioglu [1961a] as the maximum reduction achievable. This large and controlled change in the thickness of the workpiece is often cited as the crucial difference between flow forming and conventional spinning (where the thickness remains essentially constant) (Wong et al. 2003). The flow forming process has two main variants known as forward and reverse (or backward) flow forming. In forward flow forming, the blank is located (i.e. clamped) through the tailstock and mandrel (requiring the blank to have a suitable flange geometry to enable this fixture) [Wong et al., 2003]. The arrangement constrains the workpiece material to "flow" in the same direction as the roller's axial movement.

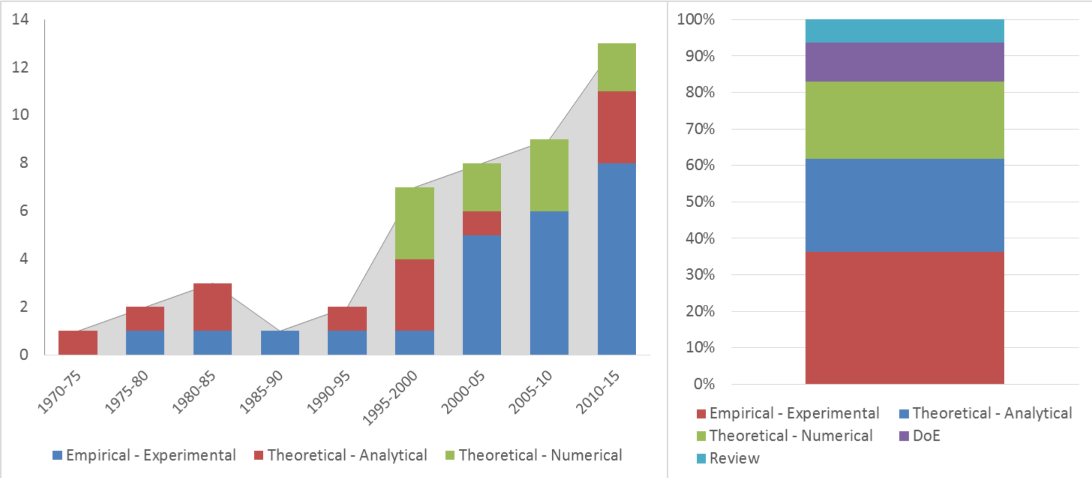


Figure 5.3: Chronological distribution of flow forming publications.

In other words it is pushed ahead of the rollers as the progress down the mandrel.

In backward flow forming, the workpiece is located against the headstock of the mandrel which forces the material to "flow" in the opposite direction to roller's motion (i.e. squeezed out from under the rollers themselves). Although this removes the need for the initial blank to have a locating flange, Singhal et al. [1987] observe that it is easier for defects to occur (compared to forward processes). This is because the large axial deformations (material can be flowed along the length the mandrel) results in residual stress that can cause distortions and local weak-points. Consequently backward flow forming is also more susceptible in a loss of accuracy in the axial direction [Xu et al., 2001b, Runge, 1994]

The differences between conventional spinning, shear forming and flow forming, in both mechanics and nomenclature are presented in Appendix D.1.

Table 5.1 and 5.2 summarizes flow forming terminology and nomenclature found in the literature.

According to the systematic literature review approach presented in Figure 5.2, the literature about flow forming process and mechanics has been surveyed for investigating the existing prediction models and experimental approaches. According to NeNeShO, the research papers have been reviewed accordingly to adopted methodologies, dividing them into:

Term	*Alternatives*	*Description*
Conventional Spinning	Multi-pass spinning, deep-drawing spinning, spinning, simple spinning (spinning in a single pass)	Spinning process where a sheet blank is formed into a desired axisymmetric shape without a change in the wall thickness and with a deliberate reduction in diameter either over the whole length or in specific areas.
Shear spinning	Shear forming, flow forming, shear/flow turning, power spinning, hydrodynamic spinning	Spinning process where a sheet blank is formed by a roller into an axisymmetric part with a desired shape and thickness distribution. The thickness is deliberately reduced to obtain a desired distribution while the diameter of the part remains constant.
Flow Forming	Flow turning, Tube spinning	Spinning process where a blank is formed into a desired axisymmetric shape with possibility of changing in wall thickness and with a constant or variable reduction in diameter in whole length or in specific areas
Roller(s)	-	Rigid roller that forms the sheet over a mandrel.
Tailstock	-	Circular disk clamping the sheet to the mandrel. May be flat or curved to fit over the mandrel and further support the sheet while it is being formed.
Preform	Blank, cup, disk	Initial workpiece with different possible shapes, dependent to final required shape of product
Initial thickness (t_0)	-	Original thickness of the part
Final thickness (t)	-	Final thickness or thicknesses if variable with along component.
Mandrel	Chuck	Rigid axisymmetric tool with the profile of the final component. Supports the workpiece during deformation

Table 5.1: Flow forming terminology and nomenclature (Part I).

Term	*Alternatives*	*Description*
Roller feed rate	Feed rate	Linear speed of the rollers in axial direction [mm/s]
Mandrel speed	Rotational Speed	Rotational speed of the mandrel [rpm]
Feed ratio	Feed per rotation, feed per revolution	Stoke of the roller for every rotation [mm/rev]
Tangential force	-	
Axial force	-	Three mutually perpendicular components of the roller force
Radial force	-	
Roller nose radius	Nose radius	Blending radius between the two flat surfaces on the outer surface of the roller
Roller attack angle	Attack angle, leading angle, approach angle	Angle lying between mandrel axis and inclined surfaces of the roller
Roller diameter	-	Roller main dimension (mm)
Reduction ratio (R_0)	Degree of thinning, thickness reduction ratio, spinning ration, forming ratio, maximum reduction	Proportionality between initial thickness and final thickness
Thickness reduction	Diameter reduction, depth of cut	Reduction in thickness and diameter imposed by the rollers
Limit degree of thinning	Limit thickness reduction, spinnability, critical reduction ratio	Limit reduction ratio before failure occurring
Circumferential Flow (S)	-	Length of circumferential contact between workpiece and roller, proportional to the material beneath the roller flows in circumferential direction
Axial Flow (L)	-	Length of axial contact between workpiece and roller, proportional to the material beneath the roller flows in radial direction

Table 5.2: Flow forming terminology and nomenclature (Part II).

- Experimental
  - DoE
- Theoretical
  - Analytical
  - Numerical

A survey of the theoretical and experimental in the literature approaches is presented in Appendix D.1. The flow forming mechanism is analysed through the models used by various authors for prediction of different process parameters and issues. Papers about conventional spinning, judged relevant to flow forming applications, are also presented in Appendix D.1. The prediction models in the literature can be classified as follows:

- Prediction of product final geometry
- Prediction of surface properties
- Prediction of mechanical proprieties
- Prediction of microstructure and its effects
- Prediction of power and tool forces
- Prediction of failure

Summarizing the failure prediction in flow forming process, Table 5.3 maps the influence of process parameters on the insurgence of defects.

5.2.1 Concluding Remarks

The sensitivity of the flow forming process to material properties affects the prediction accuracy and, so the impact, of theoretical models. The literature survey has identified several knowledge gaps:

Defects types	Feed rate	Mandrel speed	Depth of cut	Reduction Ratio	Preform initial thickness	Roller Dimension	Roller attack angle	Preform Microstructure	Preform Hardness	Lubricant	Heat treatments
	Possible Influences										
Diametral growth	Hi	Lo	n/c	Hi	Lo	Hi	Hi	Lo	Lo	n/a	Lo
Ovality	Hi	Lo	Hi	Hi	n/c	Hi	n/c	Hi	Hi	n/a	Lo
Fish Scaling	Hi	Lo	Lo	Hi	Hi	n/c	Hi	Hi	n/a	n/a	Hi
Wrinkling	Hi	Lo	n/a	Hi	Hi	n/c	Hi	n/a	n/a	n/c	Hi
Springback	Hi	n/a	n/a	Hi	Hi	Hi	n/a	Hi	Hi	n/a	Hi
Cracking	Hi	Lo	Hi	Hi	Hi	n/c	Hi	Hi	n/c	n/c	Hi
Microcracks	n/c	n/a	n/a	n/c	n/c	n/a	n/a	Hi	n/c	n/a	n/c

Table 5.3: Influences of process parameters on defects and geometrical inaccuracies (*H, high; L, low; n/a, not available; n/c not clear*).

- Stress and strain tensors evolutions are not fully determined for workpiece, due to the high computational cost and the difficulty in identify the best finite elements approach.

- Ratio of circumferential to axial contact is widely used as a defect prediction parameter, although the process' failure mechanism is still not fully understood.

- Forming forces and powers are defined, analytically and numerically, in correlation with process parameters.

- None of the authors surveyed in this review connects microstructural evolution with instant stresses and accumulated strains in order to obtain a general model of failure. Final microstructure is often evaluated for specific cases but its evolution during plastic deformation is not widely studied or understood.

- Residual stress, springback and some final material proprieties, such as corrosion behaviour, have been not studied numerically or experimentally.

- Tool path impact and alternative geometries are not deeply explored. Similarly, microcracks investigation and causes are not well investigated.
- Process experimental optimization and characterization through DoE is still limited to a few papers and usually not well developed.
- Lack of accurate numerical models makes it difficult to do process optimization through algorithms.

Many attempts have been made in order to predict failure and defects. Roles of material microstructure and properties are still not well understood. Relationships between microstructure and failure are implicit and are usually not considered by researchers. New theoretical approaches and numerical methods for prediction of strains is the target of ongoing research. Hollomon's power law (Equation (5.3)) is deployed by some authors [Podder et al., 2012, Jalali Aghchai et al., 2012] for predicting the ultimate strength of formed components and shows good agreement with experimental data.

$$S_u = K\ {\varepsilon_u}^n \tag{5.3}$$

Where: S_u, ultimate tensile strength (MPa); $\varepsilon\ _u$, total plastic strain; n, strain hardening exponent; K, strength index (MPa). After every deformation, variations in hardening exponent and the strength index modification make it difficult to predict accurately the final strength values. Erasmus law (5.4), used in Rajan et al. [2002a], is derived from Hollomon's one. This formula considers section variation (A_r) and accuracy in its prediction is tested by the authors.

$$S_u = K\left[n + ln\left(\frac{1}{1 - A_r}\right)\ \right]^n \tag{5.4}$$

Key to flow forming process is the S/L ratio (empirical model), developed by Gur and Tirosh [1982] and validated by several authors [Jahazi and Ebrahimi, 2000, Jalali Aghchai et al., 2012, Parsa et al., 2008, Podder et al., 2012, Rajan and Narasimhan, 2001, Roy et al., 2010]. It expresses plastic flow quality for given process parameters and roller/component geometries. The model allows the failure insurgence to be predicted by the evaluating the plastic flow ratio (axial against circumferential) using workpiece and roller geometries. Initial thickness, feed rate, roller attack angle and reduction ratio need to be balance in order to obtain a defectless part. Using Gur and Tirosh [1982] formula is possible to correctly evaluate the influence of these parameters. Material failure is connected with tension and stress tensors, crack propagation mechanism and process instability. Expression of circumferential contact (S) and axial contact (L), from (Gur & Tirosh 1982) is as in (5.5) and (5.6)

$$S = R_R \; \beta \tag{5.5}$$

$$L \cong \left(\frac{T_0 - T_f + 2}{f + tan\alpha} \right) \tag{5.6}$$

Where,

1. $\beta = \; cos^{-1} \left(\frac{a^2+c^2-b^2}{2ac} \right)$
2. $a = R_R + T_{fi} + R_M$
3. $b = R_M + T_{fi} + ftan\alpha$
4. $c = R_R$

With, R_R, roller radius (mm); R_M, mandrel radius (mm); α, roller attack angle; T_0, initial thickness (mm) T_f, final thickness (mm).

Regarding power and tool forces prediction, the energy model [Hayama and Kudo, 1979a,b, Mohan and Misra, 1970, Singhal et al., 1990, Jolly and Bedi, 2010, Molladavoudi and Djavanroodi, 2010] is the one used by most of the authors, because of its most complete approach and its coherency with experimental data.

5.3 DCFA of Flow Forming Application to Case Study IA and IB

The systematic literature review suggests that analytical and empirical predictions models are robust enough to allow reliable assessment of the technological feasibility. Consequently Route 1 in NeNeShO Pro structure has been selected (Figure 5.4) and technological feasibility determined using an energy based flow model (Appendix E.2), to predict the required forming force, and the S/L ratio (Equations (5.5) and (5.6)) to estimate the process defect rate. Ultimate tensile strengths and surface roughness are defined as requirements (as well as the available forming force), predicted by the Erasmus law (Equation (5.4)) and Rajan and Narasimhan [2001] formula (Equation (D.1)) respectively.
Following the selected route, an analytical time model and corresponding cost model (related to the derived forming force) have been developed (Appendix E.3). The next subsection presents the flow forming process chains (i.e. for the riser pipe and valve seat) which: describe the component, the process parameters selection, the requirements definition and the comparison with the current process chain. AS mentioned, the different process alternatives are evaluated technologically and economically in the next subsections.

5.3.1 Flow Forming Design and Product Requirements Definition for Case Study IA and IB

This section defines the flow forming process chains studied, and the requirements that need to be accomplished by the flow forming process application. The selected process variant for both the components is forward flow forming, due to high process stability and control of formed shape [Hayama and Kudo, 1979a].
Riser pipe (Case Study IA), shown in Figure 5.5, is a very long component and is essentially a flanged pipe, so the main potential advantage of production by flow forming would be

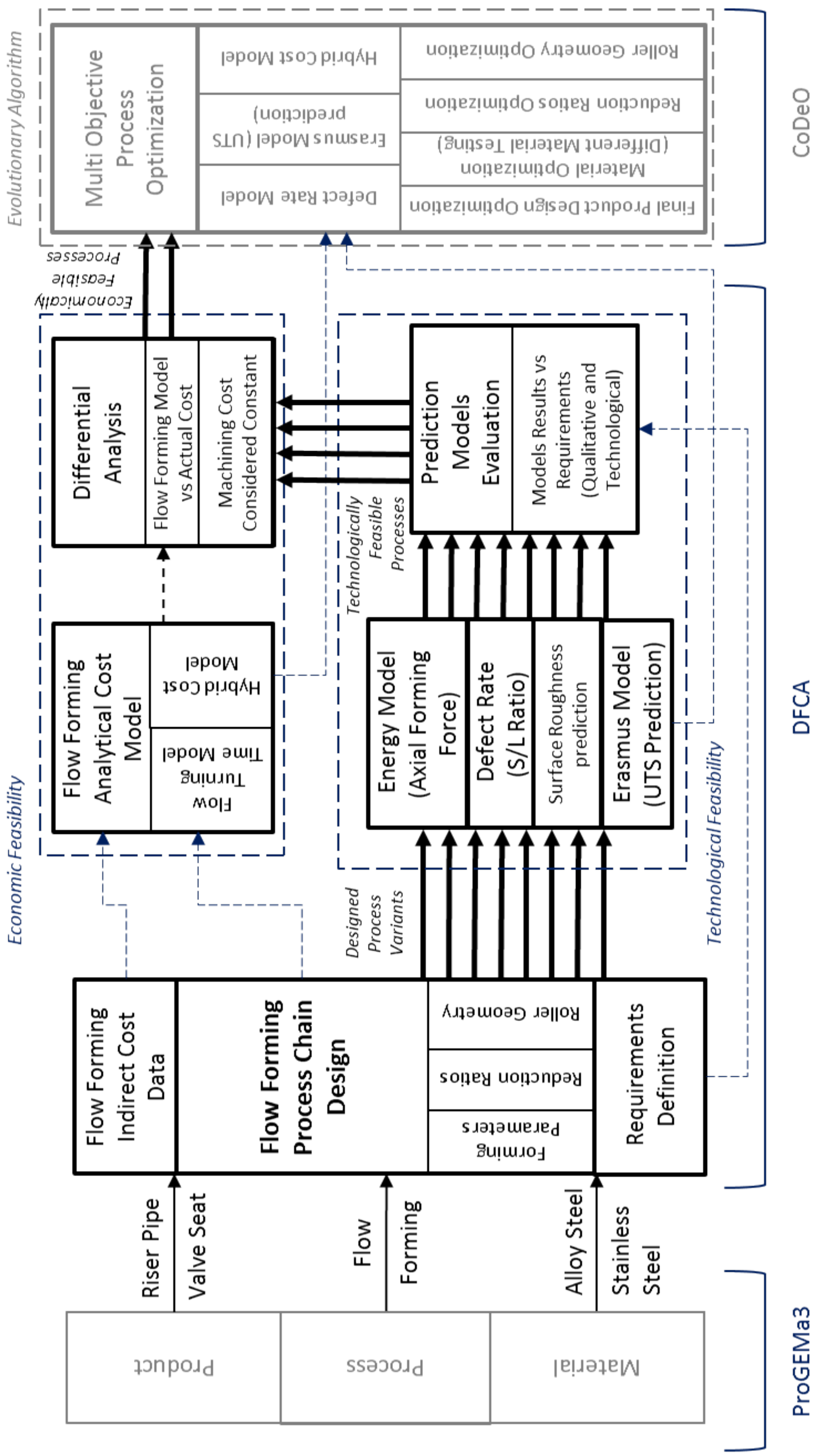


Figure 5.4: Scheme of the route 2 (NeNeSho Pro) applications to the flow forming case study.

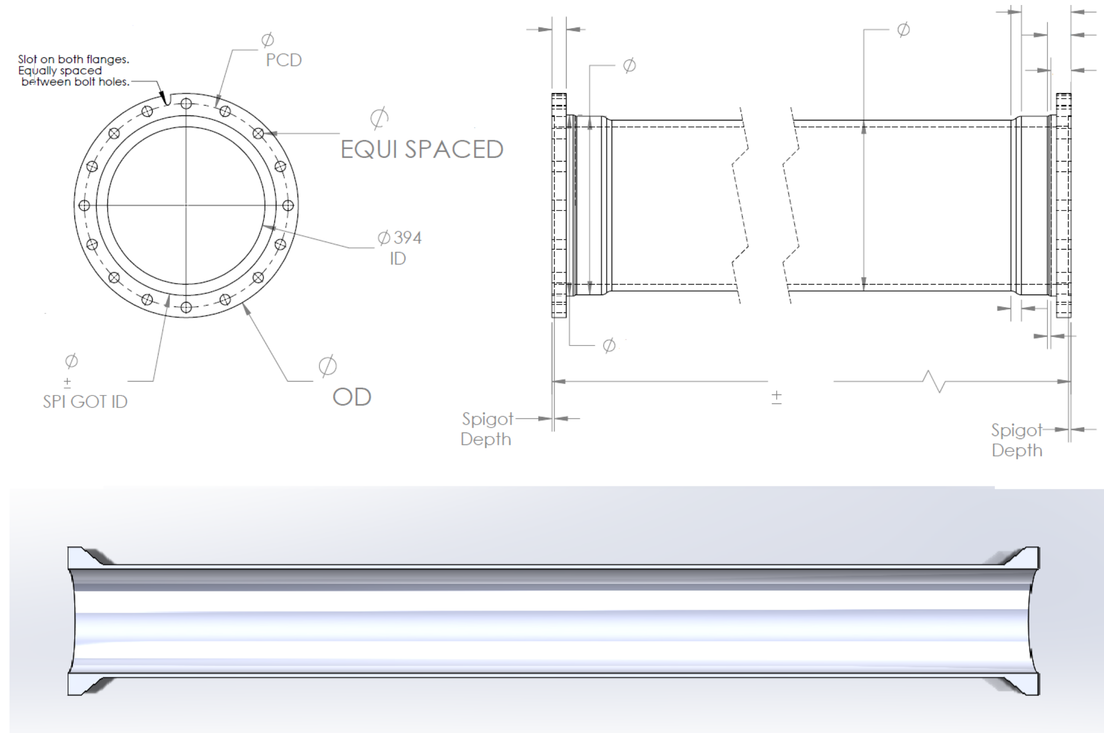


Figure 5.5: CAD representation of the riser pipe.

removal of the need for welding of the flange. Roughing machining operations were not considered after the flow forming process (finishing operations have been considered constant and so excluded from the analysis). The quality targets considered are the final tensile strength and the surface roughness. Component material has been selected by prior design, due to compatibility with corrosive environment and loads. It is an alloy steel with the following characteristics:

- Yield strength, 820 MPa;
- Ultimate tensile strength, 850 MPa;
- Hardening exponent (n), 0.25;
- Strength index (K), 820 MPa.

Riser pipe production volume is around 100 units per year. Lead time is around 12 weeks and part cost was around £ 4000 per unit. The identified lead-time, for comparison with the current process, is 80 minutes (i.e. identified by the company). Currently, the investigated component has no dimensional and material variants.

Valve seat (Case Study IB), shown in Figure 5.9, is a compact component which is subject to very high pressure, fatigue and erosion. Due to its dimensions, stacked production has been considered as a forming option. In comparison with the current manufacturing process, strength improvement, dimensional tolerances close to the final shape and less machining (i.e. even if the stacked component need to be thermal treated before being separated) can be improved by the flow forming process. Material selection is specified by prior design. A high resistance alloy steel has been selected in order to deal with the high loads, required fatigue and corrosion resistance levels.

- Yield strength, 1103.31 MPa.
- Ultimate tensile strength, 1158.31 MPa.
- Hardening exponent (n), 0.25.
- Strength index (K), 1158.31 MPa.

Target valve production is around 40000 units per year. Lead time was around 8 weeks and single part cost was £ 31.33 per unit. The closed die forging (i.e. current primary shaping process) time for production was 30 minutes. A confidentiality agreement with the company, prevents details about the components (i.e. dimensions, tolerances, materials, mechanical proprieties, costs or lead times) or about the comparative analysis (i.e. quality or cost targets) being reported.

Case Study IA

In the original riser pipe (Case Study IA) component, concentric steps (i.e. flange shoulder) were located in the flanges zone; meanwhile, in final flow forming design, they were substituted by chamfers of different degrees, as they are achievable through flow forming process

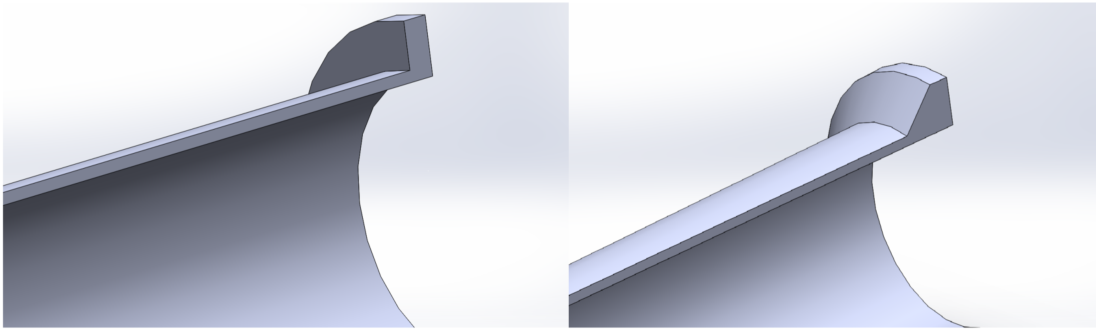


Figure 5.6: Difference between current design (welded flange) and NNS design (flow formed chamfer).

and maintain the component's functionality (Figure 5.6) . Differences between diameters allowed different chamfer solution (30 and 40 degrees angles) to be tried. The presence of slots and drilled holes, on the plain faces at pipe ends, means that a machining process is necessary after the forming process. Overall flanges diameters were defined to be the same as the original product but formed in different ways (i.e. designed flow forming process variants). These changes were considered compatible with component usage, although more material needs to be removed by a drilling process.

A comparison between the current supply chain and the flow forming processes (Figure 5.7) shows how the material removal process chain (i.e. machining) remains unaltered by the NNS process. The current primary shaping process is casting, to which the welding of flanges need to be added. However holes, slots, planar faces and the internal side of the pipe (i.e. both needed for coupling pipes through bolting) need to be machined, while the pipe's main internal and external surfaces do not require further machining. As mentioned and shown in Figure 5.7, the main advantages of the flow forming process are the avoidance of the welding process and the potential product quality improvement (i.e. ultimate tensile strength and surface roughness). The reduction ratios (Table 5.4) have been iterative selected using a geometric modeling flowchart for single pass and for multiple passes (detailed in Marini et al. [2017]). The preform and intermediate diameters and lengths were calculated using the formulas describe in Appendix E.1. The principle of volume constancy allow the initial and

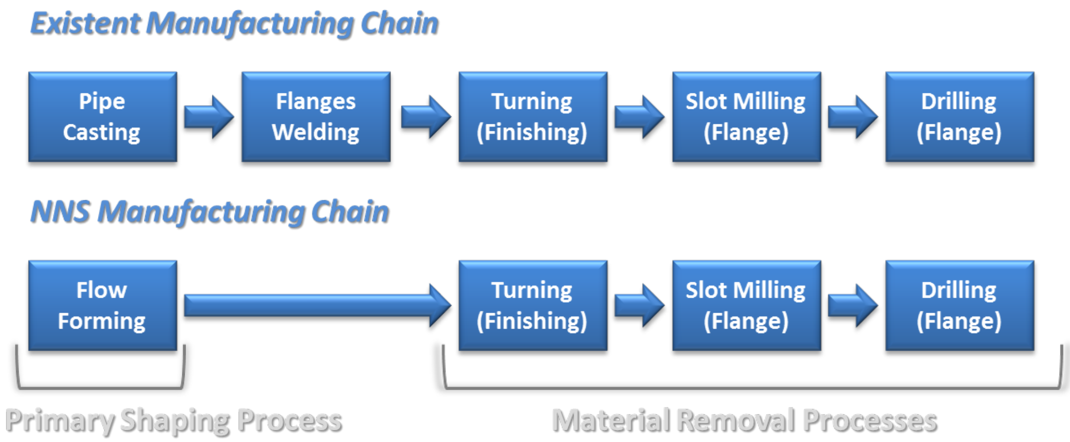


Figure 5.7: Comparison between existent (top) and NNS (bottom) manufacturing chains of the Case Study IA.

intermediate preform diameters (Equation (E.5)) and lengths (Equation (E.4)) to be calculated for obtaining the case of a hollow tube formed from a similar shaped preform. Similarly modifying the volume constancy equation (Appendix E.2) allows preform diameters (Equation (E.10)) and lengths (Equation (E.11)) to be calculated for flow forming a flanged pipe from a hollow tube. The reduction ratios' ranges were taken from the literature [Roy et al., 2009] although these are only estimates and the precise value can only be determined by dedicated experimental analysis. Several alternative flow forming process were created by forming the pipe and flange in various combinations of 1,2 and 3 steps. These process variants are described as:

- Process type A: hollow cylindrical blank is formed into flanged pipe only in the last stage, including chamfers of 30° (remaining a regular pipe for one or two stages).
- Process type B: hollow blank is formed into a flanged pipe (at second stage of three passes) with chamfers of 30°. The main diameter (i.e. pipe) is processed only in the last stages without involving the flanges.
- Process type C: hollow blank (for two stages) or pipe (three stages) is formed as flanged

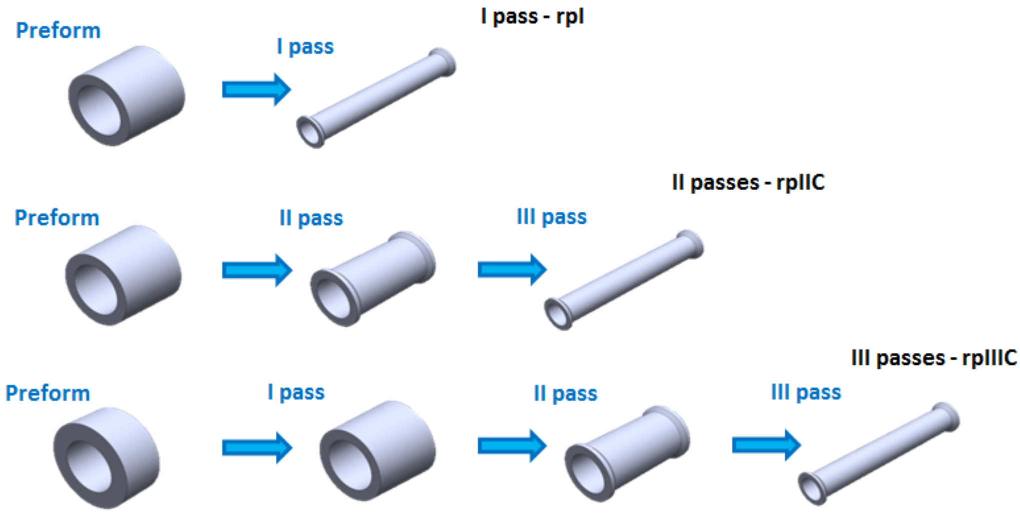


Figure 5.8: Examples of low forming processes for valve seat: rpIC (top), rpIIC (middle), rpI-IIC (bottom).

pipe (30° chamfers). In the last stage, both pipe and flange (with 45° degrees chamfers) are formed in one operation (Figure 5.8).

- Process type D (only for three stages): the entire flanged pipe geometry was formed as a series of incremental steps (i.e. chamfers and flanges variants). Hollow blank is formed with 20° chamfers, first pass with 30° and third pass with 45°.

The forming process parameters were determined by the literature [Hayama and Kudo, 1979b, Srinivasulu et al., 2012a, Rajan and Narasimhan, 2001, Podder et al., 2012], having the mandrel diameter selection constrained by the internal diameter constancy.

- Spindle speed, 300 rpm.
- Feed rate, 540 mm/min (1.8 mm/rev).
- Mandrel diameter, 83 mm.

Similarly, the roller geometry were selected accordingly to Hayama and Kudo [1979a] and [Jahazi and Ebrahimi, 2000]:

Process code	Passes nr.	Description				Redution Ratios			Total Reduction Ratio	Thickness Trend
		Blank	Pass I	Pass II	Pass III	Pass I	Pass II	Pass III		
rpI	1	Hollow Cylinder	Flanged Pipe (30°chamfeer)			0.24			0.24	
rpIIA	2	Hollow Pipe	Pipe	Flanged Pipe (30°chamfeer)		0.17	0.24		0.29	
rpIIB	2	Hollow Cylinder	Flanged Pipe (30°chamfeer)	Flanged Pipe (30°chamfeer)		0.25	0.15		0.34	
rpIIC	2	Hollow Cylinder	Flanged Pipe (30°chamfeer)	Flanged Pipe (45°chamfeer)		0.17	0.15		0.29	
rpIIIA	3	Hollow Cylinder	Pipe	Pipe	Flanged Pipe (30°chamfeer)	0.15	0.15	0.23	0.46	
rpIIIB	3	Hollow Cylinder	Pipe	Flanged Pipe (30°chamfeer)	Flanged Pipe (30°chamfeer)	0.14	0.14	0.12	0.25	
rpIIIC	3	Hollow Cylinder	Pipe	Flanged Pipe (30°chamfeer)	Flanged Pipe (45°chamfeer)	0.12	0.12	0.09	0.29	
rpIIID	3	Hollow Cylinder	Flanged Pipe (20°chamfeer)	Flanged Pipe (30°chamfeer)	Flanged Pipe (45°chamfeer)	0.15	0.09	0.11	0.31	

Table 5.4: Case Study IA: flow forming process variants description, number of stages (passes), reduction ratios and thickness trend.

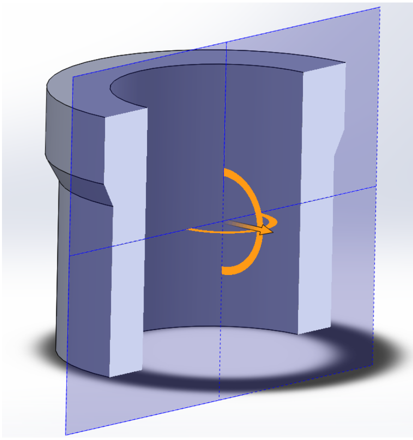
- Roller diameter, 800 mm.
- Roller attack angle, 20°.

The target quality requirements have been defined in order to evaluate the technological feasibility and to satisfy the required product quality. These targets are the comparison thresholds that qualify the flow forming processes as feasible or unfeasible.

- Qualitative requirements:
  - Target UTS improvement: 0.1 (arbitrary selected).
  - Target surface Roughness: 3.2 Ra
- Technological requirements:
  1. Axial forming force limit: 10000 KN - (AFRC) machine limit
  2. Defect rate threshold: $S/L > 1$ [Gur and Tirosh, 1982]

Case Study IB

The **Valve seat**'s geometry (Figure 5.9) made it possible to consider a stacked approach to valve production (Figure 5.11). To adapting the design for a flow forming process, the seat



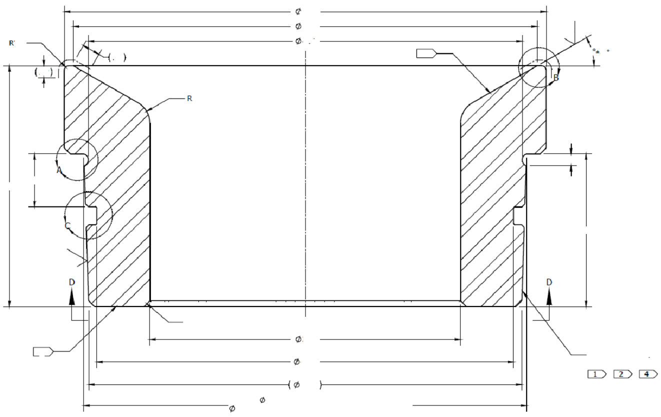


Figure 5.9: CAD representation of the valve seat (without finishing details).

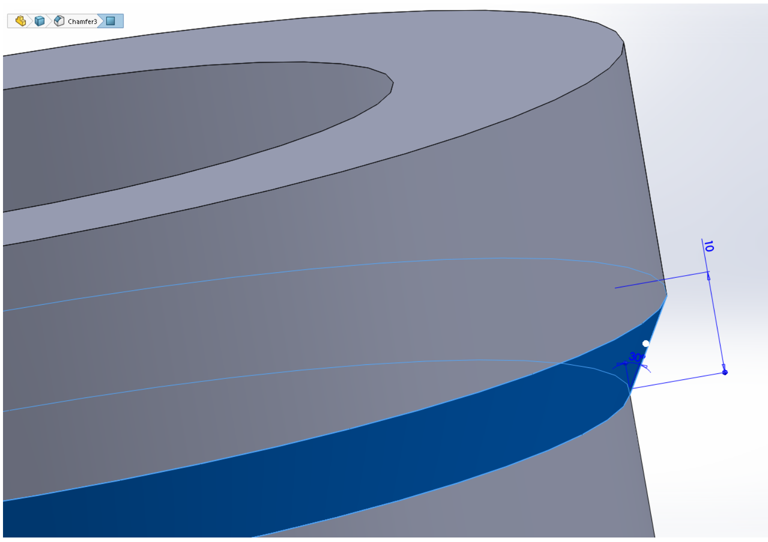


Figure 5.10: Chamfer design modification for adapting to flow forming process.

valve chamfer angles were changed from the current ones to 45 degrees (Figure 5.10), allowed by low thickness difference between top and bottom sections. For the same reason, the creation of the chamfers was introduced only at last stage of forming. Thus, the tube flanges (i.e. largest sections in the final component) have been dimensioned coherently with top diameter of the final valve seat.

This approach also allows the splitting of several formed parts from a hollow pipe preform. The NNS and current process chains are shown in Figure 5.12. Machining roughing and fin-

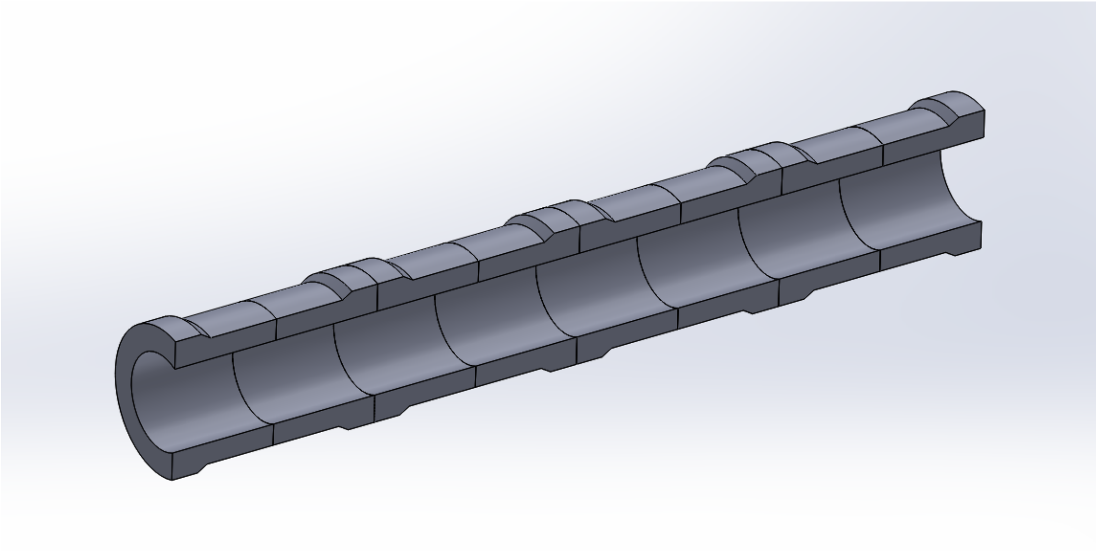


Figure 5.11: NNS design for stacked production (multiple valve seats configuration) using flow forming

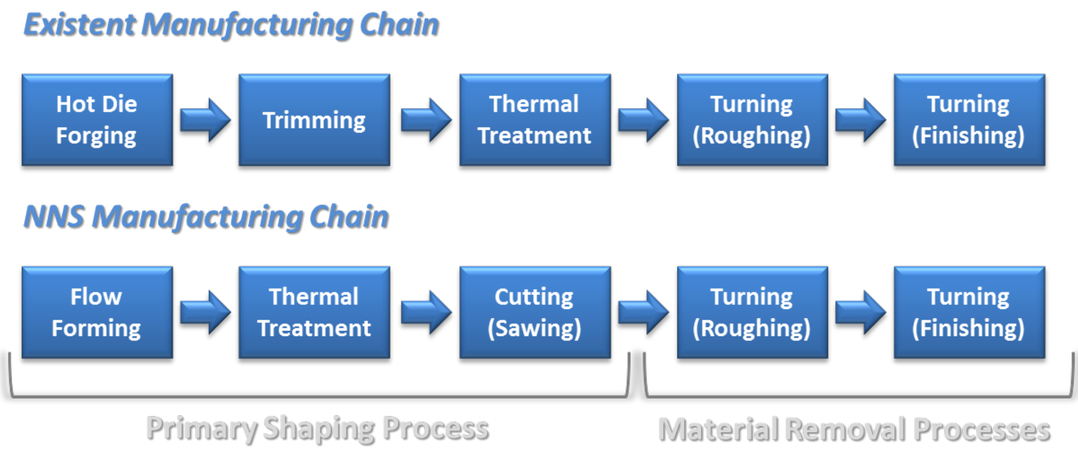


Figure 5.12: Comparison between existent (top) and NNS (bottom) manufacturing chains of Case Study IB.

ishing (i.e. turning) is required in both case because of the high tolerances required and due to the presence of a high precision slot (i.e. positioning of a seal ring). Similarly to the Case Study IA, reduction ratios and process variants are summarized in Table 5.5). The following process parameters were selected, According to Srinivasulu et al. (2012), Rajan & Narasimhan (2001) and Podder et al.(2012).

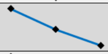
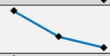
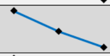
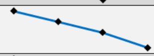
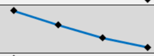
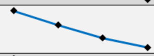
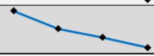
Process code	**Passes nr.**	**Description**				**Redution Ratios**			**Total Reduction Ratio**	***Thickness Trend***
		Blank	**Pass I**	**Pass II**	**Pass III**	**Pass I**	**Pass II**	**Pass III**		
rpI	1	*Hollow Cylinder*	*Flanged Pipe (30°chamfeer)*			0.24			0.24	
rpIIA	2	*Hollow Pipe*	*Pipe*	*Flanged Pipe (30°chamfeer)*		0.17	0.24		0.29	
rpIIB	2	*Hollow Cylinder*	*Flanged Pipe (30°chamfeer)*	*Flanged Pipe (30°chamfeer)*		0.25	0.15		0.34	
rpIIC	2	*Hollow Cylinder*	*Flanged Pipe (30°chamfeer)*	*Flanged Pipe (45°chamfeer)*		0.17	0.15		0.29	
rpIIIA	3	*Hollow Cylinder*	*Pipe*	*Pipe*	*Flanged Pipe (30°chamfeer)*	0.15	0.15	0.23	0.46	
rpIIIB	3	*Hollow Cylinder*	*Pipe*	*Flanged Pipe (30°chamfeer)*	*Flanged Pipe (30°chamfeer)*	0.14	0.14	0.12	0.25	
rpIIIC	3	*Hollow Cylinder*	*Pipe*	*Flanged Pipe (30°chamfeer)*	*Flanged Pipe (45°chamfeer)*	0.12	0.12	0.09	0.29	
rpIIID	3	*Hollow Cylinder*	*Flanged Pipe (20°chamfeer)*	*Flanged Pipe (30°chamfeer)*	*Flanged Pipe (45°chamfeer)*	0.15	0.09	0.11	0.31	

Table 5.5: Flow forming of a valve seat: process variants description, number of stages (passes), reduction ratios and thickness trend.

- Spindle speed, 500 rpm
- Feed rate, 625 mm/min (1.25 mm/rev)
- Mandrel Diameter, 83 mm

Roller geometry were selected accordingly to Hayama and Kudo [1979a] and Jahazi and Ebrahimi [2000].

- Roller Diameter, 300 mm
- Roller attack angle, 20°

The same requirements' categories used in Case Study IA are adopted.

- Qualitative:
  - Target UTS improvement: 0.2 (arbitrary selected).
  - Target surface Roughness: 1.6 Ra
- Technological
  - Axial forming force limit: 1000 KN (used in industrial similar case-study)
  - Defect rate threshold: $S/L > 1$ (Gur & Tirosh 1982)

5.3.2 Technological Feasibility of Flow Forming Process

Prediction models enable the evaluation of the technological feasibility for the different flow forming process variants, developed for both the case studies (i.e. riser pipe and valve seat). The technological feasibility of the process is determined by the comparison, for all the process variants, of axial forming force values and of the S/L ratios within their limit values. The first is compared with available flow forming machines' force limit and the second with threshold values (Equations (5.5) and (5.6)).
Using analytical models (i.e. energy based model), working forces and powers can be deducted, using component and roller geometries, materials and process parameters. In Appendix F (Section F.2), forming forces and powers formulas (derived from literature) have been described and adapted to this application. The prediction models also provide feedback to the process parameters and the intermediate process steps. Experimentally, a different combination of process is usually required for obtaining a suitable flow forming sequence, however, in this case, the same process parameters are used for all the generated variants (i.e. in practise the flow forming parameters selection is an iterative and experimental process). Geometric and material data of the components was extracted from the case studies manufacturer‘s data (i.e. The Weir Group PLC), meanwhile, as discussed, roller data has been taken from literature (i.e. the definition of product geometry, material and tool geometry influences the forming forces , as shown in formulas (E.23) and (E.24)).
The required quality level is determined by the comparison between the ultimate tensile strength (Equation (5.4)) and surface roughness predictions (Equation (D.1)) and their target values. In summary, to determine the technological feasibility, the target process variants need to fulfil the following requirements.

1. Axial Forming Force (E.26) $<$ Axial Forming Force Limit
2. Defect rate (S/L) (5.6),(5.6) $>$ 1

Process code	Axial Forming Force (KN)			Axial F Trend	Utimate Strenght Increasing		Predicted Surface Roughness (µm)	S/L ratio			S/L ratio Trend
	Pass I	Pass II	Pass III		Predicted UTS (Mpa)	Increment		Pass I	Pass II	Pass III	
svI4	764.36				1288.08	0.11	70.31	0.982			
svII4	896.27	148.89			1432.12	0.24	70.31	0.708	1.519		
svII6	932.28	491.31			1456.98	0.26	70.31	0.632	1.519		
svIII6	430.92	388.12	389.14		1447.75	0.25	70.31	1.173	1.351	1.519	
svIII8	1652.03	287.09	411.79		1475.17	0.27	70.31	0.856	1.080	2.090	
svIII16	1683.23	811.89	92.28		1498.57	0.29	70.31	0.990	1.437	1.996	

Table 5.6: Flow forming prediction model results for Case Study IA: axial forming forces and trend, ultimate tensile strengths and increments, surface roughness, S/L ratios and trends.

3. Surface Roughness (D.1)< Target Surface Roughness

4. Ratio of UTS increasing (5.4) > Target UTS improvement

Case Study IA: Prediction Models Application

The axial forming forces, defect rate prediction (S/L) and final predicted proprieties (i.e. ultimate tensile strength and surface roughness for the Case Study IA) have been summarized in Table 5.6. The unfeasible features (i.e. axial forming forces and S/L ratio) are shown in red, and feasible in green. Technological feasibility is established only for four cases (i.e. mostly due to the high forces involved), although even in these cases the likely defect rate is likely to be high. In the two passes processes, the last stage involved a high material displacement amount, due to high thickness differences and process parameters. In the three stages, the S/L trend changed because of the decreasing forming force. This was due to material displacement being evenly spread across a higher number of forming operations. The S/L ratio trends assume values which seem correlated with forming forces, except that in two cases (the second passes in type A and type C process chains).

As illustrated in Table 5.6, the ultimate strength increase follows the reduction in ratios trend. Surface roughness was not coherent with industrial and literature data (Wong et al. 2003), thus the model can be considered not reliable in this case. Following the mentioned criteria,

Process code	Axial Forming Force (KN)			Axial F Trend	Utimate Strenght Increasing		Predicted Surface Roughness (μm)	S/L ratio			S/L ratio Trend
	Pass I	Pass II	Pass III		Predicted UTS (Mpa)	Increment		Pass I	Pass II	Pass III	
rpI	24475				1098.26	0.29	564.06	0.638			
rpIIA	14500	26925			1123.34	0.32	564.06	0.849	1.063		
rpIIB	16695	30467			1191.77	0.40	564.06	0.570	1.063		
rpIIC	14500	26925			1201.31	0.41	564.06	0.622	0.778		
rpIIIA	4475	5642	2907		1191.77	0.40	564.06	0.840	0.904	0.814	
rpIIIB	5278	9600	3162		1151.17	0.35	564.06	1.011	1.094	1.329	
rpIIIC	4404	6172	4843		1201.31	0.41	564.06	0.904	0.992	1.297	
rpIIID	4513	9410	2530		1213.58	0.43	564.06	0.668	1.328	1.061	

Table 5.7: Flow forming prediction model results for Case Study IB: axial forming forces and trend, ultimate tensile strengths and increments, surface roughness, S/L ratios and trends.

only the process rpIIIB has been considered as feasible.

Case Study IB: Prediction Models Application

Similarly to Case Study IA, the resultant forming forces and trend, predicted UTS strength and its increment, predicted surface roughness and S/L ratio and trend are summarized in Table **??**.

The forming force is dependent on the attack angle, roller and formed piece geometry (formulas (E.23) and (E.24)) as well as on the power distribution over the workpiece. Therefore the forming force increases with the number of valves generated or when a high amount of material is displaced (svI4 and svII4, svII6 in the first pass). All axial forces followed the same trend. Values higher than the threshold at first stages were due to high material displacement in those forming passes.

As expected, the increase in ultimate strength correctly follow the reduction ratios trend. The infeasible S/L ratio could be almost completely associated with the highest flow forming forces. As in Case Study IA surface roughness did not match with industrial data and literature [Wong et al., 2003]. Following target criteria, only designed process svIII6 (Table **??**)

was considered as feasible.

5.3.3 Economic Feasibility of Flow Forming: Cost Models and Differential Analysis

A generative analytical cost model had been developed for the flow forming process, adhering to the Route 2 of the NeNeShO Pro. Economic feasibility has been evaluated only for technologically feasible flow forming processes(i.e. svIII6 for seat valve flow forming and rpIIIB for riser pipe flow forming).

The differential analysis is limited to comparing the flow forming cost with the cost of casting, in the Case Study IA, and with the closed die forging, in the Case Study IB. As mentioned, the machining processes have been excluded (as show in Figures 5.16 and 5.17) from both the differential analysis, because of the similar geometrical output between both the NNS and existent primary shaping operations. In these cases, the machining removal rate constancy could not be useful for identifying differences in machining costs, although they would remain minimal and therefore negligible.

Flow Forming Time and Cost models For evaluating the flow forming economic feasibility, a process time model has been developed by assuming the forming tool motion exhibits similarity between flow forming and turning processes. The time model has been constructed taking into consideration the flow forming process dynamic. For this reason, a time-model is inspired by classic G-code, which is used for programming CNC machines roller motion during flow forming process is schematized in Figure 5.13. Process time is obtained by the developed model, meanwhile the idle times and indirect costs have been estimated based on industrial case studies. As shown in Figure 5.13, forming lengths (green) and transverse lengths (red) can be treated differently as in turning and consequently they can be associated with process feed rate and transverse rate relatively. The derivation of the process cost and time

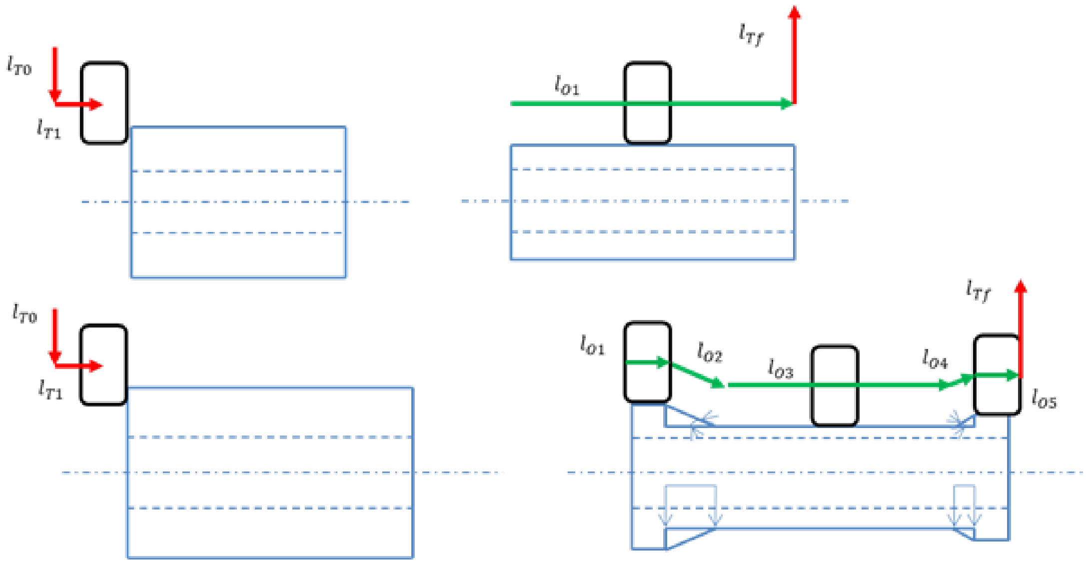


Figure 5.13: Flow forming time model schematization for hollow tube (up) and flanged pipe (down).

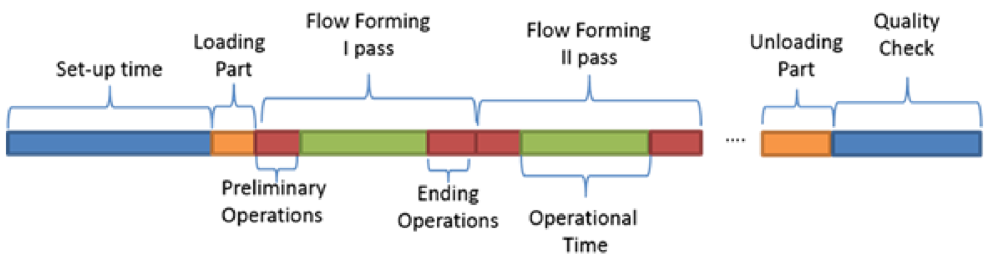


Figure 5.14: Flow forming time model schematization for hollow tube (up) and flanged pipe (down).

models are presented in Appendix E.3 and E.2. The model is derived from cost models used in Kalpakjian and Schimd [2009], Allen and Swift [1990]. The obtained values of cost and time need to be compared with the current or the targets ones. Flow forming times (including idle and set-up times) and costs data have been taken from previous industrial case study and from the data available at Advanced Forming Research Center (AFRC). These information have been also used for validating the model's assumptions. The cost model takes into consideration the flow forming process costs, relating them to the different required operations, as shown in Figure (Figure 5.14).

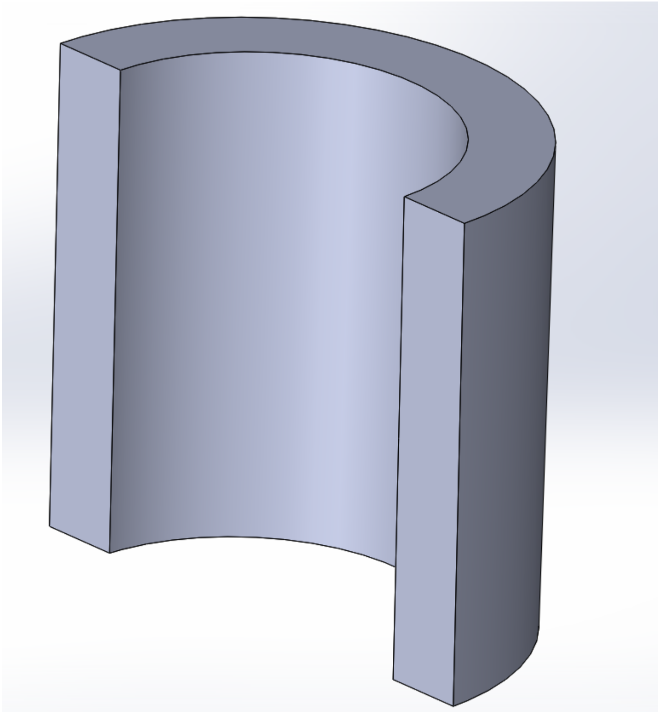


Figure 5.15: Flow forming preforms geometry for Case Study IA and IB.

Differential Cost Analysis of Case Study IA

In the Case Study IA, the NNS and existent process chain can be compared as shown in Figure 5.16. The technologically feasible flow forming process (rpIIIB) have been compared with the pipe casting and welding cost. The differences in turning and drilling (i.e. due to the highest thickness of the flow formed flange) have been considered negligible.

The flow forming cost and time calculations are documented in Appendix E.4. Working cost and working time were evaluated for every flow forming pass, as in Appendix E.3. Blank material volume was evaluated in order to evaluate raw material costing, as in Figure 5.15. Worker costs were evaluated on the national UK average. Increasing idle times has been considered, due to dimensions of the part to form (loading and unloading time), while set-up time has remained low because of the simplicity of toolpath. Process time remained relatively high because of the length of the part. For the flow forming (rpIIIB process variant), the final process time shows a reduction of 60% with the current production time, although predicted

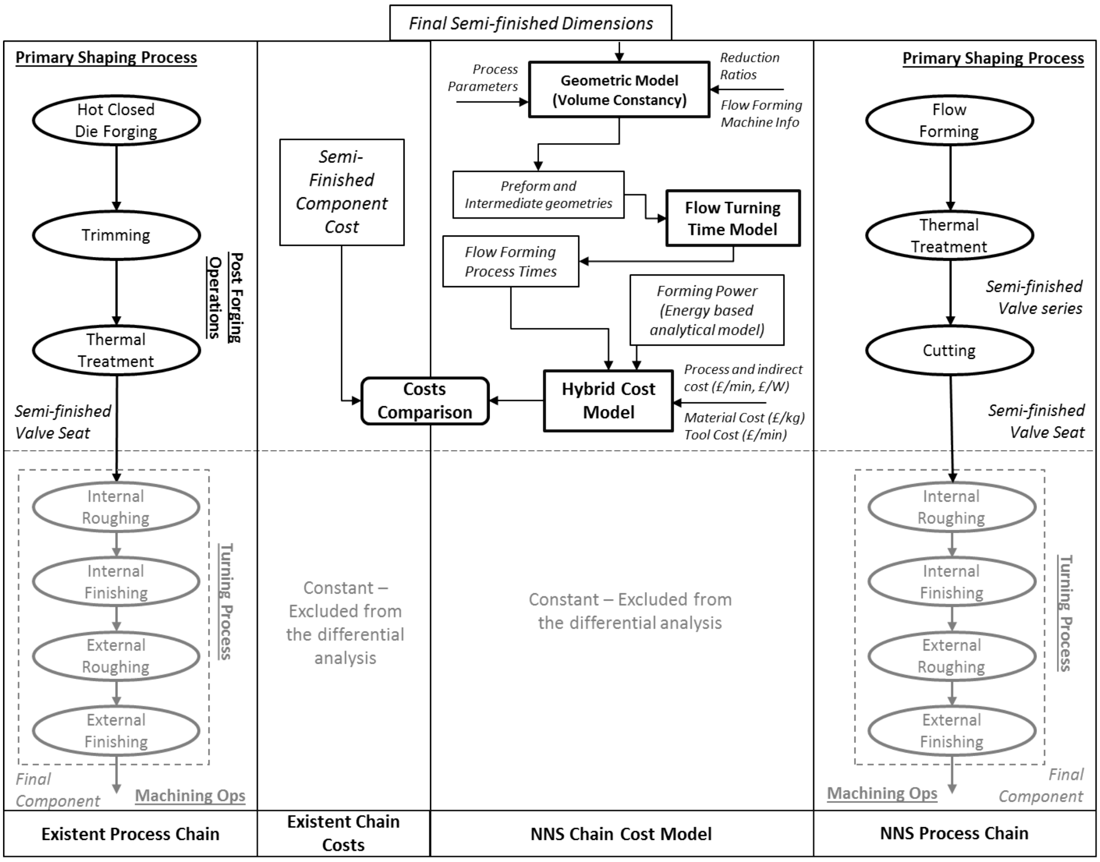


Figure 5.16: Differential cost analysis between the existent and NNS manufacturing processes of Case Study IA.

cost result 25% higher than the current one. Even reducing the lead time, the process has been considered as economically unfeasible. Cost calculations are detailed in Appendix E.4.

Differential Cost Analysis of Case Study IB

In Figure 5.17, the differential cost analysis scheme of the differential analysis between the valve seat process chains is illustrated. Both the NNS and existent process chains include thermal treatments, for adjusting the mechanical properties after the hot forging process and for relaxing the residual stress after cold forming (i.e. flow forming), in order to obtain the single valve separation without breakage. Trimming and post forging operations are also required after the hot die forging operation. These operations have been considered equivalent

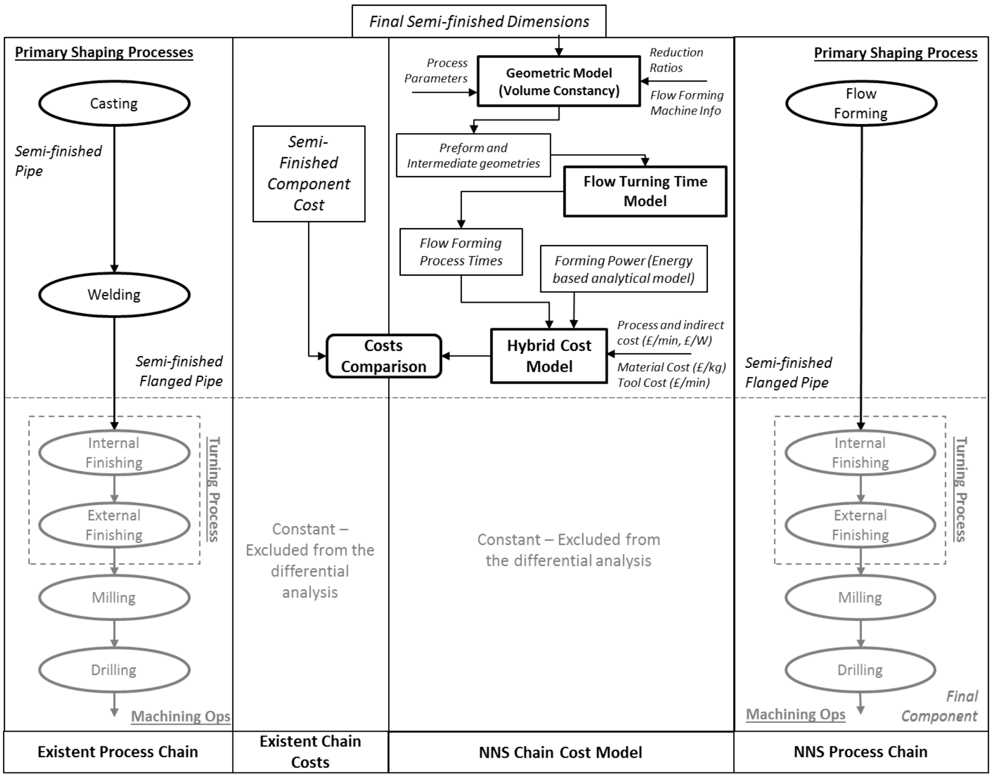


Figure 5.17: Differential cost analysis between the existent and NNS manufacturing processes of the Case Study IB.

in cost and time. As stated, removal rates processes are not included in the analysis. Set-up, idle and loading time was considered similarly to Case Study IA.

In Appendix E.4, the differential cost analysis calculations are shown. Similarly ot Case Study IA, only one process has been considered technologically feasible(svIII6 process variant): its process time shows a sensible reduction of the lead time (around 90% less) but an increasing of the 50% in the final cost. The process has been considered economically unfeasible for this reason.

5.4 Conclusion

The case studies IA and IB present two “borderline” components for the flow forming process because of the dimensions of the first and the necessity of “stacked production” and the high yield alloy, of the second.

Forming force and power show good correlation with a defect rate prediction model (i.e. a real "thermometer" of the flow forming process, which reliability is well stated in literature, as previously discussed) and, proportionally, with the literature [Hayama and Kudo, 1979a, Singhal et al., 1990, Roy et al., 2010]. Qualitative prediction of surface roughness has been excluded from the analysis, due to the high unreliability of the results. The roughness has been deemed as acceptable for both the component, as the average roughness achievable by flow forming is much higher than the requested ones [Srinivasulu et al., 2012a, Prakash and Singhal, 1995]. The ultimate tensile strength prediction is developed according to the literature, and it resemble the results presented in the literature [Rajan et al., 2002b, Podder et al., 2012, Jalali Aghchai et al., 2012].

Time model simulates correctly the flow forming process. Cost models are able to match the analytical prediction (i.e. and their dependency on workpiece geometry) with the process direct and indirect costs. In both cases, the machining processes have been exclude from the differential analysis, due to similar geometrical output between the existent and NNS primary shaping processes.

However, an increasing in the tensile strength could affect tool wear and turning force in the machining process, but, due to the minimal difference, it has been considered as negligible. Even though two process variants (i.e. one for each of the investigated components) result technologically feasible, and the prediction models show that the process might enhance tensile strength and surface roughness and reduce lead times, the cost increase resulted in the conclusion that the process was not a feasible proposition for the component. (i.e. very high cost impact on the comparative analysis). In conclusion, flow forming processes was not feasible for both the components.

Chapter 6

Validation: Case Study II Centrifugal Casting of Valve Cages

6.1 Introduction

The ProGeMa3 methodology (Subsection 3.1.1) identified centrifugal casting process as potential candidate for the NNS manufacturing of the valve cage. A literature survey of academic work on centrifugal casting (presented in Section 6.2) resulted in an experimental approach for the process (NeNeShO's Route 3).

Differently from Case Study I, DFCA has to consider the size and material variants of the component by comparing NNS process chain design with the existing one (i.e. assessing the feasibility for every size variant) through development of a centrifugal casting model. Technological feasibility has been evaluated experimentally by testing a full component prototype. Using the casting model and an innovative turning model, the CoDeO investigate the optimization of manufacturing process parameters (i.e. centrifugal casting and turning processes) and final product design, using a Genetic Algorithm (GA).

6.2 Systematic Literature Review - Centrifugal Casting

In centrifugal casting, a permanent mould is rotated continuously about a fixed axis at high speeds (300 to 3000 rpm depending on the mould diameter) as the molten metal is poured and until the solidification takes place. The molten metal is centrifugally “thrown” towards the inside mould wall, where it solidifies after cooling. The resulting casting is usually fine-grained with size of the grains decreasing towards to the outer diameter. Small impurities and inclusions are concentrated on the inner diameter because of the lowest amount of centrifugal force exerted due to their lower density (i.e. usually machined away). The combination of grain structure and purity results in final properties that are superior to conventional casting and close to hot forging.

The process can use a rotating semi-permanent, or expandable, mould to both guide the melted material movement under centrifugal force, and catalyse the solidification while enhancing quality. Most metals suitable for static casting are also suitable for centrifugal casting (i.e. all steels, iron, copper, aluminium, and nickel alloys). As described in Appendix B the processes most common variants are "true centrifugal casting", "semi-centrifugal casting" and "centrifuge casting".

In true centrifugal casting, the axis of rotation is usually horizontal, but may be vertical for short work pieces (Swift and Booker 2013). Good quality castings (i.e. low defect rate and impurities), high dimensional accuracy (i.e. in comparison with other casting processes), and external surface detail are produced by this process. Properties of castings vary by the distance from the rotational axis. Mechanical properties and grains structure are comparable with forged product ones. Centrifugal casting has the lowest porosity among casting processes [Schey, 1999]. True centrifugal casting variant is usually applied to cylindrical components with high duty applications.

Similarly to the previous case study, a systematic approach has been adopted when analysing the literature. The papers in the literature have been classified into categories, diving them into:

- Analytical investigations
- Numerical investigations
- Experimental investigations

The surveyed analytical, numerical and experimental papers are presented in Appendix D.2. In the literature, experimental articles [Chirita et al., 2008, Huang et al., 2011, Jain et al., 2016, Karun et al., 2015, Lee and Hyun, 2012, Liu et al., 2005, Luan et al., 2010, Sui et al., 2016, Watanabe et al., 2003] focus mainly on the impact of process parameters and interaction between materials (i.e. moulds and workpiece) on the final product microstructure and mechanical properties. Numerical articles [Chang et al., 2001, Fu et al., 2008, Keerthiprasad et al., 2011, Ping et al., 2006, Song et al., 2012, Zagorski and Sleziona, 2007, Long and Zebin, 2016] investigate the prediction models of microstructure mechanics (in macroscale and microscale), fluid dynamic behaviour (turbulences and fluid states), temperature and velocity fields, and mould filing conditions for different process parameters and mould geometries.

6.2.1 Concluding Remarks

The following observations can be made, based on the surveyed papers

- The analytical articles, which are largely focused on functional grade material modelling, cannot be used for predicting the feasibly of component production or predicting final properties without extensive validation. The reason is the high complexity and inaccuracy of the models.

- The experimental papers typically investigate final microstructural properties and influence of process parameters on the distribution of the carbides, defects and mechanical properties. However none of them are able to develop any empirical relationship for connecting the final properties to the mould/workpiece geometries and process parameters. Microstructural and qualitative predictions are strongly dependent on the materials' microstructure and the product geometry, therefore not easily applicable to a general centrifugal casting process.

- The reported numerical models develop robust relationships between process parameters and process mechanics. Furthermore, some of the authors were able to give validated results between final part quality and process parameters. Using flow modes, velocity fields and mould filling, some authors were able to give a numerical evaluation of the process design's quality and so optimize the selection of its parameters. Although the failure modes and prediction are still not categorized and clearly understood.

The literature survey suggests that none of the existing analytical models are able to predict the feasibility of the process in a reliable way. Even though numerical models are able to predict some of the features, their high-level application is only able to predict particular characteristics of the process. Furthermore, researchers are still discussing the validity of the various numerical approaches and models. A multi-physics approach is necessary because of the process‘s complexity (i.e. thermal, fluid-dynamical and mechanical models need to be combined) and its applications (e.g. functionally graded materials production).

6.3 DCFA of Centrifugal Casting Application to Valve Cage manufacturing

Given the target requirements to satisfy, in this case assuring the functionality the assembly (i.e. control valve) to which the component belong, analytical and numerical models cannot be used for DFCA. Both approaches would require extensive validation and empirical corrections (according to the literature survey), which is out of the scope of this work. Therefore, because the process is well established and easily accessible, an experimental approach should be selected for evaluating the technological feasibility. For this reason, Route 3 of the NeNeSho Pro has been selected (Figure 6.1)

Following Route 3, a valve cage prototype (i.e. 420 Stainless Steel) was produced to validate the results of an analytical cost analysis. A statistical derived cost model has been developed (Appendixes F.1 and F.2) to evaluate the economic feasibility, by comparing all the geometrical variants of the component and considering a constant material selection (i.e. 420 Stainless Steel). In the next subsection, the product variants, existing process, and NNS process chains are also described.

6.3.1 Centrifugal Casting Process Application to Valve Cage Manufacturing Process

Valve Cage (Case Study II), shown in Figure 6.2, is a hollow cylindrical trim element that is used in industrial flow control valves as a guide to align the movement of a valve plug with a seat ring or to retain the seat ring in the valve body. The cage is a part of the valve that surrounds the plug and is located inside the body of the valve to control the fluid pressure and velocity. The design and layout of the openings can have a large effect on the flow of the material (the flow characteristics of different materials at temperatures, pressures that are in a range). The walls of the cage contain openings that usually determine the flow character-

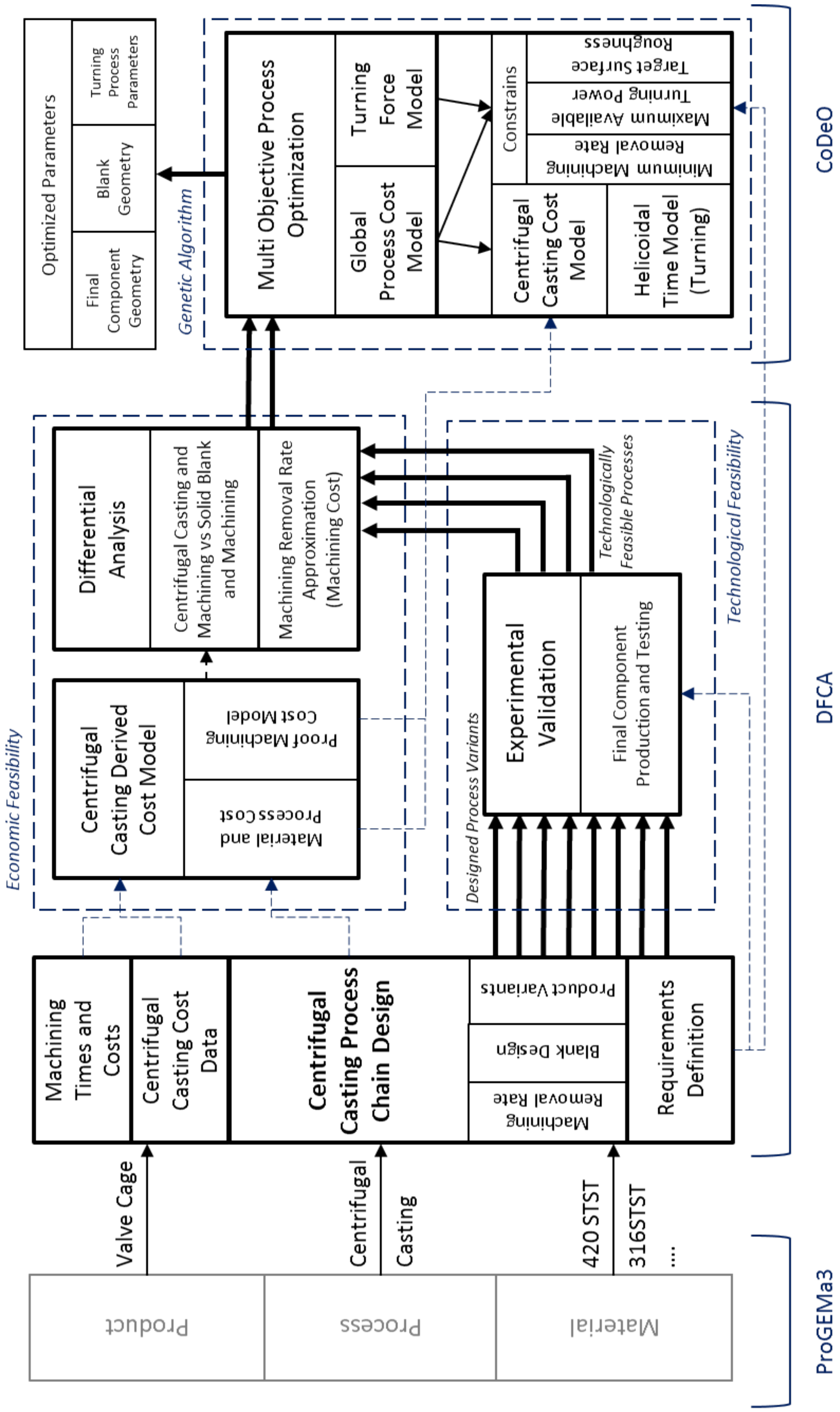


Figure 6.1: Schematic of Route 3 (NeNeShO Pro) application to Case Study II.

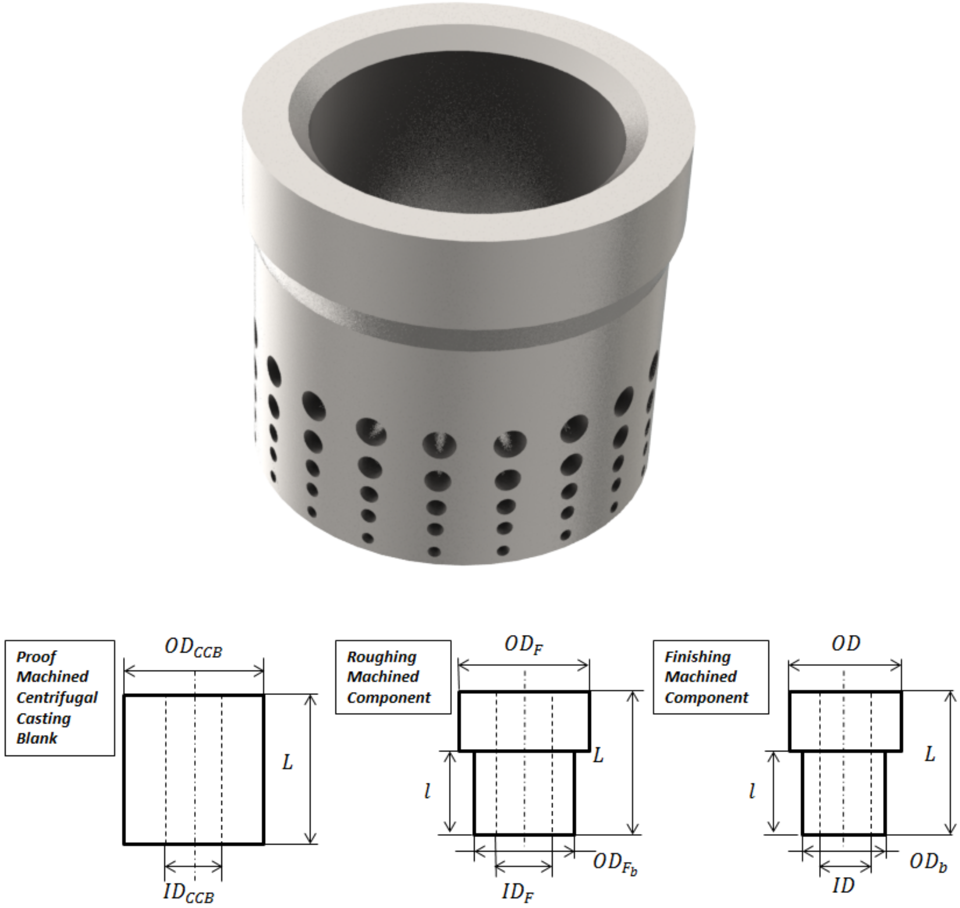


Figure 6.2: CAD representation of the valve cage and schematic of its nomenclature.

istic of the control valve.

The valve cages used in this study varied in diameter from 80 mm to 700 mm, corresponding to the valve nominal size range, which varies 40mm to 600mm (11/2" to 24") (i.e. reference for the cages dimensions). Table 6.1 summarize the main product variants dimensions, weights and biennial production volumes (2014-2015). The cage materials varied across the following range of steel: 420 Stainless Steel (STST), 316 STST, 17-4PH STST, Monel K500, Hastelloy, Duplex and Inconel.

Similarly to the other case studies, detailed drawing could not be shown for reasons of commercial confidentiality.The cage has also other variants in dimensions and design, however in

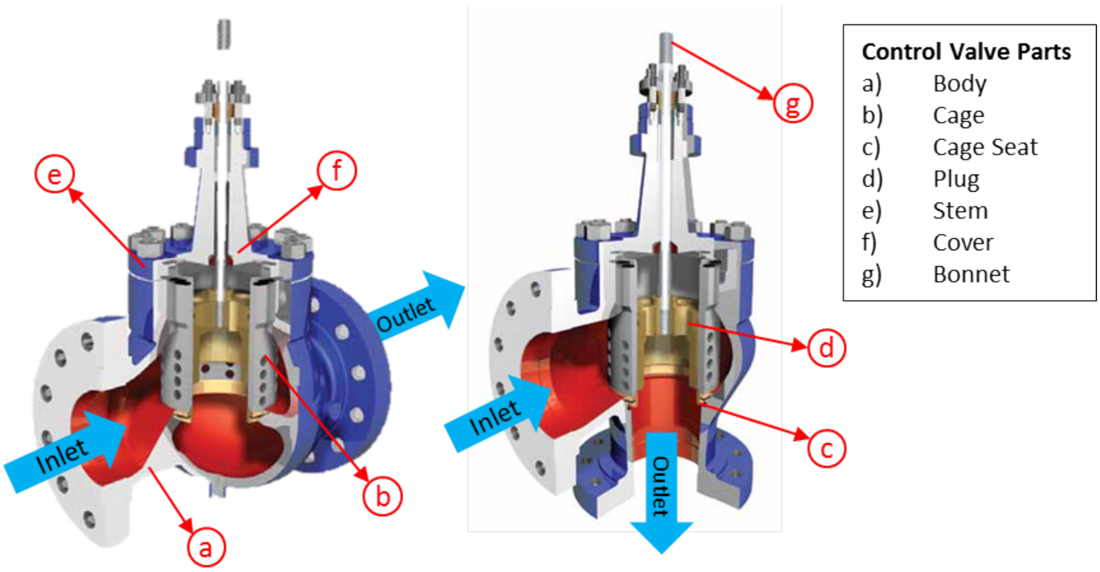


Figure 6.3: Control valve schematic showing the valve cage (Case Study II).

this study every dimensional variant has been considered as constant, because of similar manufacturing process' similarity.

To achieving the final product geometry with centrifugal casting process, no design modifications have been necessary because final production steps are similar and geometrical features are constant.

Centrifugal Casting Process Design and Requirements Definition for Case Study II In Figure 6.4, the current process chain and the proposed NNS process chain are illustrated. For both small and large diameters, the current process line includes cold rolling (solid blank), internal/external roughing and finishing turning followed by filleting/chamfering and drilling. The existing process chain can be considered as constant (even though in practice several different suppliers are involved) for all the product variants.

On the other hand, the proposed NNS process line consists of centrifugal casting (centrifugal casting blank) followed by the same machining operations (i.e. internal and external roughing, internal/external finishing and subsequent filleting/chamfering and drilling). All the ma-

Valve Dimensions		Cage						
		Dimensions [mm]					Production Volume [number of part per 2 years]	Cage Weight [kg]
Size [mm]	Travel [mm]	*ID*	*OD*	OD_b	*L*	*l*		
30,40,50	28.5	62	88	83.5	82	30	237	2
80	38	90	120	117.5	110	26	62	4
100	57	115	145	141.5	150	50	140	6
150	89	165	205	194	163	37	168	11
200	127	125	260	249	308	89	72	84
250	127	265	320	314.5	314	92	81	53
300	127	310	370	364.5	355	117	51	76
350	178	350	418	410	434	96	30	115
400	178	420	500	491.75	436	70	10	164
450	198	465	560	540	601	22	7	259
500	254	500	598	579	601	127	7	306
600	305	610	708	689	701	115	3	424

Table 6.1: Valve cage variants valve dimensions, cage dimensions (nomenclature presented in Appendix F.1, Figure F.1), production volumes and weights.

chining operations are executed on a CNC lathe at the valve manufacturer and it can be observed that drilling and turning are the main machining operations.

The cage design requires that finishing turning (including chamfering and filleting) is considered as different from the turning operation on the main body. This will be the same if a centrifugal casting is used so the cost can be considered as constant for the product, even if any design modifications occur. In other words even if drilling and finishing turning operations are different for each valve cage design, they can be considered constant when comparing the process of machining from a solid blank or a centrifugal casting blank (NNS chain). In this case, the manufacturer's design has no detailed requirements for the product (e.g. specific mechanical properties). Therefore, the feasibility targets can be synthetized as follows:

- Technological requirements:
  - Component needs to be assembled to the control valve and pass a high pressure hydrostatic test (i.e. standard test for control valves) to be considered acceptable.
  - Defect rate needs to be less than 5% (current defect rate)

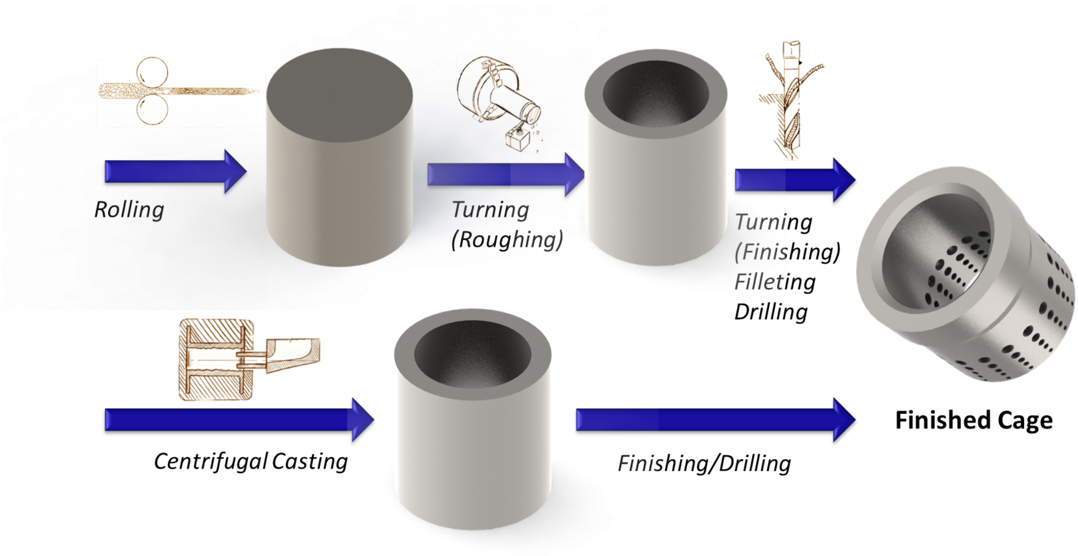


Figure 6.4: Schematic of the existing manufacturing process chain (top) and NNS manufacturing process chain (bottom).

6.3.2 Technological Feasibility of Centrifugal Casting Process: Experimental Validation

Experimental trials have been conducted in order to determine the technological feasibility of employing centrifugal casting in the production of the component. An initial 400 mm cage, made in 420 STST was manufactured form the centrifugal casting supplier (AMPO) and machined to the final shape (Figure 6.5). The experiments helped to define the centrifugal casting allowances for inner and outer diameter. Despite the best material proprieties (i.e. highest density, hardness, tensile strength) being on the external diameter (i.e. density is highest on the periphery, due to the centrifugal force exerted during centrifugal casting operation) of a centrifugally cast component, a machining allowances was used on both sides of blank (i.e. internal and external). Consequently a 20 mm allowance is required on both the inner and outer part of the cylinder, to allow finishing machining of the dimension to the final tolerances. Machining allowances and component machining has been used for defining both the cost models (Appendix F.1) and turning process model for optimization (Appendix F.4).

Figure 6.5: Centrifugal casting blank (left), semi-finished valve cage (right).

The resulting prototype satisfied the geometrical tolerances and was correctly assembled in the control valve after machining. The cage has been assembled in a 400 mm nominal diameter valve and has been tested at a high static pressure test. The valve, including the centrifugal casting component, passed the test successfully [The WEIR group PLC, 2016].

The centrifugal casting parts' defect rate (non-conformances) was identified as a requirement and the centrifugal casting supplier's rate of 1.19% [AMPO, 2016a] of non-conformity was considered as satisfactory.

The machining operations for the centrifugal casting are smaller because less roughing is required. The finish machining operations act on very similar surfaces (i.e. the difference is just the centrifugal casting's machining allowances), lastly the chamfering/filleting and drilling operations results are unchanged from the existing to the NNS manufacturing chains (i.e. as the work on the same geometry and material).

6.3.3 Economic Feasibility of Centrifugal Casting: Cost Models and Differential Analysis

Following the NeNeShO Pro Route 3 and using the supplier data, it was possible to develop a derived cost model for the centrifugal casting process (Appendix F.2). Using a constant machining removal rate (i.e. as explained in Chapter 3.3), it was possible to estimate the machining cost in both cases. As illustrated in Figure 6.6, the differential analysis model is based on the evaluation of both existing and NNS process being considered. The cost models aim to give an estimation of the costs difference between the two processes chains (i.e. existing and proposed NNS), by estimating the blanks production and machining costs (Appendix F.1). For the purpose of the case study, the material considered is 420 STST in both the manufacturing processes, similarly to the material used in the experimental trials.
Figure 6.6 shows the differential analysis which determines the process economic feasibly. The analytical cost model (detaild in Appendix F) has been derived from supplier information (i.e. centrifugal casting and solid blank) and machining cost estimation by removal rate approximation. Information on moulding and centrifugal casting costs make the creation of an initial realization of a first centrifugal casting cost model (Appendix F.2).
The cost of machining from a solid blank (i.e. existing manufacturing chain) can be written as the sum of the solid blank cost, machining cost (i.e. roughing and finishing turning) and indirect costs(Equation (6.1)), in contrast the NNS chain's total cost is the sum of centrifugal casting blank cost (casting operation and proof machining), machining cost (finishing turning) and indirect costs (Equation (6.2)) . As stated above, the machining is performed in the same facility and both the solid blank and the centrifugal casting blank are acquired from suppliers, therefore the indirect costs can be considered constant and so excluded from the differential analysis. Consequently, Equations (6.3) and (6.4) represent the new costs of the

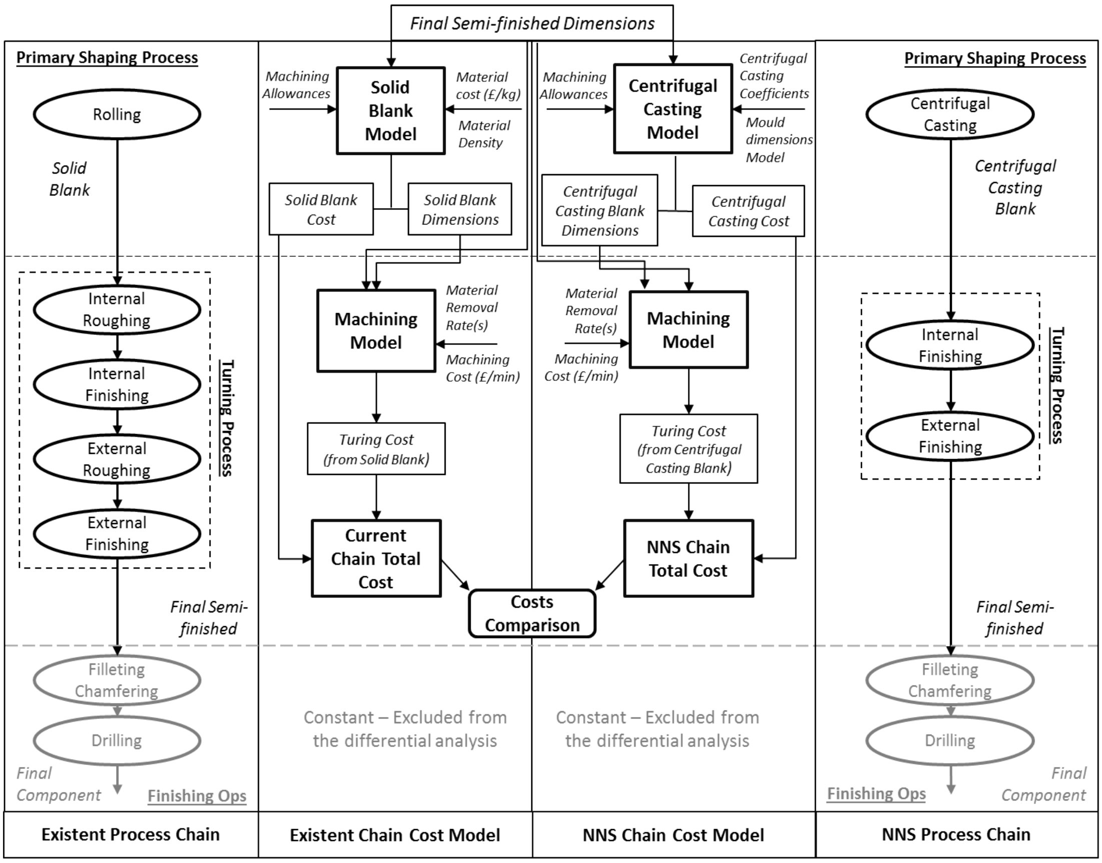


Figure 6.6: Differential cost analysis between the existent and NNS manufacturing processes of Case Study II.

existing and NNS manufacturing respectively.

$$C_{T_M} = C_{SB} + C_{Tu} + C_I \tag{6.1}$$

$$C_{T_{CC}} = C_{CCB} + C_{Tu} + C_I \tag{6.2}$$

$$C_{T_M} = C_{SB} + C_{Tu} \tag{6.3}$$

$$C_{T_{CC}} = C_{CCB} + C_{Tu} \tag{6.4}$$

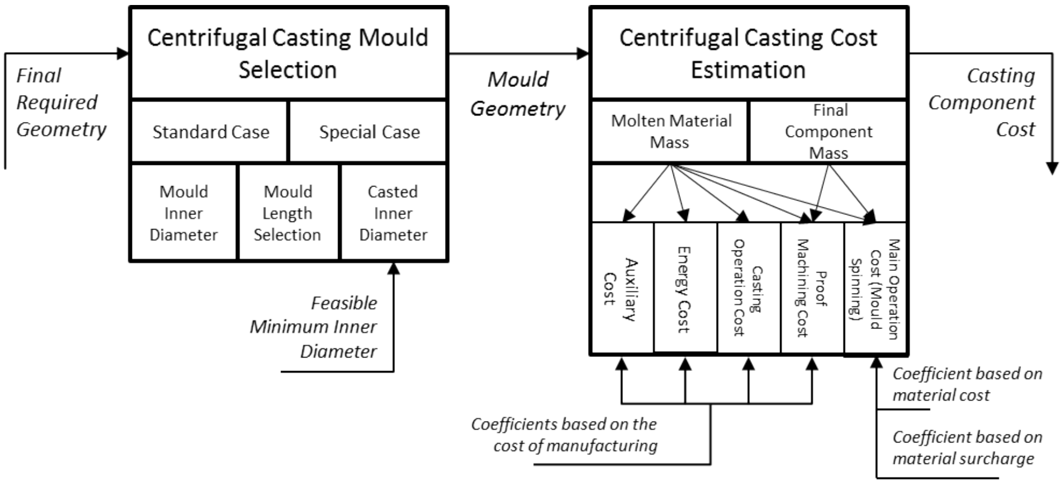


Figure 6.7: Schematic of the developed centrifugal casting cost model.

With: C_{T_M}, total cost of existing process; $C_{T_{CC}}$, total cost of NNS process; C_{SB} cost of the solid (forged) blank; C_{CCB}, cost of centrifugal casting blank; C_{Tu}, turning cost; C_I indirect costs.

The complete **machining cost model** formulation can be found in Appendix F.1.

In Figure 6.7, the developed **centrifugal casting cost model** is schematized. Using the cost and mould data provided by the suppliers [AMPO, 2016b], it was possible to derive a cost model for a centrifugal casting process (Appendix F.2). The model's input is the final dimensions which are required for the casted blank (including machining allowances, as in Equation (F.6)). The model is defined by two phases: the mould selection phase, which is important for defining the cost and the process mechanics, and the centrifugal casting cost estimation phase. The complete formulation of the model is presented in Appendix F.2.

Differential Cost Analysis

Differential cost analysis results allow the feasibly of a range of component sizes to be assessed. Although commercial confidentiality does not allow the final cage dimension to be stated they can be compared though the nominal valve size.

Centrifugal casting and material data have been derived from supplier data [AMPO, 2016b].

Valve Dimensions	Machining Time [min]							MRR [mm3/min]
	Internal Turing		External Turning		Total Time			
	Set-up	Operation 1	Set-up	Operation 2	Operative	Idle	Global	
30,40,50 mm	30	25	30	20	45	60	105	1.08E+04
80 mm	30	30	30	20	50	60	110	2.53E+04
100 mm	30	40	30	25	65	60	125	3.81E+04
150 mm	30	60	30	45	105	60	165	4.47E+04
200 mm	30	120	30	120	240	60	300	3.16E+04
250 mm	30	200	30	190	390	60	450	6.25E+04
300 mm	30	310	30	300	610	60	670	5.68E+04
350 mm	45	460	45	460	920	90	1010	5.78E+04
400 mm	45	680	45	680	1360	90	1450	5.47E+04
450 mm	45	760	45	760	1520	90	1610	8.53E+04
500 mm	45	820	45	820	1640	90	1730	8.86E+04
600 mm	45	880	45	870	1750	90	1840	1.39E+05

Table 6.2: Machining times and MRR of the existent process chain (i.e. solid blank machining).

Meanwhile, machining cost has been set equal to the case study company's cost [WEIR, 2016]. The data and coefficients used for the centrifugal casting models [AMPO, 2016b] are detailed in Appendix F.2.

Table 6.2 summarizes the machining information gathered at the production facility (Weir Valves & Controls, Elland, Machining department), including machining times and material removal rates (MRR). Figure 6.8 display the different cost predicted for different valve sizes. Figure 6.8 (a) and Figure 6.8 (b) compare the prediction for blank costs (i.e. centrifugal casting blank and solid blank) and machining cost for the NNS chain and the existing chain respectively. The resultant machining cost (i.e. wasted material) is less in the NNS chain for every size considered, even though the blank costs are higher for the smaller sizes variants (they reduce as the dimensions increase). Figure 6.8 (c, d, e) show the costs break downs for different valve sizes (100, 250, 400 mm respectively): it is interesting to note how the centrifugal casting cost is bigger than the solid blank cost but decreases as the size increases. On the other hand, the machining cost on NNS chain (i.e. using centrifugal casting) is always smaller than the existing manufacturing chain (i.e. using a solid blank), and the magnitude of this difference grows with the component size. Figure 6.8 (f) show the break point between

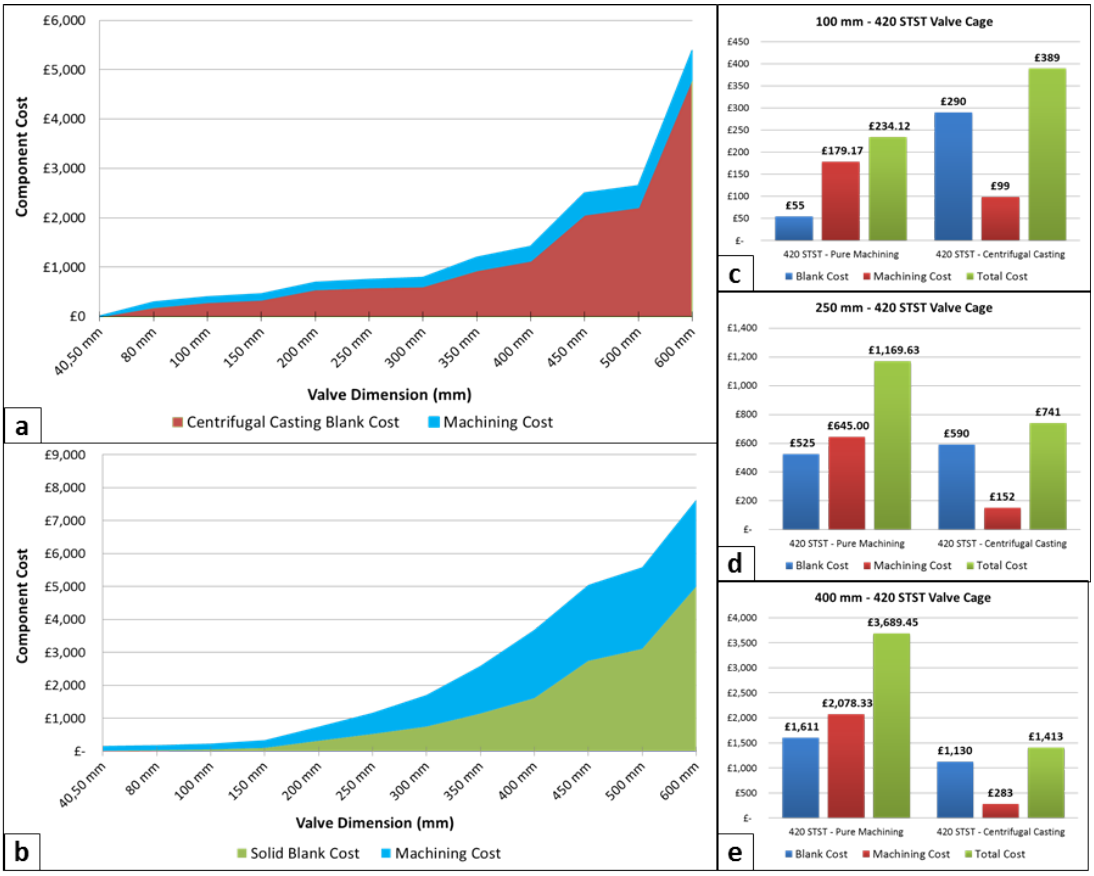


Figure 6.8: Cost comparison for the NNS process chain (a) and existing chain (b). Cost details for different cages sizes: 100 mm (c), 250 mm (d) and 400 mm (e). Component cost comparison of component evaluated costs for the NNS process chain (i.e. centrifugal casting and finish machining) and the existing process chain (i.e. machining from solid blank) (f).

the two different process chains for a range of cage sizes suggesting that the NNS chain will be economic for all cages having outer dimensions over 200 mm.

Figure 6.9 shows the break point between the two different chains for the cage sizes variant: the NNS chain is economic for all the productions over 200 mm. Table 6.3 summarizes the cost differences, for the valve cages variants (i.e. single product and total production), between the existent and the NNS process chain. The potential impact of the introduction of NNS methods for larger parts (i.e. assuming current production methods are retained for cage < 8") on a biennial production of 636 products, change the manufacturing process (i.e. from current process to centrifugal casting application) of 113 cages. The total biennial cost

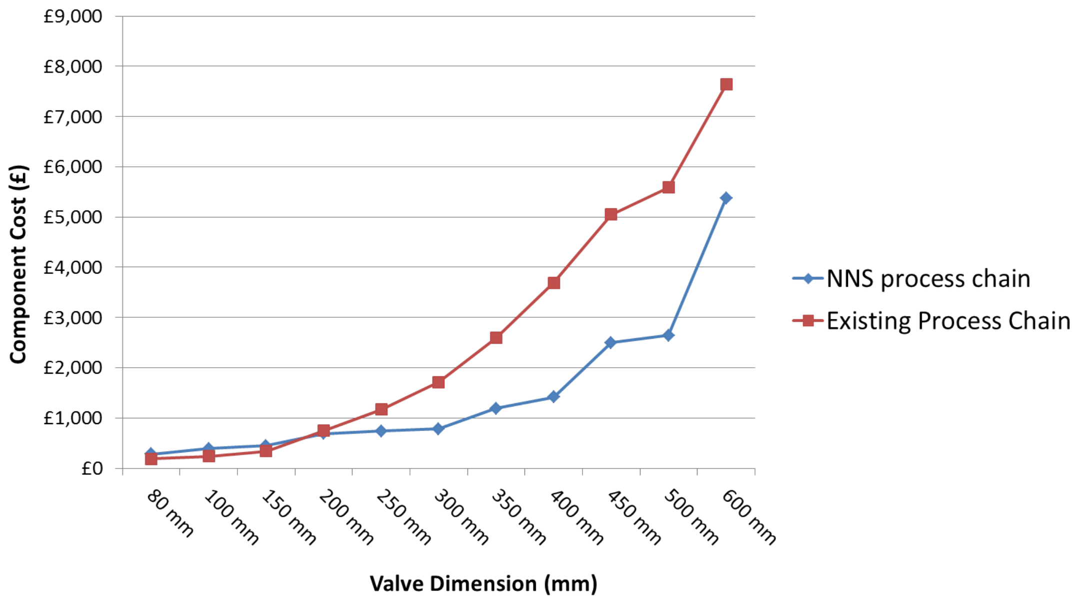


Figure 6.9: Component cost comparison of component evaluated costs for the NNS process chain (i.e. centrifugal casting and finishing machining) and the existing process chain (i.e. machining from solid blank).

of the current process is £305,150 (i.e. machining costs and raw materials), whereas the use of centrifugal casting would result in a reduction of 26.5%, with an estimated biennial saving of 490 machining hours and 18.9 tons of raw materials (The Weir Group PLC, 2015). It is interesting to note that for more expensive material (e.g. 316 STST, Inconel) the impact of centrifugal casting would be even larger. As a collateral advantage, the lead time has also been reduced from months to weeks, due to blank production (i.e. production of large solid blank components takes longer than centrifugal casting) and savings in machining time.

As result of this study, all the cages for valves over 250 mm are currently produced through centrifugal casting process, using the designed NNS chain.

Introduction of centrifugal casting into the production plan of a control valve's cage can reduce waste and machining time by between 19% and 22% respectively, generating expected savings of around £50,000 per year [The WEIR group PLC, 2016].

Valve Dimensions	Existent Cost per component [£]	Existent Cost (2014-2015) [£]	NNS Cost per component [£]	NNS Total Cost (2014-2015) [£]
30,40,50 mm	162.18	38436.67	Not Produced	Not Produced
80 mm	186.98	31412.94	278.16	46731.49
100 mm	234.12	16856.36	378.9	27280.85
150 mm	338.35	27406.18	439.82	35625.51
200 mm	747.79	38137.08	679.13	34635.66
250 mm	1169.63	35088.84	689.18	20675.34
300 mm	1709.47	17094.68	715.09	7150.94
350 mm	2593.6	18155.17	1108.43	7759
400 mm	3689.45	25826.17	1319.44	9236.11
450 mm	5051.22	15153.67	2360.06	7080.19
500 mm	5588.01	22352.05	2477.72	9910.87
600 mm	7638.31	7638.31	5081.47	5081.47

Table 6.3: Comparison of valve cages costs (single component and biennial production) between existent and NNS process chains.

6.4 CoDeO of NNS Valve Cage Manufacturing Process

The CoDeO framework has been applied to the valve cage (Case Study II) manufacturing process chain. The main aim of the optimization is to minimize the cost by varying systematically product design and process parameters. In the Case Study II, the optimization framework has been applied to the 400 mm cage manufacturing chain.

The next subsection describes the optimization problem, defining the variables and the optimization targets. The analytical equations used for optimizing the total cost (i.e. using both the primary shaping and machining cost models), machining process feasibility are also detailed.aa The optimization algorithm's selection has been based on a systematic review of the existent turning optimization literature.

As identified by the literature survey, an evolutionary algorithm, in particular a genetic algorithm, is the best candidate for optimizing the machining process. Having the cost optimization as the primary aim, it is possible to use the developed centrifugal casting cost model for optimizing the whole process chain.

In the following subsection, the optimization models and constraints fir turning process (adapted

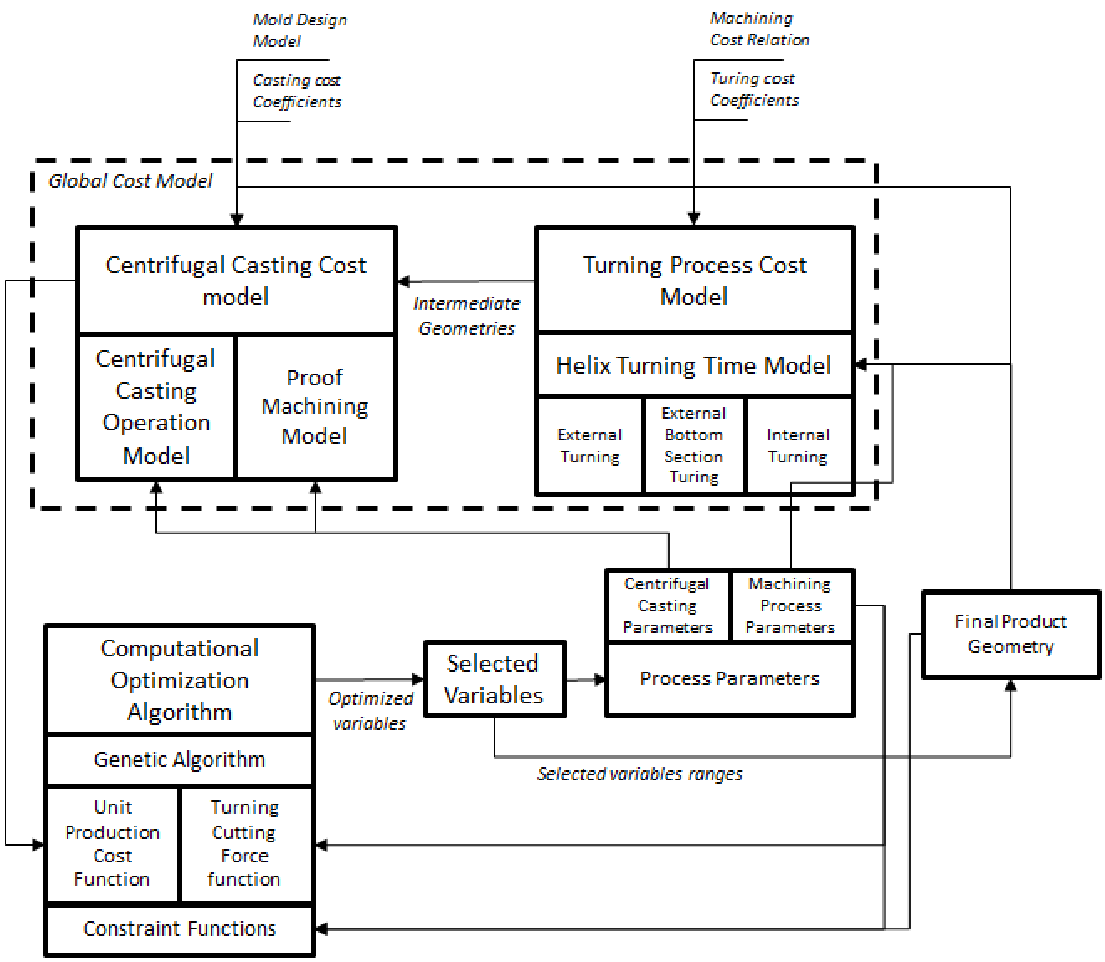


Figure 6.10: Conditional Design Optimization (CoDeO) methodology applied to the Case Study II.

from the literature), the algorithm settings and the optimization results have been presented and discussed.

6.4.1 Valve Cage Optimization: Problem Formulation

Figure 6.10 displays the application of the CoDeO to the Case Study II. In the Case Study II process chain, the centrifugal casting (i.e. including proof machining) and roughing machining process affect the total component cost, depending on component dimension and process parameters. The process chain parts, which are modelled for optimising the process, are displayed in Figure 6.11. The process chain steps are listed as follows:

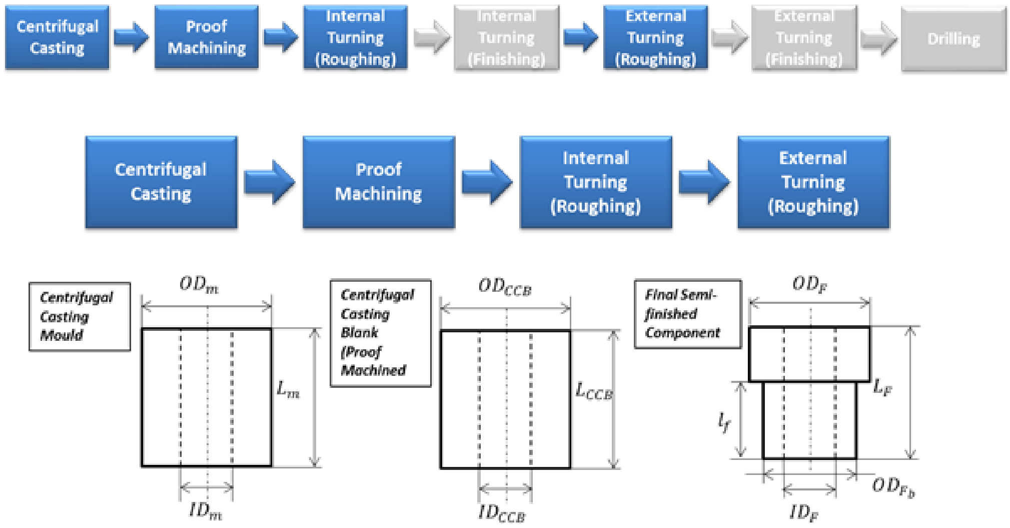


Figure 6.11: Valve cage manufacturing process chain model for optimization.

- Centrifugal Casting
- Proof Machining (considered as part of the centrifugal casting process)
- Internal roughing
- External Roughing

The finishing turning and drilling processes have been excluded from the models because they are constant regardless of any dimensional change of the component (as in the feasibility analysis in Subsection 6.3). However, the finishing allowances (Figures F.5 and F.6) have been used by the turning model (Appendix F.3) for referring the cost model to the final component dimensions directly (i.e. finishing allowances are used for modelling the connection between final and semi-finished dimensions). This simplification is coherent with the limiting assumption on the optimization's search space (Section 1.2.7).

Accordingly to the NNS optimization formulation (Section 3.1.3), the variables to be optimized for minimizing the considered manufacturing cost are:

- Final Product Dimensions (valve cage final length, internal diameters and outer diameters)

- Centrifugal Casting Parameters (mould dimension)
- Machining Parameters (feed rate, spindle speed, depth of cut)

In order to achieve a sensible cost reduction and keeping the turing process into feasible boundaries, the optimization targets are defined as:

- Minimize the global cost by minimizing the machining time and centrifugal casting cost.
- Obtain a combination of feasible machining process parameters (i.e. trade-off with the production level increasing) by considering the turning process mechanics (i.e. turning force), current capabilities (i.e turning power), production targets (i.e. MRR) and qualitative targets (i.e. surface roughness).
- Optimize the centrifugal casting blank dimension and final component dimensional variables for achieving the previous two.

6.4.2 Process Chain Modelling: Global Cost Model and Variables Definition

For achieving the optimization targets, the cost of the considered processes needs to be modelled accordingly to the NNS optimization formulation (Section 3.1.3), taking into considerations the variables to be optimized. Figure 6.12 display the variables to be optimized and their collocation in the manufacturing chain and final and semi-finished product designs. Nine variables have been considered for the optimization problem (red circled in Figure 6.12).

- Three Machining Process Parameters:
  1. Feed rate ($F,\ mm$)
  2. Spindle rotational speed ($n,\ RPM$)
  3. Depth of cut (a, mm)

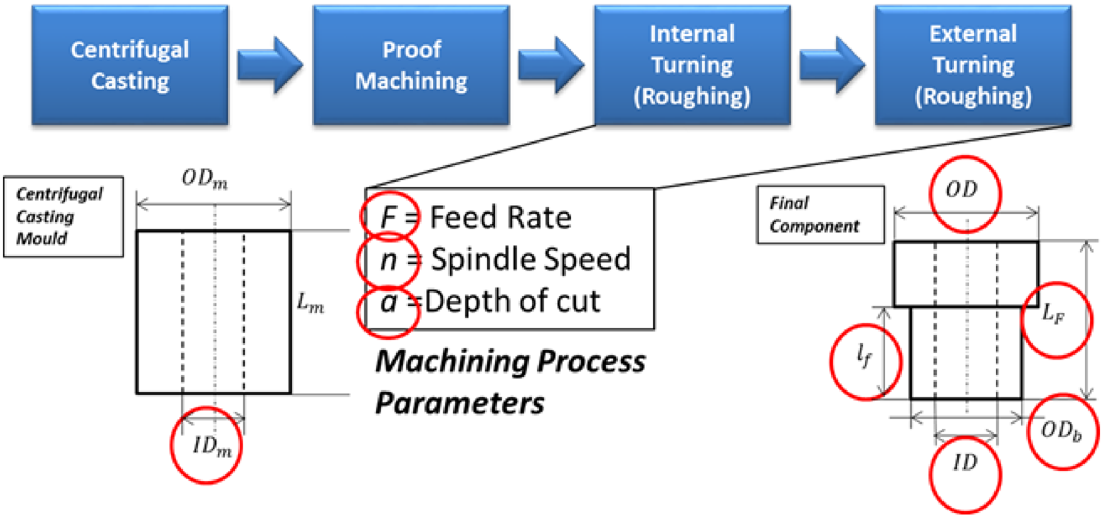


Figure 6.12: Valve cage manufacturing optimization: schematic of process parameters and design variables.

- One Geometric/Process Variable (Centrifugal Casting Process):
  1. Blank internal diameter (ID_m, mm)
- Five Geometric Variables (Final Component Shape):
  1. Top section outer diameter (OD, mm);
  2. Bottom section outer diameter (OD_b, mm);
  3. Internal diameter (ID, mm);
  4. Total length (L_F, mm);
  5. Bottom section length (l_f, mm).

Referring to the nomenclature in Appendix F.1, the total cost model is expressed in the equation (6.5).

$$C_{TOT} = C_{T_{CC}} + C_{Tu} = C_{CCB} + C_{IN_T} + C_{EX_T} + C_{EX_{bT}} \tag{6.5}$$

The cost components refer to centrifugal casting and proof machining cost ($C_{T_{CC}}$) and roughing turning cost (C_{Tu}).

Centrifugal Casting Model. The centrifugal casting blank cost (C_{CCB}) equation (6.6) has been used in the previous differential analysis. The centrifugal casting cost equation's derivation of the cost equation can be found in Appendix F.1, meanwhile the formulation of the centrifugal casting cost is in Appendix F.2 (Equation F.18).

$$C_{CCB} = \left(\left(OD_m^2 - ID_m^2\right) K_c - \left(OD_{CCB}^2 - ID_{CCB}^2\right) K_v\right) \rho_m \frac{L_f}{4} \pi 10^6 \tag{6.6}$$

Where, gathering the several centrifugal casting cost coefficients (Appendix B2), two new parameters have been created in Equations (6.7) and (6.8)

$$K_v = (c_{ChM} + c_{PrM}) \tag{6.7}$$

$$K_c = (c_{MaM} - c_{ChM} + c_{Aux} + c_{En} + c_{PrM}) \tag{6.8}$$

Turning model. For a general turning process pass, the turning cost (C_{i_T}) is proportional to the turning time (t_{i_T}) and the cost per hour (c_m), as in Equation (6.9)

$$C_{i_T} = t_{i_T} c_m \tag{6.9}$$

The total turning cost is connected to the component machining strategy (Figure 6.13). The roughing turning process is divided into three main operations, which correspond three different machining times (i.e. refer to nomenclature in Appendix B4).

1. External turning (t_{EX_T}: external turning time; C_{EX_T}: external turning cost)

2. External bottom section turning ($t_{EX_{bT}}$: external bottom turning time; $C_{EX_{bT}}$ external bottom turning cost)

3. Internal turning (t_{IN_T}: internal turning time; C_{IN_T}internal turning cost).

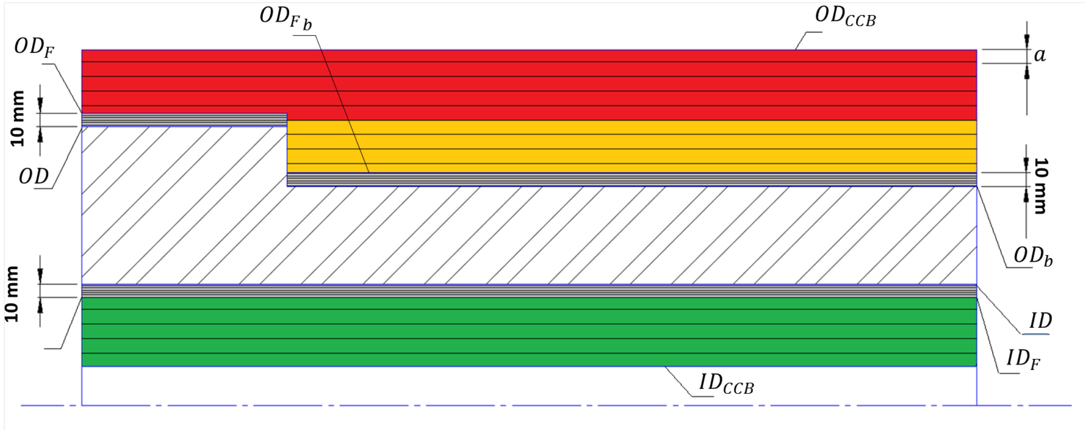


Figure 6.13: Turning strategy scheme and diameters: external turning zone (red); external bottom section turning (yellow), internal turning (green).

The total machining time can be written as in Equation (6.10)

$$T_{Tu} = t_{IN_T} + t_{EX_T} + t_{EX_{bT}} \tag{6.10}$$

The turning time expression has been written with an innovative approach: the helix turning formulation. The turning process has been analysed as a helicoidal motion, resembling the cutting trajectory, instead of a linear one (i.e. classic turning formulation), resembling the tool motion. The aim of this new formulation is to gather the process parameters and the cutting diameters in a single formula, in order to achieve a simultaneous optimization. The new formulation has equivalent resulting turning time to the classic formulation. The derivation of the turning time formula is showed in Appendix F.3. The generic helix turning formula for machining time can be rewritten as in Equation (Appendix F.4)

$$t_T = \sum_{i=1}^{N} t_i = \frac{60NL}{n}\sqrt{\frac{1+\pi^2\sum_{i=1}^{N} D_i}{F^2+\pi^2\sum_{i=1}^{N} D_i}} \tag{6.11}$$

With: t_T, total machining time for the operation(min); t_i, machining time for a single pass (min); N, necessary number of passes for the operation; L, cutting length (mm); D_i, cutting diameter (mm); n, rotational speed F.

In Appendix F.4, the new machining time equation has been applied to the internal and external turning cases. The nomenclature of the various diameter is detailed in Appendix F.4. The Equation can be applied to Equation (6.10), obtaining the case study turning time model Equation (6.12). The full derivation and nomenclature is showed in Appendix F.4.

The optimization's solution should be a set of identified variables that minimizes the Equation (6.5) (composed by Equation (6.12) and Equation (6.6)). Considering the developed models, the selection of the correct optimization algorithm is fundamental for achieving the optimization targets. The machining operation model is a theoretical one, although solving it in a closed way does not seem the correct approach, due to high number of variables and to Equations (6.6) and (6.12) forms. Given the process and variable natures (i.e. selected from a feasible range), an iterative solution should be preferred to a deterministic one (i.e. able to provide only a local solution). Either way, the solving algorithm needs to take into consideration the machining process mechanics and its constraints (e.g. cutting force).

$$
\begin{aligned}
T_{Tu} = t_{IN_T} + t_{EX_T} + t_{EX_{bT}} = \\
\frac{60 N_E L}{n} \sqrt{\frac{1+\pi^2\left(N_E\left((OD-10)-\frac{N_E\left(N_{i_E}+1\right)a}{2}\right)\right)^2}{F^2+\pi^2\left(N_E\left((OD-10)-\frac{N_{i_E}\left(N_{i_E}+1\right)a}{2}\right)\right)^2}} + \\
+\frac{60 N_I L}{n} \sqrt{\frac{1+\pi^2\left(N_I\left((ID+10)+\frac{N_I(N_I+1)a}{2}\right)\right)^2}{F^2+\pi^2\left(N_I\left((ID+10)+\frac{N_I(N_I+1)a}{2}\right)\right)^2}} + \\
+\frac{60 N_{E_b} l}{n_i} \sqrt{\frac{1+\pi^2\left(N_{E_b}\left((OD_b-10)-\frac{N_{E_b}\left(N_{E_b}+1\right)a}{2}\right)\right)^2}{{F_i}^2+\pi^2\left(N_{E_b}\left((OD_b-10)-\frac{N_{E_b}\left(N_{E_b}+1\right)a}{2}\right)\right)^2}}
\end{aligned}
\quad (6.12)
$$

6.4.3 Computational Optimization: Review of Numerical Approaches to Turning Process Optimization

Machining optimization has been approached with several different techniques and strategies. The evolution of computational models and algorithms has deeply influenced the turning and, generally, the machining process optimization, making it possible to investigate the process with even more resolution and accuracy.

The optimization of process parameters is key for economic efficient machining operations [Khan et al., 1997], however optimizing the machining conditions is a complex problem, which had a considerable evolution and expansion in modelling techniques and their complexity over the years.

In Appendix G, a comparison between the different application of heuristics algorithms to turning process is presented. The literature investigating numerical methods to turning process optimization has been surveyed by comparing the performances of different evolutionary and other existing meta-heuristic (e.g. Tabu Search) algorithms.

As an outcome of the literature survey, it is possible to say that, the GA is very appealing for single and multi-objective optimization problems [Deb, 2001]. The main advantages of GA application can be summarized as follows:

1. Not requiring continuous or convex design space (as non-gradient based)
2. Able to explore large search space and have a high chance of avoiding local optima (due to is probabilistic and non-deterministic nature)
3. Provides multiple near-optimal solutions.
4. Able to solve multiple objectives and non-linear response function problems, in both discrete and continuous cases.

Therefore, the GA is generally preferred when near-optimal improved cutting condition(s) instead of exact optimal conditions are cost effective and acceptable for implementation by the manufacturers [Mukherjee and Ray, 2006].

Genetic Algorithm (GA): Introduction and Application to Turning Process

The Genetic Algorithms (GAs), created by John [Holland, 1975] in his book Adaptation in natural and artificial systems (importantly developed by other authors as [Goldberg, 1989, Deb, 2001] is a stochastic heuristic search method, based on the imitation of the natural processes of evolution. The GA, like nature, works by evolutionary steps on a population of individuals, aiming to obtain the fittest final population: natural evolution has two primary processes, the natural selection and reproduction. The first determines population members that are fit enough to survive and, so, reproduce, on the other hand the second ensures mixing and recombination among the genes of their offspring.

An initial population of solutions (randomly generated from different combination of process variables) is modified iteratively by the three main GA operators: selection, crossover, and mutation. The three operators modify (generating new individuals and selecting the most fittest to survive and reproduce) the population after each iteration (generation), until one of the termination criteria is reached. The main evolutionary operators are crossover and mutation.

Depending on the function or functions used as the target(s), the optimization can be single or multi-criteria (Figure 6.14). In the single criteria optimization, only one objective function (fitness function) is the optimization target, therefore the GA has only one solution as output. In multi criteria, the optimization has multiple objective functions, which are mutually conflicted (i.e. improving one of these fitness functions may compromise the others). Therefore there is not a single solution but a set of trade-off solutions, called the Pareto optimal set (i.e. non-dominated or not inferior individuals). The solution of the problem is a Pareto frontier: a set points that is the set of choices that are Pareto efficient. This means that none

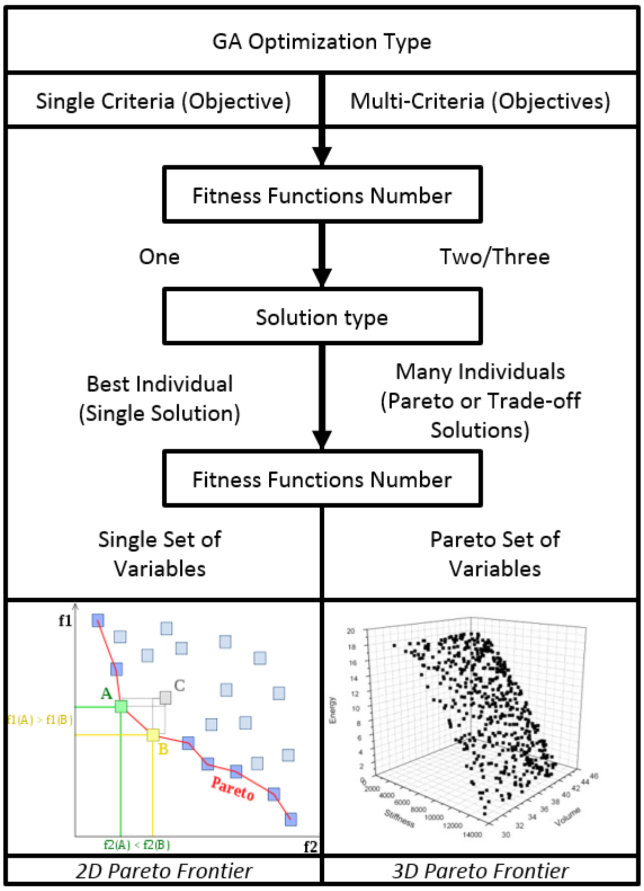


Figure 6.14: Single and Multi-criteria Optimization in GAs

of the point of the Pareto frontier can be defined as more efficient than the others, due to the conflict between the optimized functions. Figure 6.14 shows an example of the Pareto frontier. The Pareto frontier is particularly useful in engineering: because the choice among the different sets of solutions give, at the same time, both trade-off selection and evaluation of whole search space (i.e. the optimization domain).

Currently, the GA counts many developed variants, although, regardless of the structure, the GA's most important parameters are

1. Population size
2. Crossover rate

3. Mutation rate

A more complete description of the GA features and operators is presented in Appendix G.2. Many different applications for turning process optimization through metaheuristic search based algorithms have been reported in the literature. In Appendix G.3, the main papers on GA application for single and multi-passes turning optimization models have been reported. Table 6.14 summarizes all the reviewed papers, investigating single pass models for turning. Most of the authors use only the main turning process parameters as variables (feed rate, cutting speed and depth of cut). Similarly, all the authors used the unit production cost as the fitness function (or as a part of it). Similar settings are applied also in the crossover and mutation functions and coefficients. All the authors include linear and non-linear constraints for limiting the individuals' feasibility.

For multi-passes turning, the researchers tend to use iterative cycles, optimizing separately every pass, usually, having every pass interacting with the previous and next ones. In this case, the authors apply mostly single objective optimization, using the unit process cost [Onwubolu and Kumalo, 2001, Yildiz, 2013, Alberti and Perrone, 1999, Wang et al., 2002] or customized linear function (i.e. combining tool life and cost [Schrader, 2003].

6.4.4 CoDeO Application to Case Study II through a Genetic Algorithm

The optimized process is the manufacturing of a 400 mm valve cage, made in 420 Stainless Steel. The turning tool used for roughing process is a ceramic coated carbide tool.

As mentioned, the fitness function and variables range definitions are fundamental for a GA application. Using the global cost model showed in the previous section and following the NNS optimization formulation (Section 3.1.3), a GA can be used to optimize the variables for the selected ranges. Depending on the variables nature, the ranges have to be defined from the literature (i.e. process parameters feasible ranges for the given material), manufacturing

GA characteristics		Cus & Balic (2003)	Saravanan et al. (2003)	Amiolemhen et al. (2004)	Yildiz & Ozturk (2006)	Sardiñas et al. (2006)	Yang & Natarajan (2009)	D'Addona & Teti (2013)
Fitness Function(s)	Objective Functions number	One	One	One	One (Two)	Two	One	One
	Minimization Objective(s) -	Exponential function (combining Machining Removal Rate, Operation Cost, Surface Roughness)	Unit Production Cost	Unit Production Cost	Unit Production Cost	Unit Production time, Tool Life	Linear Function	Unit Production time
	Minimization Function(s) Type	Analytical	Analytical	Analytical	Analytical	Cost (An), Tool Life (Ex)	Machining Removal Rate, (An), Tool Wear (Ex)	Analytical
	Variables Number	3	2	3	5	3	3	3
	Variables	Depth of cut (a), Feed rate (F), Cutting speed (v)	Feed rate (F), Cutting speed (v)	Depth of cut (d), Feed rate (F), Cutting speed (v)	Depth of cut , Feed rate , Cutting speed , Number of rough cuts	Depth of cut (a), Feed rate (F), Cutting speed (v)	Depth of cut (a), Feed rate (F), Cutting speed (v)	Depth of cut (a), Feed rate (F), Cutting speed (v)
Constrain Functions (Linear-NonLinear Functions)		Cutting Force (An), Cutting Power (An)	Cutting Force (An), Cutting Power (An), Tool Tip Temperature	Tool Life (An), Cutting Force (An), Cutting Power (An) , Chip-Tool Interface Temperature (An), Dimensional Accuracy (An), Cutting region stability (An), Surface finish (An), Roughing and finishing parameters relation (?) [for both Finishing and Roughing]	Cutting Force (An), Tool-Life (An), Cutting region stability (An), Surface finish (An) [for both Finishing and Roughing]	Cutting Force (Ex), Cutting Power (Ex), Tool Life (Ex), Surface finish (An)	Surface Roughness (Ex), Cutting zone Temperature(Ex)	Cutting Force (An), Cutting Power (An), Tool Life (An), Surface finish (An)
Initial Population	Coding Type	Not known	Binary Coding (Bit String)	Binary Coding (Bit String)	Binary Coding (Bit String)	Binary Coding (Bit String)	Binary Coding (Bit String)	Binary Coding (Bit String)
	Size (Number of Individuals)		20	20	80	500 static (10 dynamic)	100	20-100
	Creation Function		Random Generation	Random Generation	Random Generation	Random Generation	Random Generation	Random Generation
Reproduction	Selection Function	Not known	Rank Order	Roulette Wheel	Unknown	Tournament Selection	Tournament Selection	MATLAB default (Stochastic uniform)
	Elite Count (Fraction)		None	None	None	0.25	Adaptable (DE)	MATLAB default (0.2*Population Size)
Crossover	Function	Not known	One-point Operator	One-point Operator	Unknown	Two-points Operator	Ranking (DE)	Single Point (Two-Points) Operator
	Fraction		0.8	0.8	0.9	Not Known	0.9	0.8
Mutation	Fraction	Not known	0.01	0.01	0.5	0.0001	0.1	0.1
Supplementary Applied Optimization Techniques		None	Simulated Annealing	None	Taguchi Robust Parameter Design (S/N ratio, ANOVA)	Dynamic GA approach (micro-GA)	Differential Evolution (DE)Algorithm	None

Table 6.4: Summary of the literature GAs settings, fitness functions and constraint function (Ex = experimental function; An = analytical function)

process constraints (i.e. minimum internal diameter for centrifugal casting) and design constraints (i.e. final component dimensions).

Using only the process cost as objective function (i.e. without constraints), the optimized solution would converge to the maximum process parameters values, obtaining the smallest process time. As discussed in the literature survey, the turning process optimization is a trade-off between maximizing the time performances and keeping the process into feasible boundaries, in particular regarding cutting forces and product quality, by considering the turning process dynamics. In the literature, researchers introduce turning process models (e.g. turning power, cutting force, obtainable roughness equations) into the optimization algorithm in different ways: using these equations as part of or as fitness functions (i.e. for having a trade-off single solution) or functions (i.e. having a multi-criteria optimization and so a Pareto solution), in the non-linear constraints or even in both of the previous cases.

Therefore, a multi-objective optimization has been realized, accordingly to the NNS optimization formulation (Section 3.1.3), by defining the optimization's objective functions as:

1. Total cost model (C_{TOT}) (6.14)
2. Turning cutting force (F_T) (6.15)

In this way the solution is so a trade-off between the cost minimization (thus the process time minimization) and the cutting force minimization (the two Equations (6.14) and (6.15) are concurrent and form a Pareto frontier).

Following the literature, inequality constraints have been introduced for limiting the feasible population members. The following constraints have been added for controlling the solution range (i.e. particularly the machining parameters), satisfying the non-linear inequalities.

1. Turning power (W_{Tu}): a feasible solution has to guarantee a turning power smaller than a threshold value (W_{Max}).
2. Surface roughness (Ra_{Tu}): a feasible solution has to guarantee a surface roughness

Variable	*Min*	*Max*
OD (mm)	480	500
ID (mm)	430	410
a (mm)	2.5	7.6
n (1/min)	80	261
F (mm)	0.15	0.75
OD_b (mm)	460	480
l_f(mm)	50	70
L_f(mm)	415	425
ID_m (mm)	340	370

Table 6.5: Variable ranges used in the GA settings.

smaller than the target value (W_{Max}).

3. Machining (MRR): a feasible solution has to guarantee at least the target machining removal rate value (MRR_{Min}).

The next subsection explains the GA structure, formalizing the fitness functions, non-linear constraint equations, variable ranges and algorithm settings. The following subsection discusses the optimization results and compares them with the current set of parameters.

GA Structure: Fitness Functions, Variables Boundaries and Non-linear Constraints

Table 6.5 displays the variable range settings. The minimum centrifugal casting process parameters (ID_m) has been set by the application of the minimum casting diameters equation (Equation F.12, in Appendix F.1). On the other hand, the maximum has been set by the final cage geometry. All the final cage dimensional variables (OD, ID, D_b, l_f, L_f) are set through the current 400 mm cage final geometry, using a ±10 mm range for maintaining the same component functionality (the company has no other clear dimensional targets). The cutting speed (v_c), depth of cut (a) and feed rate (F) ranges are defined as in Kalpakjian and Schimd [2009] for medium and high C steel workpiece (i.e. 420 STST) and ceramic coated carbide tool. The spindle speed range(n) has been defined through the minimum and maximum internal and external diameters, following equation (6.13).

$$n = v_c \frac{1000}{OD\ 3.14} \ or \ n = v_c \frac{1000}{ID\ 3.14} \tag{6.13}$$

Process Parameters	*Min*	*Max*
v_c (m/min)	120	410
Spindle Speed Ranges		
n (max OD) [1/min]	93	272
n (min OD) [1/min]	80	261
n (max ID) [1/min]	93	318
n (min ID) [1/min]	89	304
Minimum Selected Range	80	261

Table 6.6: Spindle speed available ranges, calculated form cutting speed and diameter ranges.

Table 6.6 show the calculation of the allowable cutting speeds ranges for the minimum and maximum external and internal diameters. Due to the level of approximation (i.e. tool - material interaction), the lowest calculated spindle speeds have been selected as minimum and maximum boundaries.

As explained in the introductory subsection, a multi-criteria optimization has been set for the GA, having two objective functions. The first object function is the total cost) (6.14) (i.e. including centrifugal casting and machining cost). Similarly to the literature [Cus and Balic, 2003], the second fitness function is the turning force (6.15):

$$FF_1 = C_{CCB} + (t_{IN_T} + t_{EX_T} + t_{EX_{bT}})\, c_m \tag{6.14}$$

$$FF_2 = F_T = \frac{6.56\left(10^3\right) F^{0.917} a^{1.1}}{{v_c}^{0.286}} = \frac{6.56\left(10^3\right) F^{0.917} a^{1.1}}{\left(\frac{OD\ n\ 3.14}{1000}\right)^{0.286}} \tag{6.15}$$

The turning force equation (6.15) is the same used by Sardinas et al. [2006]: it has been selected because of similarity in the application (similar material and cutting parameters ranges).

Non-linear constrains have been added to the GA, limiting the feasible individuals in order to match turning process limit capabilities (i.e. power constraints), quality targets (i.e. surface roughness constrain) and production targets (machining removal rate constraints).

Turning power non-linear inequality constraint (6.16) has been used by several authors for selecting correctly the process parameters [Sardinas et al., 2006, Cus and Balic, 2003, Saravanan et al., 2003, Amiolemhen and Ibhadode, 2004, Yildiz, 2013]. The turning power constraint in (6.16) is taken from Sardinas et al. [2006]

$$W_{Tu} \ = \left(n \ OD \frac{3.14}{1000} \right) a \ F \frac{k_c}{6010^3} < \ W_{Max} \tag{6.16}$$

Similarly to the literature [Sardinas et al., 2006, Amiolemhen and Ibhadode, 2004, Yildiz, 2013, D'Addona and Teti, 2013, Yang and Natarajan, 2010], the surface roughness non-liner inequality, as shown in equation (6.17) and adapted Sardinas et al. [2006]), is used for optimizing the machining process parameters, achieving the target roughness value.

$$Ra_{Tu} \ = \ \left(\frac{F^2}{8 r_{TN}} \right) 1000 < \ Ra_{Max} \tag{6.17}$$

The machining removal rate constraint (6.18) ensures the required production volume by a machining parameters feasible setting (i.e. previous constraints and the "traded-off" by the turning force fitness function). The machining removal rate constraint inequalities has been formulated by [Sardinas et al., 2006, Amiolemhen and Ibhadode, 2004], as in equation (6.18).

$$MRR \ = \ \pi \ OD \ n \ Fa > \ MRR_{Min} \tag{6.18}$$

The machining removal rate inequality needs to be adapted to the GA structure. In the algorithm, the inequalities are used as an upper bound for limiting the feasible population individuals. So equation (6.16) needs to be rewritten as in (6.19)

$$-\pi \ OD \ n \ Fa < \ -MRR_{Min} \tag{6.19}$$

Depending on the available tool and workpiece materials used, the following input data have been used for the constraint equations from [Kalpakjian and Schimd, 2009].

1. Tool Nose Radius (r_{TN}): 1.6 mm

2. Specific cutting force (k_c): 2100 N/mm^2

According to the target requirements and available machinery, the constraints maximum values have been set as follows.

1. Maximum Roughness (Ra_{Max}): 12.4 μm. Accordingly to the target component roughness (i.e. on the surfaces that do not require finishing)

2. Maximum Turning Power (W_{Max}): 82 kW. Accordingly to the available turning power (i.e. in Weir Group facilities)

3. Minimum Removal Rate (MRR_{Min}): 3.5 10^5 (mm^3/min). Doubling the maximum removal rate applied by the Weir group facility has been used as optimization target.

GA Optimization: Results and Discussion

The GA has been implemented in MATLAB, using the Optimization Toolbox package and the settings described in Table 6.7 . Differently from the authors in the literature, different combinations of initial populations and maximum generations have been tested. Similarly, the algorithm was tested with and without the non-linear constraints. A total of 19 runs have been successfully executed as follows:

- No Non-Linear Constraints.
  - 500 generations: 100, 200, 500 individuals (population size).
- Non-Linear Constrained GA.
  - 50 individuals: 50, 100, 200, 500 generations.
  - 100 individuals: 50, 100, 200, 500 generations.
  - 200 individuals: 50, 100, 200, 500 generations.

GA Settings		
Fitness Function(s)	*Objective Functions number*	Two (Multi-Objective Optimization)
	Minimization Objective(s) - Fitness Parameter(s): min F_1,2,3 (v_1, ... , v_i, ... v_N)	Unit Production Cost (FFI), Cutting Force (FFII)
	Minimization Function(s) type	Analytical (FFI), Experimental (FFII)
	Variables Number	9
	Variables (v_1,.. V_i,... ,V_N)	Feed rate, Cutting speed, Depth of cut, Outer diameter, Outer bottom section diameter, Internal diameter, Bottom section Length, Total Length, Casting blank Internal diameter
Constrains	*Parameters (Linear-Non-linear Functions): K v_1^a v_2^b ..., v_n^g ≤ K_max*	Turning Power (An), Surface Roughness (An) Machining removal Rate (An)
	Constrain Functions (Non Linear)	Cutting Force, Cutting Power (An), Tool Tip Temperature (An)
	Coding Type	Binary Coding (Bit String)
Initial Population	*Size (Number of Individuals)* *Creation Function* *Selection Function*	50, 100, 200, 500 Random Generation Tournament Selection
Reproduction	*Elite Count (Fraction)* *Function*	0.05% Population Size (Default) One-point Operator
Crossover	*Function* *Fraction*	Scattered Crossover 0.8
Mutation	*Function* *Fraction*	Adaptive Feasible Mutation Function 0.01
Termination Criteria	*Maximum Generations Number*	50, 100, 200, 5000

Table 6.7: GA settings implemented in MATLAB

– 500 individuals: 50, 100, 200, 500 generations.

The aims of using multiple generation and population options are to:

- Validate the whole model convergence: similar average results should be obtained increasing population and generation numbers.
- Demonstrate the validity of the multi-criteria and constrained approach: in the non-constrained cases, the machining removal rate and process time should be lowest, on the other hand the cutting force should increase. In turn, the turning power and surface roughness must also be not acceptable.
- Decrease machine time (having low turning force and limiting surface turning power and surface roughness).

In Table F.7 (Appendix F.5), the average results from all the runs are gathered. As expected, the fitness functions values (i.e. total component cost and cutting cost) are influenced by the population size and generations number, although the results are consistent for all the different options. The small differences between the fitness functions values can be explained with the algorithm randomization. Similarly, the turning power and surface roughness are similar for all the GA settings. Accordingly, the machining time and cost results vary among all the different combinations, although the results maximum difference is 10 minutes. The centrifugal casting cost remains constant for all the different combinations. Given this, it is possible to say that the model is consistent and reliable, independently form the maximum generation and population size settings, and therefore convergent.

As expected, the resulting machining removal rate on the non-constrained runs is higher than in the constrained ones, resulting in lowest machining times. On the other hand, the turning force values are doubled, in comparison with the constrained case. However, even using the turning force fitness function (i.e. creating a trade-off- between cost and force, so avoiding the global maximization of the parameters), the turning power and surface roughness case are not acceptable, demonstrating the validity of the approach.

However, the average between the optimum results is not a robust way for identifying the impact, as every solution needs to be taken into consideration individually (i.e. every optimized variables set represents a single optimal solution to the problem). For this reason, the 100 generations and 100 individuals run has been used for investigating the impact of the GA optimization (similarly to Sardinas et al. [2006], Saravanan et al. [2003], Amiolemhen and Ibhadode [2004]). The optimized set of individuals (i.e. last generation) is shown in Tables F.8 and F.7 (Appendix F.5): 35 different optimal solutions (i.e. set of variables) have been found for the 100 individuals and 100 generations setting.

Figure 6.15 shows the final results (i.e. last generation) of the optimization results for the considered settings, showing clearly the formed Pareto frontier. In the last generation, it is possible to notice how the average distance between the individuals (i.e. depending on value of the set of variables) rapidly decreases to its minimum value (after 20-30 generations). However, the variability of the individuals is still maintained, as it is possible to notice in the individuals' histogram and distances (Figure 6.15). The early convergence of the model causes the difference GA settings similar to obtain similar results.

Taking as an example a particular optimization set, Table 6.8 show an optimal set of variables, taken from the 100 population individuals and 100 machining generation case (i.e. individual nr.1). The set of variables and results is compared with the current process line, when the highest MRR is applied (i.e. actually lower than the 400 mm case).

Accordingly to the machining parameters, the cutting force remain in the acceptable range. The surface roughness improves, although the turning power increases (both limited by the constraints). The highest improvements are the machining removal rate and, jointly, the machining time (decreasing consequently the machining cost).

Regarding the optimized variables, it is possible to notice a general reduction of the final dimensions, with the exception of the bottom section length, which increased. The machining parameters can be set higher from the applied ones (except from the feed rate that remaining unchanged).

GA Optimization: Concluding Remarks

The following observations can be made

1. Outer diameter, outer bottom section diameter and inner diameter are almost constant (first decimal place millimetre difference).
2. Total length and bottom section length remain constant.
3. Casting blank diameter remain constant.
4. Feed rate remains constant.
5. Depth of cut and spindle speed vary in every solution.

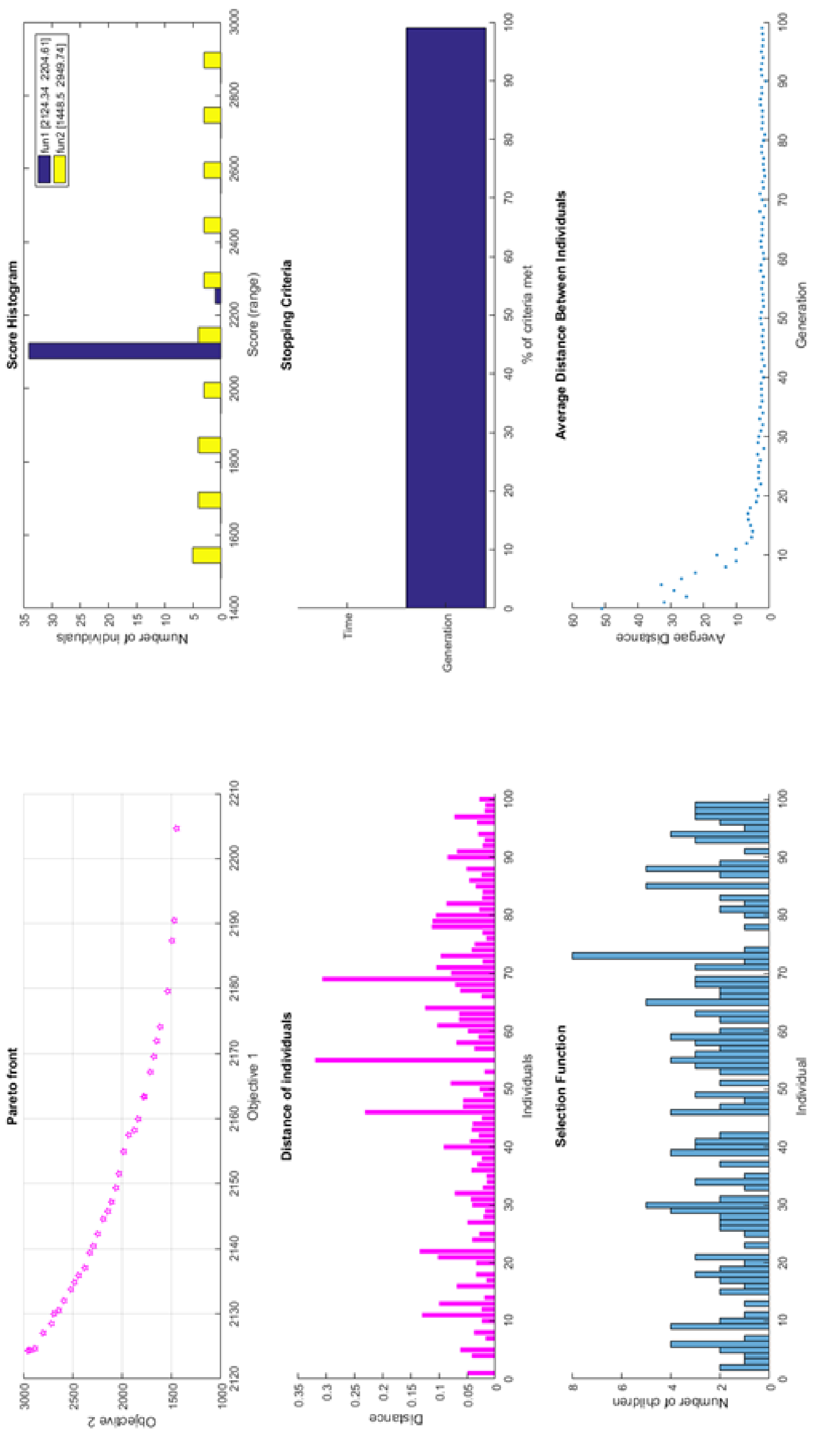


Figure 6.15: GA results for 100 individuals and 100 generations. Top left: Pareto frontier of the last generation individuals. Top right: histogram of the individuals scores. Middle left: distance between the last generation individuals; Middle right: termination criteria, % met (in this case, generation number indicator). Bottom left: number of children for every individual. Bottom right: average distance between individuals, plotted on the number of generations.

Final Geometry	*GA Optimized*	*Current Process (Highest MRR)*
OD [mm]	495	520
ID [mm]	410	400
a [mm]	7.3	3.4
n [RPM]	254	100
F [mm/lap]	0.25	0.25
OD_b [mm]	478	492
l_f [mm]	65	55
L_f [mm]	415	420
ID_m [mm]	370	370
FF2 -Cutting Force [N]	2949.7	1649.2
Power [kW]	25.1	4.8
MRR [mm^3/min]	7.17E+05	1.39E+05
Roughness [Ra]	3.86	3.90
Machining Time [min]	56.08	148.2
Machining Cost [£]	80.20	212

Table 6.8: MRRs, machining times and costs of the GA optimized and NNS chains (current MRR, highest MRR) and original process chain.

6. Total cost varies and remain coherent with current total cost
7. Cutting force and turning power vary coherently with machining parameters
8. Surface roughness varies with the machining parameters, satisfying the target requirements.
9. Machining removal rate varies with the machining parameters, although it remains sensibly higher than the current rate (average of 5.28 10^5 mm^3/min).
10. Similarly, machining time varies with machining parameters, remaining lower than current value (75 min on average).

Table 6.9 shows the improvement on MRR and machining time/cost by passing to the GA optimized process parameters, excluding the optimization of the design variables (i.e. keeping the existing final shape and casting blank dimension, as considered in the differential cost analysis). The impact is higher taking into consideration the current MRR for the 400 mm valve cage production. It is possible to notice how the machining process parameters influence severely the final cost, decreasing severely also the cost of the NNS chain. Table 6.10

Process Chain	*Blank Type*	*MRR [mm^3/min]*	*Machining Time [min]*	*Machining Cost [£]*
Original Process Chain	Solid Blank	5.33E+04	1945	2781
NNS chain, with current MRR	Centrifugal Casting Blank	5.33E+04	153	219
NNS chain, with highest MRR		1.39E+05	59	84
NNS chain, with GA optimized MRR (Average 100 p, 100g)		5.06E+05	13	18

Table 6.9: Comparison between MRRs and machining times of the GA optimized and NNS chains (current MRR, highest MRR) and original process chain.

Process Chain	MRR/MRR(GA)	Process Time (GA)/ Process Time
Original Process Chain	9.5	0.007
NNS chain, with current MRR	9.5	0.083
NNS chain, with highest MRR	3.64	0.216

Table 6.10: Comparison between MRRs and machining times of the GA optimized and NNS chains (current MRR, highest MRR) and original process chain.

visualizes the same data in perceptual improvement: the GA optimized machining parameters give a 9.5 times higher MRR and a 7% machining time compared with the current process chain (i.e. solid blank). Using centrifugal casting blank, the machining time decreases to 8.3% or 21.6%, using the current MRR or the highest one respectively

6.5 Conclusion

The Case Study II represents a classic NNS application because of the possibility of using a process that gives saving in raw material and machining time.

The nature of the process made necessary the technological feasibility assessment through an experimental validation (prototype). An adaptable cost model has been created for centrifugal casting, and a methodology (DCFA) has been established for assessing a differential analysis between the old and new process chains. The methodology shows furthermore its generalizability and usability for assessing the economic feasibility of a process. The process is currently adopted by the manufacturing company, generating the expected savings.

The centrifugal casting cost models, developed from supplier real data, has been developed and used also for the optimization methodology (CoDeO) has been tested for a particular product (400 mm valve cage). The machining process parameters selection is a complex and highly constrained problem' however the GA results show acceptable trends and good correspondence with the literature and previous data. The GA selected process parameters increased the MRR and decreased machining time, corresponding to proportional savings and machining strategy improvement. The methodology provides a framework for the optimization of a whole process chain, identifying and selecting the key parameters and shapes variables.

Chapter 7

Validation: Case Study III Closed-die Forging of a Valve Body

7.1 Introduction

Another case study candidate identified by the ProGeMa3 methodology was the hot closed-die forging of a valve body. The resulting application of the NeNeShO is shown in Figure 7.1. Route 2 has been selected, due to the possibility of simulating the forging process via FEM. Differently from the other two case studies, the next subsection provides the plan and main models for the Differential Cost and Feasibility Analysis (DCFA) and Conditional Design Optimization (CoDeO) of the component. The technological feasibility (DFCA) consists in a FEM simulation of the forging process, considering the maximum required forging force and testing different process designs (i.e. with the aim to obtain the most convenient forging operation sequence, similarly to the flow forming case study). The differential cost analysis has been developed through a cost model (Appendix H) that incorporates the results obtained by the FEM runs. Forging force and wear prediction are used for both evaluating the technological and economic feasibility. The CoDeO has been developed by applying a DoE approach to FEM runs. A first selection of the variables and responses (using an influence map) developed the potential DoE, which changing the identified variables in a systematic way aim to obtain product (and preform) design and forging optimization (forging parameters).

7.2 DFCA and CoDeO Planning

7.2.1 Systematic Literature Review

In the literature, many authors focus on the hot forging process design and optimization using expert systems [Duggirala et al., 1994, Caporalli et al., 1998, Esche et al., 2001] and numerical investigations [Han et al., 1993, Bonte et al., 2010, Altan and Vazquez, 1996, Zhao et al., 1997, Groenbaek and Birker, 2000, Vazquez and Altan, 2000].

The DoE approach has been extensively used by authors for experimental investigations [Wei and Lin, 2011, Sanjari et al., 2008, Zhang et al., 2014, Equbal et al., 2014, Kermanpur et al., 2010], although only recently DoE has been applied to the numerical approach. Even though the process variables and response interactions are modelled numerically, the complexity of the approach makes it difficult to understand the impact of every single variable on the final results and to optimize the whole variables set. Using FEM, the possibility of multi-objective optimization makes the application of DoE suitable for optimizing many hot forging problems [Walters et al., 2003, 2015a,b], particularly for problem where the objectives model are difficult to formalize (e.g. microstructural analysis).

Wear predictions models [Thompson and Thompson, 2002, Lee and Jou, 2003, Kim et al., 2005a, **?**] has been developed extensively from the Archard [1953] work.

Several authors developed cost models for hot forging: some of the models are dedicated to

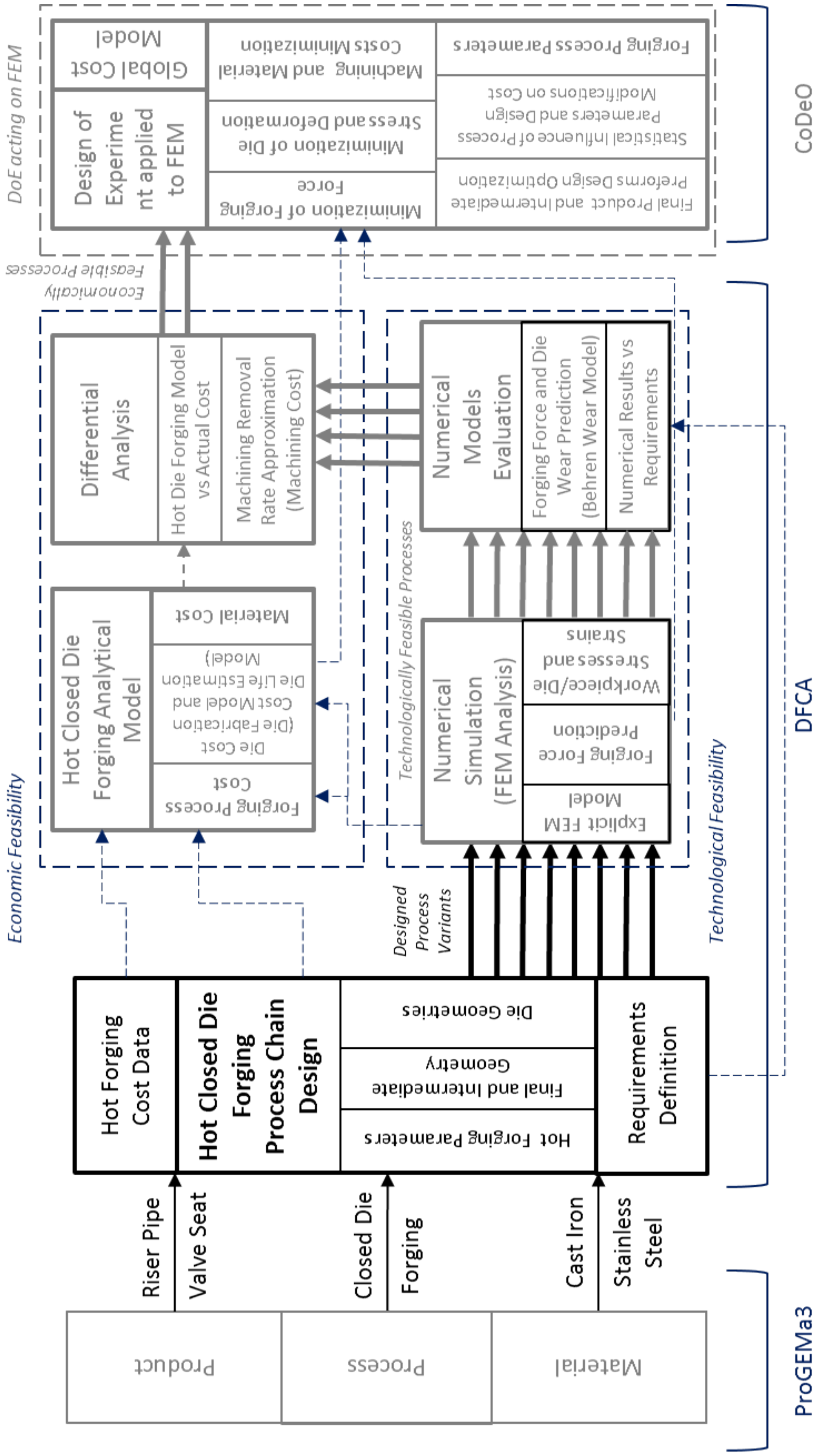


Figure 7.1: Scheme of the route 2 (NeNeShO Pro) applied to the valve body forging case study.

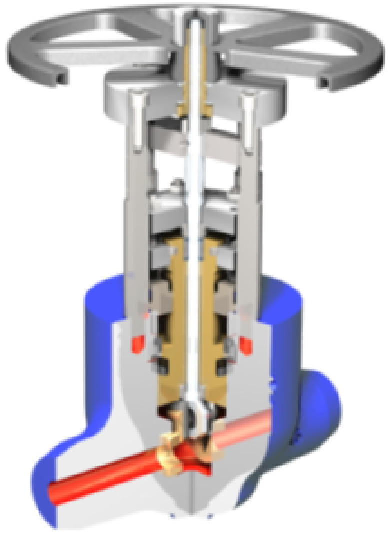


Figure 7.2: Parallel gate valve.

the whole cost process estimation [Rankin, Boothroyd et al., 2011, Knight, 1992, Elanchezhian and Kesavan, 2004, Kalpakjian and Schimd, 2009], on the other hand, some models are predicting exclusively the die cost (for example Groseclose [2010]).

A brief literature survey is detailed in Appendix D.3

7.2.2 Hot Forging Process Design and Requirements Definition

The **valve body (Case Study III)**, shown in Figure 7.3), is a central component of a parallel gate valve (Figure 7.2) and needs to be resistant enough to contain its working pressure. In fact, the valve elements usually transfer the pressure, created by the fluid, to the body through bolts or by being directly in contact with the body itself. The component variants have sizes that vary from 15 mm to 900 mm. The production volume has been estimated to be between 200 and 300 components per year. The materials used for this production are: carbon steels, alloy steel and stainless steel.

Currently, the manufacturing process of the valve body varies depending in the component size. For small sizes (15-200 mm, nominal valve size), the primary shaping process is open-

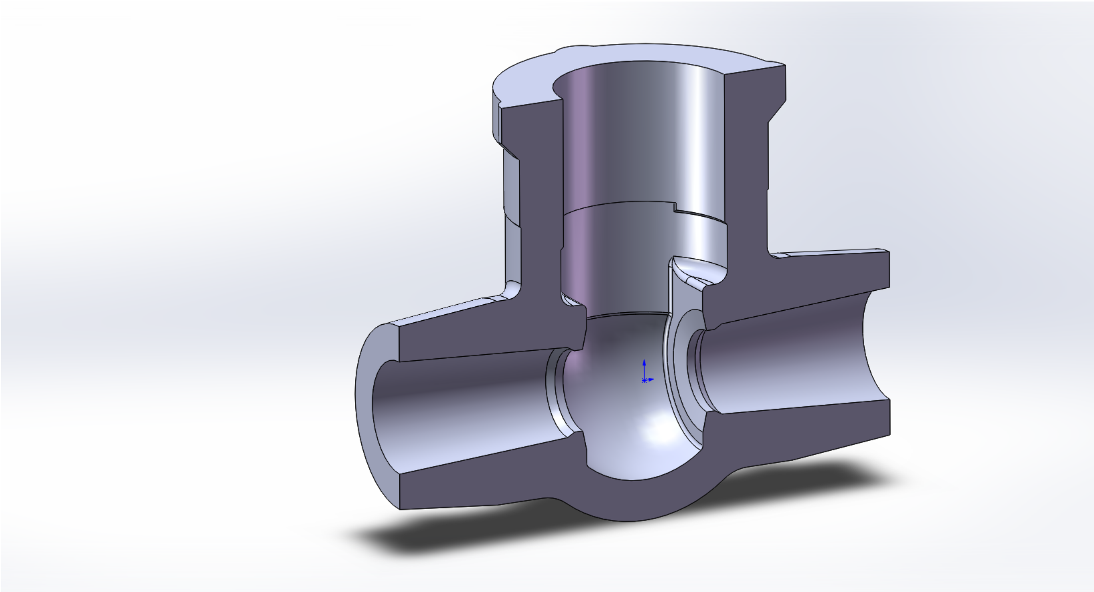


Figure 7.3: Body of a parallel gate valve.

die forging. From a solid block, the valve is machined to its final shape. For medium sizes (200-450 mm, nominal valve size), the primary shaping process is open-die forging, although sometimes casting have been use for low pressure requirements. Different processes variants have been taken into consideration for the production of medium size bodies(Figure 7.4):

- Single piece: a billet is open-die forged and after machining from a single block. The machining process is a major factor of cost in this production.
- Two pieces: two parts of the body are separately open-die forged. After a machining phase for each of the parts, the two parts are welded and after machined to its final shape
- Four pieces: the body is divided in four parts instead of two. The welding and machining processes are similar to the two piece processes

The welding process has a high impact on the manufacturing cost, because of its cost (around 25% of the total) and the defects caused by its application (which caused the product to be reworked or to fail meanwhile operating). The non alignment of parts is not an uncommon

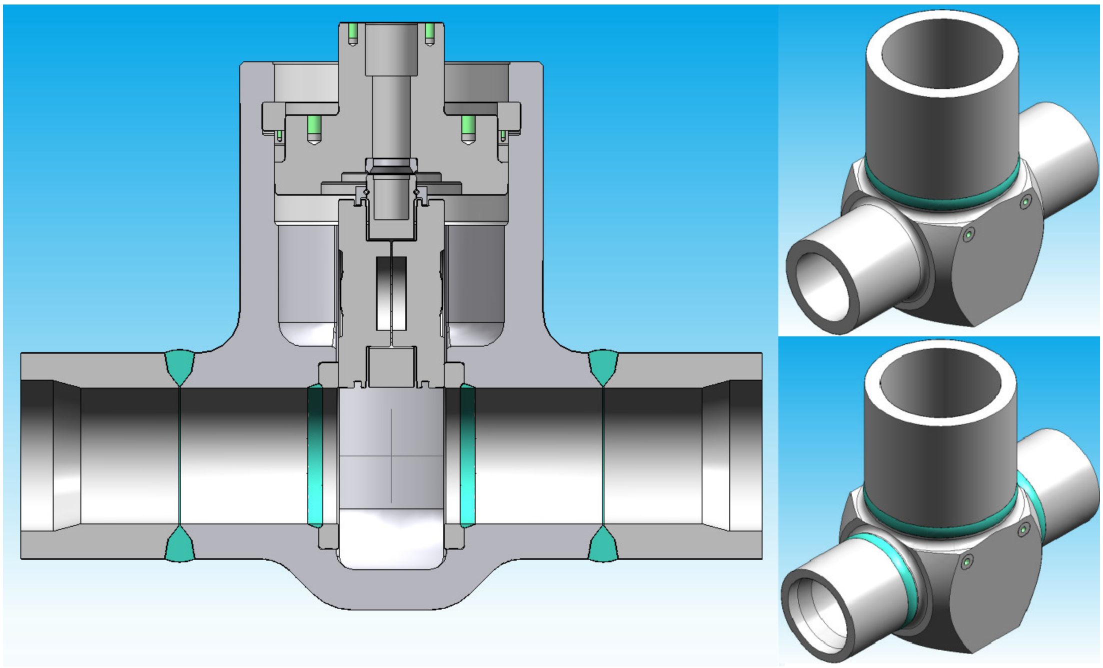


Figure 7.4: Different options for open die forging of a valve body: two piece (*left* and *right-top*) and four pieces (*right-bottom*).

defect after the welding. However, major issues in welding are due to high thickness of the parts to be jointed (i.e.the weld bead penetration is a major cause of defects in the production of this component). The possibility of avoiding the welding process is a major target for the NNS manufacturing of this component.

For the largest size, the valve boy is usually cast and after finished by machining process. Sometimes the valve body is forged in two or four parts, as in the medium sizes. The request for forging valve bodies is mainly due to the customer, even if the forging processes is often not economic (i.e. due to the low product levels) and exceeding the specifications (i.e. due to the high thickness, which cannot be lowered due to normative standards).

The possibility of achieving a most forgeable shape, reducing the forging force and the subsequent machining process made the processes economically feasible for the medium size components. For this reason, the DFCA has been limited to components with lengths from 200 to 450 mm. The possibility of changing the component design for adapting to the closed-die

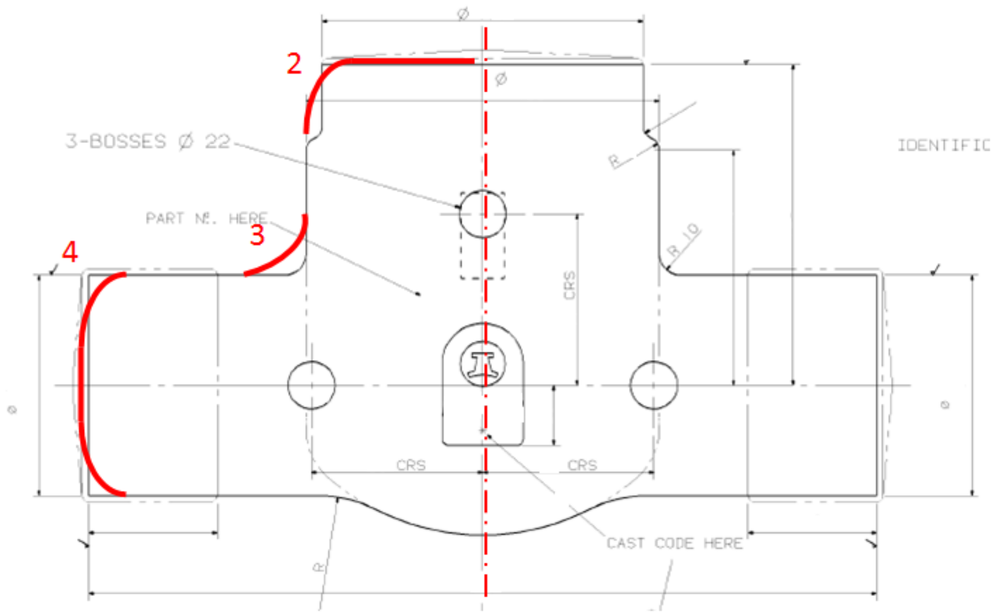


Figure 7.5: Schematic of the parallel gate valve, including the considered design variables (2, 3, 4).

forging process has been evaluated by the modification of its external shape. The considered design modifications were as in Figure 7.5:

- Bonnet connection fillet (2 in Figure 7.5)
- Body perpendicular fillet (3 in Figure 7.5)
- Pipe connection fillets (4 in Figure 7.5)

7.2.3 DFCA and CoDeO of Hot Forging Application to Case Study III

The possibility of adapting this new design makes possible the avoidance of the machining in the external zone of the body (i.e. the contact zones with other components still need to be machined) while remain unchanged in the internal part.

The design standards to be used are the ASME section III (ASME B16.34 RCC-M), with

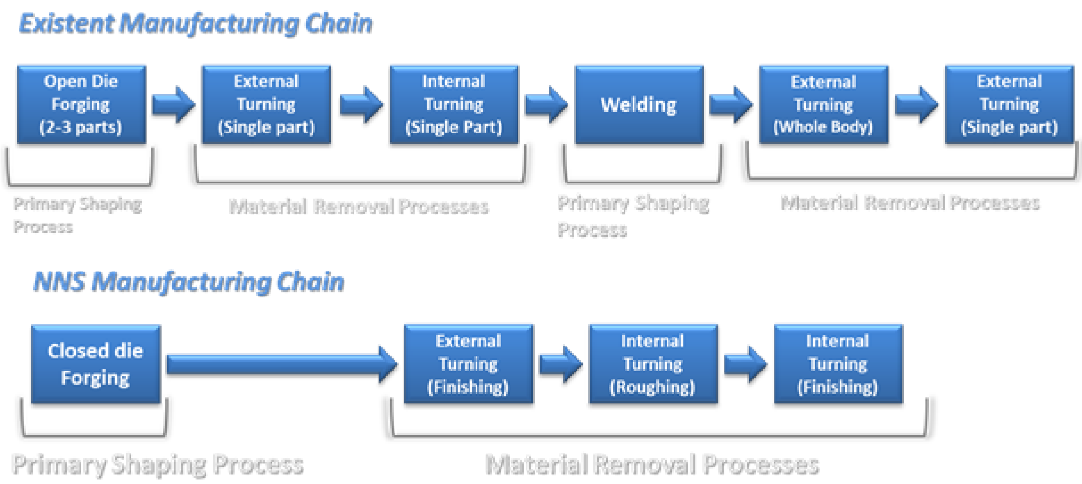


Figure 7.6: Comparison between existent (top) and NNS (bottom) manufacturing chains of the Case Study III.

3-24 inch (DN 80-600) in sizes and pressure class ASME 150-4500. The NNS and existing process chain for the components are shown in Figure 7.6.

The technological feasibility target (to establish using FEM) has been defined as follows:

- Acceptable value of forging forces
- Acceptable material stresses

The feasibility evaluation of single block closed die forging of the valve body has been planned by using DEFORM. Different process parameters and process designs will be tested in order to evaluate the forging forces and material stresses (hence the forgeability of the piece for the given materials), operating a first preform optimization.

The first exploratory FEM runs were conducted using the new design and a round solid block as the preform. The FEM runs show the possibility of achieving the final shape in one step defining feasible forging speed, force and temperature ranges.

For the DFCA and CoDeO, a model for evaluating the impact of the hot closed-die forging on the total cost, including an estimation of the die-life, has been developed (Appendix H). The model is able to provide the total cost (H.1), diving it in different cost factors:

- Material cost (H.2): dependent on the product geometry and proportional to the preform volume (H.3)
- Forging cost (H.4): dependent on labour cost (H.5) (function of the forging time, thus on the forging parameters), equipment cost and operational cost (H.6), which is a function of the forging force (H.7) and time, both functions of the forging parameters and product geometry.
- Die cost (H.8): dependent on die wear (H.12) and die total cost (H.9). The first can be roughly estimated using Archard (H.10) or Behrens (H.11) wear models and using a wear threshold (H.12). In this way it would be possible to roughly estimate the die life and, using the forging time (function of the forging parameters), the percentage of life used for a single operation.
- Machining Cost (H.13): dependent of the geometry (difference between forging product and final product volume) and machining parameters.

Based on the examples in the literature, a DeO approach on the FEM runs was planned in the CoDeO phase. Using a qualitative influence map (shown in Table 7.1 and developed from Caporalli et al. [1998], Kalpakjian and Schimd [2009], Schuler [1998], Wei and Lin [2011], Zhang et al. [2014], Sanjari et al. [2008], Equbal et al. [2014], Kermanpur et al. [2010], Chen and Jung [2008], Walters et al. [2003, 2015a,b]) a selection of dependent and independent variables has been made. The considered independent variables in the manufacturing chain are:

- Preform or intermediate blank: initial geometry, geometrical complexity, workpiece material.
- Forging process:

  - Process Variables: forging sequence (i.e. number of steps and their design), final forging geometry, workpiece temperature distribution, lubricant, ram velocity.
  - Die: initial temperature, material.

- Machining Process: cutting depth, feed rate, spindle speed.

The considered dependant variables were as follows:

- Preform: volume, production process.
- Forging process.
  - Process Variables: strain rate, contact time, forging force.
  - Die: die(s) geometry(-ies), temperature distribution, stress distribution, friction conditions.
- Machining Process: removal rate, removed volume.

The direct costs have been considered as follows:

- Material cost.
- Forging operation direct costs.
  - Forging Costs: operative forging cost, forging equipment selection.
  - Die Costs: life impact, fabrication cost.
- Machining Cost.

As shown in Table 7.1, the material and machining costs have been considered as primary target of the optimization as well as the final forging geometry. From the influence map, a first variable and response selection has been developed, selecting the connected variables with the aforementioned targets. The seven considered independent variables and their levels, needed for setting the DoE are as follows:

Independent Variables			Preform Volume	Preform Production Process	Removal Rate	Removed Volume	Cutting Forces	Die(s) Geometry(ies)	Die Stress distribution	Die T Distribution	Friction Conditions	Strain Rate	Contact Time	Forging Force
Preform or Intermediate Blank		Initial Geometry	D(A)	D	D	D	N	D	D(?)	D(?)	?	D(?)	D(?)	D(A)
		Geometrical Complexity	D	D	N	N	X	D(?)	D(?)	D(?)	?	D(?)	?	D(?)
		Workpiece Material	D	D	D	D(?)	D(A)	D	D(A)	D(A)	D	D(A)	?	D
Forging Process	Forging Operational Variables	Forging Sequence	D	N	N	D(?)	D(?)	D	D	N	N	X	D(?)	D
		Final Forging Geometry	D(A)	N	D(A)	D(A)	D(A)	D	D(?)	D(?)	?	D(?)	D(?)	D
		Workpiece T Distribution	?	X	?	N	D(?)	D(?)	D(A)	D(A)	D(A)	D(A)	D(?)	D
		Lubricant	N	X	N	N	N	N	D(A)	D	D	D(A)	N	D
		Ram Velocity	?	X	?	N	D(?)	D(?)	D(A)	D	D(A)	D(A)	D(A)	D(A)
	Die	Die Initial Temperature	?	X	N	X	X	D	D(?)	D(A)	D	D	N	D(?)
		Die Material	?	X	X	X	X	D	D(?)	D(A)	D	N	N	D(?)
Machining Process(es)		Cutting Depth	X	X	D(A)	D(A)	D(A)	X	X	X	X	X	X	X
		Feed Rate	X	X	D(A)	D(A)	D(A)	X	X	X	X	X	X	X
		Spindle Speed	X	X	D(A)	D(A)	D(A)	X	X	X	X	X	X	X
Dependent Variables														
Material Cost			££	£	O	O	O	££	?	?	?	?	?	?
Forging Operation Direct Costs	Forging Cost	Forging Equipment Selection	£	O	O	O	O	£	?	?	£	££	£	££
		Operative Forging cost	£	O	O	O	O	£	?	?	O	£	££	££
	Die Cost	Die Life Impact	£	O	O	O	O	££	££	££	££	£	£	££
		Die Fabrication Cost	££	O	O	O	O	££	£	££	£	£	£	££
Machining Cost			££	O	££	££	£	?	?	?	O	?	?	?
Direct costs														

Table 7.1: Hot closed die forging variables influence map. (D): Dependent - Directly (empirical or numerically established dependence); (D (A)): Dependent - Analytical relation; (D (?)): Dependent - Unknown relation; (N): Dependent but negligible; (X); Non-dependent; (?): Unknown. Influence of dependent variables on costs. (): High Impact; (): Low Impact; (0) No impact; (?) Unknown. Investigation targets are in red.

- Preform Geometry:
  - Complexity (categorical variable): 3 levels (cylinder, frustum, machined billet) or 2 levels.
- Final Design (numerical variables):
  - Bonnet connection fillet: 3 levels (R5, R10, R20 mm) or 2 levels (R10,R20 mm) (variable 2 in Figure 7.5)
  - Body perpendicular fillet: 3 levels (R10, R20, R30 mm) or 2 levels (R10,R30 mm) (variable 3 in Figure 7.5)
  - Pipe connection fillets: 3 levels (R5,R10, R20 mm) or 2 levels (R10, R20 mm) (variable 4 in Figure 7.5)
- Process Parameter (numerical variables):
  - Workpiece temperature (3 levels, C)
  - Lubricant, so the friction coefficient (3 levels)
  - Forming speed or strain (3 levels, m/s)

The three responses and their source of calculation have been selected as follows

- Forging Force: extracted by the FEM simulation
- Die Wear: using the equation (H.11) or (H.12)
- Total Cost: using the equation (H.1)

Using the DoE, it would be possible to map the optimum configuration of variables for obtaining the best response. Depending on the results, it would be possible to provide a statistical analysis (ANOVA) of the impact of every variable on the responses.

Different DoE configurations have been evaluated, taking also into consideration the total computational time (i.e. in hours, assuming a single FEM run' s duration of 10 minutes, congruently to the exploratory runs).
Appendix H.2 contains the DoE variants planned for the Case Study III.

7.3 Conclusions

The case study could not progress (stopped during the exploratory FEM runs) for the following reasons:

- Nuclear industry regulations: in the nuclear industry there are constrains on the possibility of re-design the component for a standard material. Every new design needs to be certified and accepted. This requires a series of extensive tests for the new component.
- Required component testing: the tests, required for the acceptance of the new design, have a particularly high cost and lead time (almost one year). The industrial partner was dubious about started this testing and the procedure for ratification, although the possibility of saving machining and not applying the welding process have incentivised them. The company asked to the customer about the possibility of applying these new process and design.
- Customer will: for the described component, the customers have total control on the requests and component requirements (pull market). The contacted customers were not willing to change the component design or any details of the manufacturing process. The customers consider the achieved component reliability essential, so they do not want to compromise it by applying any changes.

The Case Study III illustrates some of the limitations of NeNeSho. In particular, NeNeShO does not take into account the influence of both market and customer's voice on the targets definition (in ProGeMa3 phase) and product requirements (in ProGeMa3 and DFCA phases). Even proposing a NNS solution (showing potential improvements on the current manufacturing chain performances), the NeNeShO fails to consider collateral actions and costs (e.g. testing and marketing), which compromise the NNS process selection and its implementation.

Chapter 8

Discussion

In this chapter the proposed manufacturing framework (NeNeSho Pro) (Chapter 3) is summarized and discussed. The completeness and the impact of NeNeShO Protocol on the case studies is discussed. A qualitative analysis of the performances and characteristics of all three parts of the framework (i.e. ProGeMa3, DFCA, CoDeO) is carried out to evaluating their individual impacts on the framework's overall validity. NeNeShO's characteristics and constituent parts are compared with other reported manufacturing assessment frameworks. Both ProGeMa3 (Section 3.1.1) and CoDeO (Section 3.1.3) are compared respectively with other process selection and optimization approaches in the literature.
Lastly, contributions, extendibility and limitations of NeNeSHO are presented.

8.1 Summary of NeNeSho Application

The research gap (Chapter 2) identified that previously reported approaches did not provide a holistic view of the NNS production for: selecting quantitatively an efficient manufacturing process, determine its feasibility depending on the product requirements (technological and economic) and understanding how to adapt process parameters and product design to new

NNS processes. However, the manufacturing variables (i.e. process design, material and process selection) correlations make it necessary to reduce the methodology scope by introducing limiting assumptions and validate by case study approach (Chapter 1.2.6).

NeNeShO Protocol has been introduced (Chapter 3), in its three phases: Product Geometry, Manufacturing and Material Matching (ProGeMa3), Differential Cost and Feasibility Analysis (DFCA) and Conditional Design Optimization (CoDeO). The methodology associates identified technologically feasible approaches (analytical, numerical and experimental) with economic modeling, and subsequently optimisation techniques (numerical and statistical) based on their minimization. Chapter 4 describes the application of the process selection methodology, applied to four case studies.

In case studies IA and IB (Chapter 5), an innovative forming process was identified in place of traditional forming and casting processes. However, the flow forming process was assessed as unfeasible (using analytical models), for economic reason in one case and for technological in the other. The Case Study IA and IB have been described together, because of the application of the same process. For these cases, the Route 1 (analytical investigation) has been selected. The Differential Cost and Feasibility Analysis (DFCA) (Section 3.1.2) has been applied to both the components eval;uating the unfeasiblity.

In Case Study II (Chapter 6), a conventional forging process was substituted by a centrifugal casting process. For the Case Study II, an experimental investigation has been selected (Route 3). The DFCA and CoDeO (Section 3.1.3) have been both applied. The NNS approach has had a great impact on the manufacturing chain performances of this component.

In Case Study III, the numerical approach has been developed (Route 2). The process feasibility was assessed experimentally (i.e. technological) and deriving economic models, by collaborating with a casting supplier. The third phase optimizes the component shape and process parameters showing substantial reduction in machining time and material wastage. The process is currently used by the company for the selected production.

In Case Study III (Chapter 7), a numerical investigation (FEM) and theoretical (partially analogous) cost models were applied (Route 2) together with an optimization strategy based on DoE applied to FEM simulation of the forging process. The DFCA and CoDeO have been planned, although the case study has been interrupted (i.e. by customer preference reasons not evaluated or accounted in the framework construction).

8.2 Case Study Analysis

Table 8.1 shows a qualitative analysis of the four case studies presented in the thesis. Case Study IA and IB have only partially been developed because the process was found to be unfeasible (flow forming). Both the technological and economic models produced good agreement with the available literature and data. The case studies were both on the limit of the unfeasibility, due to their material and 'difficult' to produce geometry. In these two cases, the CoDeO phase was not applied, and so the manufacturing process defaulted to the current production method. Case studies IA and IB were only partially successful because the process lead to the selection of flow forming. Unfortunately flow forming proved to be unviable because of the required product properties (i.e. mechanical properties). A different definition of the product target could lead to different results in the process selection, allowing the methodology to be applied completely. In the Case Study II, NeNShO was completely and experimental feasibility investigation and statistical (derivative) cost model were selected. In Phase III, an analytical optimization technique (i.e. a Genetic Algorithm) was applied to the process model (centrifugal casting and machining) and cost model was developed as specified by the framework.

In contrast to the Case Study II, the NeNeShO Protocol could not completely apply to Case Study III. The framework could not implement a NNS techniques because of the impossibility of changing product design (i.e. extensive tests required for nuclear standards satisfaction)

Table 8.1: Qualitative analysis of the four developed case studies: (p), planned activity.

Case Study Analysis	Case Study IA	Case Study IB	Case Study II	Case Study III
Framework Application	Partial	Partial	Complete	Fail to apply
Reached NeNeShO Phase	Phase II	Phase II	Phase III	Phase I
Reason for incomplete application	Process unfeasibility	Process unfeasibility	None	Customer will/regulations
Process Investigation Approach	Analytical	Analytical	Experimental	Numerical (p)
Cost Model Approach	Theoretical	Theoretical	Statistical	Analytical (p)
Process and Design Optimization Approach	Analytical	Analytical	Analytical	Numerical (p)
Application to Current production	Unfeasible	Unfeasible	Applied	Inapplicable
Prediction Coherency	Fair	Fair	High	Unknown

or manufacturing process (i.e. unwillingness of the customers to accept a new primary shaping process). Extensive and expensive tests must be used to validate the process and product design. The company was reluctant to apply the new process and product design. Furthermore, the customers were unwilling to accept any of these changes. However, overall the case studies suggest that the ProGeMa3 methodology within the NeNeShO is viable and effective. The ProGeMa3 (Phase I of the NeNeShO Pro) is a fundamental part of the framework, because it associates existing components and their materials, with potential process candidates. The ProGeMa3 part of the framework was assessed as having a "medium" level of flexibility in Table 8.2 because the combination of selection matrix and fuzzy logic provides a very efficient mechanism for quickly focusing the process selection on a small number of potential candidates. The approach reduces the amount of subjectivity in the process and consequently supports non expert-users [Sáenz et al., 2015]. However its successful application to Case Study II must be contrasted with the reasons for its partial application in case studies IA and IB and the unsuccessful application in Case Study III, which can be related to a lack of information in the process selection phase.

The DFCA (Phase II of NeNeShO) allows the selection of an appropriate investigation method-

Table 8.2: Qualitative analysis of the three NeNeSho Pro phases (ProGeMa3, DFCA, CoDeO).

NeNeShO Pro Section Analysis	ProGeMa3	DFCA	CoDeO
Flexibility	Medium	High	High
Subjectivity	Low	Medium	Medium
Reliability	Medium	High	Medium
Expertise Needed in Usage	Low	Very High	Very High
Influence of Existent Models and Approaches	Low	Very High	High
Influence of Target Definition on Results	High	Medium	Low
Novelty of the Approach	Low	Medium	High
Theoretical Validity	High	Very High	High
Empirical Validation	Partially Achieved	Achieved	Achieved

ology ((i.e. analytical, numerical or experimental based on the existing models and the target requirements), that links the technological model with the cost model selection (e.g. estimating the machining cost from the material removal rate). The flexibility of the framework is particularly high in this case, as it can adapt to every existing process. In other words, the feasibility analysis can be theoretical, or experimental depending on extent and reliability of the knowledge available. The same observations can be made about the cost model and its differential analysis. The cost model can either be derived or modelled theoretically, based on the selection of the previous steps. However, in this case, the requirements definition influences the selection of the investigative approach for investigating the satisfaction of the requirements themselves. In this case though, the impact on the results is smaller than in ProGeMa3, because of the flexibility of the approach (the requirements do not directly influence the formulation as they do it in the fuzzy logic application).

In any case to confirm the methodology's validity it is sufficient to establish that either models from the literature or experiments can determine cost given the material and process. The availability of models in the literature has a significant impact on the framework application and the consequent development of the case study. However, this also gives high flexibility to the methodology (although obviously a certain degree of subjectivity is need for judging the literature and review outcomes). The expertise needed for the application in Phase II is particularly high, due to the interpretation of the literature, extrapolation and adaptation of the models, interpretation and coherency with the defined requirements and complexity of development and application. Consequently, this part gives high theoretical validity to the application.

The CoDeO (Phase III of the NeNeShO Protocol) connects the models and decisions taken in Phase II with the selection of a process/design optimization method. The method selected is focused on the process parameters and route determined by the previous steps of the methodology. Like the previous step (i.e. DFCA), the flexibility of CoDeO is rated high in Table 8.2 but involves a subjective degree of decision making. Because not all the manufacturing steps are considered (primary shaping processes and machining are excluded) the results cannot be guaranteed to be optimum.

Although aligned with the DFCA, CoDeO effect on existing processes is rated high in Table 6.1 because it can be easily adapted to consider the constraints (i.e. process parameters) that determines process feasibility (e.g. non-linear constraints optimised by the GA used in Case Study III). The target influence of the definition in this case is rated low in Table 6.1, because the main target is the cost, or time, reduction, maintaining the process as closely to the feasibility as possible. The connection between investigative and optimization models can be classified as a novel approach (Table 8.4), because nothing similar has been reported in the literature following the NNS principles.

8.3 Comparison with Literature

Tables 8.3 and 8.4 compare NeNeShO Protocol with other manufacturing frameworks reported in literature (Swift and Booker [2013], Lovatt and Shercliff [1998b], Caporalli et al (1998), Albiñana and Vila [2012]).

In contrast to qualitative methodologies (Lovatt and Shercliff [1998b], Albiñana and Vila [2012]) and Swift and Booker [2013] (which uses historical data and empirical formula derived from them), NeNeShO Pro limits its scope to NNS processes for metal, establishing a sub-field in NNS studies (e.g. the expert system presented by Caporalli et al. [1998]). The qualitative frameworks (Lovatt and Shercliff [1998b], Albiñana and Vila [2012]) extend the process searching to consider the availability of every manufacturing process, meanwhile Caporalli limit its research to forging processes. Relying on regressions and charts developed from a large amount of data, Swift and Booker [2013] include only well-established processes, excluding new innovative ones. In contrast the use of fuzzy logic allows, the consideration of well-established and innovative processes, thus encompassing all existing and emergent forging, casting and additive layer manufacturing technologies. The quantitative process selection approach of ProGeMa3 (that will also be discussed in Table 8.5) is substantially different from the quantitative approaches of Swift and Booker [2013] and Lovat & Shercliff (1998). The first uses a process selection matrix (PRIMA matrix) and a cost analysis, using charts and parameters for assessing the similarity with existent process costs. Caporalli et al. [1998] and Albiñana and Vila [2012] used a qualitative process selection approach, the first based on product similarity, selecting process and designing process chains in comparison with existent ones. In contrast, the second used a knowledge-based system, where information about several processes are sorted and selected by criteria, depending on the product design and material. Similarly to the first two NeNeShO's quantitative approach filters the candidate processes by using a selection matrix and then ranking the remaining processes using fuzzy logic. The newly developed framework uses also a material selection approach (using fuzzy logic), which is applied prior to the process selection step, giving the material as input for the process. Using a rule-based approach Albiñana and Vila [2012] used a a qualitative approach to material selection, and their framework is able to select simultaneously and interactively manufacturing processes and product materials.

The determination of process feasibility approaches are tackled in a different way by every reported framework. For example Swift and Booker [2013] and Albiñana and Vila [2012] rely on qualitative feasibility based on knowledge based systems. Their approach uses estimation and analogy by a similarity of the target component with an existing successful application of particular processes. However, the process feasibility can only be based on a specific material, because of the extreme difficulty of quantifying the process and product requirements independently of a specific material. Differently, Lovatt and Shercliff [1998b] base their approach to feasibility assessment on technical modelling, a mixture of empirical (based on existing relationships, developed from experimental investigations), theoretical and experimental approaches. Their feasibility analysis is based on understanding the correlation between product and process requirements as well as the selected material. Caporalli et al. [1998] use both numerical and experimental investigation, based on process and product requirements (e.g. die-filling) and selected material. NeNeShO uses either an analytical, numerical or experimental approach, basing the specific selection on the product requirements and its material. Based on an existing process chain, a new chain design is generated by NeNeShoO, similarly to Caporalli et al. [1998]. Differently, Albiñana and Vila [2012] use a knowledge based system for generating an optimal design chain, based on the combination of material and product design. Swift and Booker [2013] and Lovatt and Shercliff [1998b] do not generate the whole manufacturing chain, as they are focused on the primary shaping process. The primary shaping process is treated in isolation from the rest of the chain, which is designed to align with its selection.

Table 8.3: Comparison between NeNeSho and manufacturing framework in literature - Part I

Manufacturing Framework Comparison	NeNeShO	Swift & Booker (2013)	Lovatt & Shercliff (1998)	Caporalli el. (1998)	Albiñana & Vila (2012)
Framework Target	Process and material selection, process technological and economic, process and product design optimization	Process selection	Process selection and economic/technological viability	Hot forging Process design, planning and optimization	Product selection, development and cost
Target Material	Metal	Metal, Composites, Plastic	All	Metal	All
Target Process	Forging, Casting, AL manufacturing	Forging, Casting, AL manufacturing	All	Forging	All
Process Selection Approach	Quantitative (Fuzzy Logic, Selection Matrix)	Quantitative (Selection Matrix, Cost Analysis)	Quantitative (Activity Based Costing and Technical Modelling)	Qualitative (Similarity with existent product manufacturing lines)	Qualitative (Knowledge-based framework)
Material Selection Approach	Quantitative (Fuzzy Logic, prior to process selection)	None	None	None	Qualitative (Rule-based)
Process Feasibility Approach Selection based on	Product requirements, Material	Material	Correlation between product requirements, process attributes and material	Analogy with existent process	Material
Process Feasibility Approach	Analytical, Numerical or Experimental	Qualitative (Knowledge based)	Technical Modelling	Numerical and Experimental	Qualitative (Knowledge based)

Table 8.4: Comparison between NeNeSho and manufacturing framework in literature - Part II

Manufacturing Framework Comparison	NeNeShO	Swift & Booker (2013)	Lovatt & Shercliff (1998)	Caporalli el. (1998)	Albiñana & Vila (2012)
Process Chain Design	Analogous Generation (based on existent chains)	None (Primary shaping process treated singularly)	None (Primary shaping process treated singularly)	Analogous Generation (based on existent chains)	Knowledge-based generation, related to material and product design
Differential Cost Analysis	Quantitative (based on Generative-Analytical, Statistical or Analogous Cost Models, depending on the process feasibility approach)	Quantitative (based on Analogous formulas)	Quantitative (Activity Based Costing)	Not applied	Qualitative (Component Cost Analysis)
Process Optimization Approach	Analytical, Numerical or Experimental (based on Feasibility Investigation Approach Selection)	Not Selected	Not Selected	Numerical Approach	Not Selected
Process parameters optimization Approach	Multi-criteria (Process feasibility Cost)	None	None	Single Criteria (Flow Stress)	None
Product Design Optimization	Multi-criteria (Process feasibility Cost)	None	None	Single Criteria (Flow Stress)	Knowledge-based optimization
Tool and Equipment Selection and Optimization	None	None	None	Achieved	None
Chain Design Optimization	Partially Achieved	None	None	Partially Achieved	None

Differential cost analysis is used quantitatively by three frameworks (NeNeShO, Swift and Booker [2013], Lovatt and Shercliff [1998b]) and qualitative by Albiñana and Vila [2012]. Caporalli et al. [1998] does not provide an economic assessment. The qualitative cost analysis developed by Albiñana and Vila [2012] uses a component cost analysis, related to the manufacturing chain developed in the previous stages. Swift and Booker [2013] based their cost analysis on statistical and analogous models, which estimates the cost of a manufacturing process as a multiple of an existing process cost, based on the similarity of the product's attributes and requirements. Lovatt and Shercliff [1998b] quantitative analysis is an activity based costing analysis, which determine the operations required for operating the primary shaping process. NeNeShO differential cost analysis is based on generative-analytical, statistical or analogous cost models, depending on which process feasibility approach is selected. Lovatt and Shercliff [1998b], Albiñana and Vila [2012] and Swift and Booker [2013] do not include any process or product optimization methods in their frameworks. However, Caporalli et al. [1998] use a numerical approach for optimizing a hot forging process' parameters and the resultant product geometry. The authors develop a single criteria optimization function with minimization of the flow stress of the material as its main target. This is also used for selecting and optimizing the tool and equipment needed to carry out the hot forming process. NeNeShO use analytical, numerical or experimental approaches based on which method of feasibility assessment in selected and the cost/process models developed. The process parameters and design optimization are multi-criteria functions whose target is the minimization of the total cost while maintaining process feasibility (e.g. keeping the turning force in acceptable ranges). In the NeNeShO, the tool and equipment selection cannot be optimized because the models used are specific to a particular manufacturing process' settings. In contrast, Caporalli et al. [1998] use parametric models for optimizing forging dies geometry. Consequently, the process and product design optimization that can be fully performed by Caporalli et al. [1998] , can only be done partially by the NeNeshO. A justification of this can be found in the difficulty to develop general models for a complete process optimization. The only framework to take into consideration external factors (such as the voice of the customer or market analysis for selecting the product design and assessing its requirements) is the one developed by Albiñana and Vila [2012]. The qualitative frameworks (Lovatt and Shercliff [1998b] Albiñana and Vila [2012]) can take into consideration the correlation between process, product design and material simultaneously, although they only provide rule-based and knowledge-based correlations between variables. It is interesting to observe that the quantitative frameworks (Caporalli et al. [1998] , Swift and Booker [2013] and NeNeShO) can only define relationships between process and product design variables, when the material is known.

In Table 8.5, ProGeMa3 is compared with methods reported in material and process selection papers: the following observations can be made. ProGeMa3, Er and Dias [2000] and Campbell [2000] have the most restricted range of material, investigating only metals. Swift and Booker [2013] investigate metals, composites and plastic, meanwhile the methodologies of Giachetti [1998], Albiñana and Vila [2012] and Ashby [2000] can be applied to all material and target process. On the other hand, ProGeMa3 and Swift and Booker [2013] approaches are limited to forming, casting and additive layer manufacturing. Er and Dias [2000] and Campbell [2000] approaches are exclusively dedicated to casting processes. Consequently the most general methodologies (Giachetti [1998], Albiñana and Vila [2012] and Ashby [2000]) are also the most adaptable ones, and the casting-dedicated approaches the least flexible. Giachetti [1998] uses fuzzy logic approach to process selection, ranking the process candidates feasibility for the target production, meanwhile Swift and Booker [2013] use a combination of a selection matrix (used as a filter) and cost analysis (use a final decisional criteria). ProGeMa3 use a combination of process selection matrix (similarly to Swift and Booker [2013]) and fuzzy logic, ranking the process candidates, using NNS criteria. Ashby [2000] use an analytical value function for mapping the process selection on single or multi-criteria deci-

Table 8.5: Comparison between ProGeMa3 and Process/Material selection papers in literature

Process and Material Selection	ProGeMa3	Giachetti (1998)	Swift & Booker (2013)	Ashby (2000)	Campbell (2000)	Albiñana & Vila (2012)	Er & Dias (2000)
Target Material	Metal	All	Metal, Composites, Plastic	All	Metal	All	Metal
Target Process	Forging, Casting, AL manufacturing	All	Forging, Casting, AL manufacturing	All	Casting	All	Casting
Process Selection Methodology	Selection Matrix, Fuzzy Logic	Fuzzy Logic	Selection Matrix, Cost Analysis	Analytical Value Functions (Single or Multi-objective)	Selection Tables (dimensional variability evaluation)	Knowledge-based framework selection	Rule-based selection
Attributes Considered for Process Selection	Material, Product geometry, Mechanical Properties, Production Volume, Cost	Material, Product geometry, Process Features, Mechanical Properties, Production Volume, Cost	Material, Product geometry, Production Volume, Cost	Working loads, Product Geometry, Material, Cost	Product Geometry, Attributes Variability	Material, Product geometry, Mechanical Properties Production Volume, Cost	Material, Product Complexity, Process Accuracy, Production Volume, Cost
Material Selection Tool	Fuzzy Logic (prior to process selection)	Fuzzy Logic (in parallel with process selection)	None	Trade-off Surfaces	None	Knowledge-based framework selection	None
Material Optimization Methodology	None	Variable Fuzzy Sets and Compatibility Ranking	None	Cost and/or target requirements minimization	None	None	None
Model Adaptability	Medium	Very High	Medium	High	Low	High	Medium
Process Data Source	Literature Data	Literature Data	Archival data	Experimental Data	Archival data	Archival data	Archival and Experimental Data
Needed quantity of information	Medium	Medium	Low	High	Low	High	High
Computational/Automated Application	Not Developed	Graphical User Interface	None	None	None	Not Achievable	Graphical User Interface
Impact of product requirements precision on process selection	High	High	Low	Medium	Low	Low	Low

sions. Campbell [2000] develop selection tables by statical evaluation of industrial data: the most suitable process can be selected based on the lowest achievable dimensional variability. Albiñana and Vila [2012] and Er and Dias [2000] both use qualitative methods, the first using a knowledge-based framework selection, the second a rule-based selection. The different methodologies consider different attributes for selecting the process. ProGeMa3 use cost, product geometry, mechanical properties, production volume and materials (used into the selection matrix phase). Using fuzzy logic, Giachetti [1998] take into considerations more variables than ProGeMa3 (i.e. material, product geometry, process features, mechanical properties, production volume and cost) into his model. Ashby [2000] also take into consideration working loads and other operative variables, using a multi-objective value function(s), in addition to product geometry, material and cost. Swift and Booker [2013] consider material, production volume and product geometry for the selection matrix. Campbell [2000] uses only product geometry for selection, although considering the statistical variability of the process' attributes. Albiñana and Vila [2012] use similar attributes to ProGeMa3, meanwhile Er and Dias [2000] take into consideration product complexity and process accuracy into their qualitative selection. Swift and Booker [2013], Campbell [2000] and Er and Dias [2000] do not include any material selection tool in their methodologies and use the material as input for process selection (considering it constant throughout their methodology). ProGeMa3 uses fuzzy logic for selecting the material, but still prior to process selection. Differently, the other three approaches have interactive process and material selections: Giachetti [1998] use material characteristics (translating them into fuzzy sets) for selecting the appropriate material, as part of a fuzzy process selection methodology; Ashby [2000] develop trade off-surfaces for selecting the material, using value functions (single or multi-criteria optimization); Albiñana and Vila [2012] use a knowledge based framework selection, combined with the one they used for process selection and develop an interactive qualitative selection methodology. Differently from Albiñana and Vila [2012], Giachetti [1998] optimise the material selection using parametric fuzzy sets and compatibility rankings. Ashby [2000] also provide material optimization by an analytical minimization of the cost and/or target requirements value functions (depending on the selected decisional criteria). Both the approaches that use fuzzy logic (ProGeMa3 and Giachetti [1998]), use literature data as source of information. On the other hand, Swift and Booker [2013], Campbell [2000] and Albiñana and Vila [2012] rely on archival data, which require a higher amount of information in order to perform the knowledge based section. Er and Dias [2000] use both experimental and archival data to develop its rule based methodology and again the amount of information required to use the methodology is high. Similarly, Ashby [2000] needs dedicated experimental data to develop his analytical value functions. Er and Dias [2000] develop a user interface for facilitating the use of their rule-based methodology, differently form the knowledge based selection approach (e.g. Albiñana and Vila [2012]). Giachetti [1998] make an interactive graphical user interface for the fuzzy logic implementation. The impact of product requirements' precision on the process selection is lower on the less quantitative (based on archival data) or qualitative methodologies. On the other hand, product requirements' precision is heavily influencing the quantitative ones, for example in Ashby [2000] by selecting criteria and targets of the value functions. The procedures based on fuzzy logic are highly influenced by product requirements precision, having a high impacting on the manufacturing process compatibility ranking.

In Table 8.6 the CoDeO framework is compared with other reported methods of optimization. Generally, the different investigative approaches are strictly related to the manufacturing process to be analysed. CoDeO target processes are forging, casting and additive layer manufacturing, so the investigative approach can be analytical, numerical or experimental (depending on the models created during the Phase II). In the literature, Caporalli et al. [1998] investigate hot forging process, using numerical (FEM simulation) and experimental methodologies, for minimizing the flow stress of the hot forging operation. Investigating two manufacturing lines (one producing a forging tool, another producing a workpiece though machining, annealing and forging), Denkena et al. [2011] use both analytical and experimental approaches (derived empirical formulas) for modelling the objective functions for an evolutionary algorithm. Sardinas et al. [2006] use an analytical approach for optimizing a single-pass turning process applying a GA. Using a Taguchi array (DoE), Davidson et al. [2008] optimize a flow forming process by experimental trials, maximizing the process (achievable tolerances) and product (microstructure) quality.

The optimization target is more related to the process dynamics than to the manufacturing cost in the experimental approaches. On the other hand the analytical approaches aim to optimize cost as the main target (Denkena et al. [2011], Sardinas et al. [2006], CoDeO). Differently form the mentioned approaches, CoDeOs optimize process feasibility, depending on analysed process characteristics, concurrently with the global manufacturing chain cost model. For example, turning force has been used as a trade-off (i.e. Pareto optimization) for the multi-criteria optimization of turning processes using a GA. Similarly to Sardinas et al. [2006], CoDeO's minimization of turning force makes the turning operation more feasible, as the minimization of costs tended to increase the machining parameters. In contrast, Denkena et al. [2011] use an expression of the product quality dependent on the tolerances achievable in the machining process that together with the total cost and leading time formulas achieve a multi-criteria optimization.

Table 8.6 illustrates that all the approaches target the optimization process parameters of one or more primary shaping processes and/or machining operations. All approaches focused on the primary shaping process optimization (i.e. forming, casting), with the exception of Sardinas et al. [2006], which analyses only machining processes. Differently from the others, Caporalli et al. [1998] use tool and equipment design variables, optimizing the forming die shape and characteristics, while CoDeO optimizes simultaneously only process parameters and design variables. Denkena et al. [2011] also analyses and optimize complementary processes, modelling a heat treatment process (optimizing temperature and treating time). In other words, Denkena et al. [2011] approach is the only reported method that optimize overall the manufacturing chain. In contrast with Denkena et al. [2011], CoDeO offers greater flexibility because of its ability to select the best approaches using an appropriate analysis of the process (depending on the selected primary shaping process). The experimental approaches are less case adaptable, in comparison with the analytical ones.

8.4 Contributions and Limitations

The methodology components (ProGeMa3, DFCA, CoDeO) and their results has been qualitatively assessed in the previous sections. The first part of the methodology (ProGeMa3) has the most quantitative and algorithmic approach. In this part, the only subjective decision (for a NeNeShO user) consists of fuzzy logic weight selection and target requirements definition, although the latter show fundamental impact on the process selection results. The unclear definition of targets can compromise the process selection phase (e.g. Case Study III). At this initial stage, production volume, product design, machining time required, process chain complexity and material variants are approximated. In this case, extensive data about process and component candidates should be gathered (i.e. in this case, the company was unable to provide these data). The second (DFCA) and third (CoDeO) parts need more skills and knowledge to apply. However, their flexibilities allow the investigator to deal with almost any type of process and product combinations.

In conclusion, the developed framework is the only available methodology in the literature that connects process selection, modelling and optimization. In particular, the connection between the investigative approach and the selection of the cost model has not been previously reported. Differently from those reported in the literature, NeNeShO Pro gives quantitative solutions not limited to a single manufacturing process. The framework's flexibility makes it possible to consider a large number of candidate processes, before selecting the most suitable

Table 8.6: Comparison between CoDeO and process and design optimization papers in literature.

Process chain optimization	CoDeO	Caporalli et al. (1998)	Denkena et al. (2011)	Sardinas et al.(2006)	Davidson et al. (2008)
Target Process	Forging, Casting, AL manufacturing	Forging	Hot Forging	Machining	Flow Forming
Optimization variables	Process Parameters, Product Design Attributes	Process Variables, Tool and Equipment design	Process Parameters	Process Parameters	Process Parameters
Optimization target	Cost, Process Feasibility	Flow Stress minimization	Cost, Process Quality	Cost, Process Feasibility	Process Feasibility, Process Quality, Microstructure
Investigation approach	Analytical or Numerical or Experimental	Numerical and Experimental	Analytical and Experimental	Analytical	Experimental
Optimization Method	Evolutionary Algorithm, Design of Experiments	FEM	Evolutionary Algorithm	Evolutionary	Design of Experiments
Primary Shaping Process optimization	Yes	Yes	Yes	No	Yes
Machining Optimization	Yes	No	Yes	Yes	No
Complementary process optimization (e.g. heat treatment)	No	No	Yes	No	No
Chain Design Optimization	No	Yes	Yes	No	No
Approach Adaptability	High	Low	Medium	Medium	Low

investigative methodologies (technological and economical). The formal connection between process technological model (e.g. forming force prediction), process cost model and optimization techniques is also a novel contribution.

8.4.1 Contributions

In summary the following **contributions** and further work can be associated to the NeNeSho development:

1. NeNeShO has an holistic approach to manufacturing, adhering to the NNS manufacturing
2. The empirical validation of the methodology demonstrates its flexibility and efficacy, obtaining saving and actual industrial application.
3. The Phase I (ProGeMa3), dedicated to material and process selection, has the potential to be delivered as an interactive program. A program and a graphical user interface could be created to facilitate the usage for non-expert users. The methodology can be also applied to a CAD program, giving real-time information on the most feasible process.
4. The assumption of material constancy (i.e. material selected prior to process selection and kept constant throughout the remaining NeNeShO phases) resulted viable and effective in the application to case studies.
5. The case studies demonstrates the feasibility of including variants in size and materials in the process selection methodology.

8.4.2 Limitations

The application of the NeNeShO methodology is limited by hypothesis (as describeb in Section 1.2.7)) to defined material (i.e. metal) and shapes (e.g. excluding sheet metal forming).

However the proposed methodology has other some **limitations**:

- The availability of company information can constrain and limit the first part of the process selection methodology (Economic Opportunities Screening).
- Requirements definition impacts on both the ProGeMa3 (process selection) and DFCA (approach selection for determining the requirements feasibility).
- Complementary processes have not been taken into consideration due to their complexity and the difficulty of their modelling (e.g. heat treatments).
- Material selection is prior to process selection. Therefore, the material (as variable) does not interact with the process and product design in the next phases, despite that the material to be used is decisive into the process feasibility assessment (DFCA).
- Production volume variability (e.g. market related fluctuation) and its changes in relationship to any other modifications (e.g. cost reduction or quality improvement) are not taken into consideration.
- Quality enhancement is not taken into consideration as an optimization target, neither for process parameter nor for product design (e.g. increasing deformation can increase material strength and so a thickness reduction can be operated)
- Accuracy of process costs and other characteristics in the process selection phase (ProGeMa3) can influence the case study generation (so the other phases in cascade). The sensitivity of the latter cannot be generalized and needs to be investigated case by case (e.g. Case Study III).
- Customer needs or market influence have not been taken into consideration. Complexity of quantifying this kind of information makes difficult to include these characteristics in a quantitative methodology.

Chapter 9

Conclusion

NeNeShO Protocol is the first reported holistic approach that associates manufacturing process to product and material, assessing the process feasibility and operating a process parameters and product design optimization, according to the NNS approach (i.e. minimization of machining time and raw material usage).

The flexibility and generic nature of NeNeShO allows its potential application to a wide range of existing productions, although the methodology is not designed for assisting the manufacturing of component from an early design stage (given the difficulty of quantifying both the effect of a new design on requirements definition and the compatibly between a "free of constraints" shape and manufacturing process/material selection).

Regarding the generality of the NeNeShO, the first part (ProGeMa3) can be extended to different processes and material, meanwhile the second (DFCA) and the third (CoDeO) are specifically designed for being case sensitive and flexible. The application show effective results in Casting vs Forging vs Additive Layer Manufacturing dilemma, which is the basis of manufacturing chain innovation.

The ProGeMa3 methodology has been successfully applied to the case studies and can be potentially expanded to include ceramic and plastic materials, including their dedicated processes. Similarly, sheet manufacturing and continuous processes could be included and added into the ProSMa. The combination of selection matrix and fuzzy logic provides a very efficient mechanism for quickly focusing the process selection on a small number of potential candidates. The methodology has potential to be automated as an on-line service with a graphical user interface to facilitate its usage by non-expert users. Once the process databases have been created, the ProGeMa3 methodology reduces the amount of subjectivity in the process and consequently supports non expert-users.

Customer needs, market influence and potential quality enhancement (related to the application of different processes) are difficult to quantify during the selection stage, although they have a great impact on supply chain stability, production volume variation and requirements definition. The latter is particularly critical as it could lead to different results in the process selection. Complexity of quantifying this kind of information makes it difficult to include these characteristics in a quantitative methodology. In this sense, availability of information is also critical for the application of selection methodologies.

Some dedicated methodologies can be more effective and advantageous for selecting between processes of a single category (e.g. casting processes selection methodologies), including some aspects which they can specifically categorize (e.g. topology of undercuts for selecting casting processes). However, these methodologies are only useful in environments where process selection has already been applied or where the process selection is constrained, precluding the consideration of the applications of different process categories for an existing application. Restricted methodologies are also able to optimize not only process parameters, but also process equipment and tools (e.g. FEM or experimental expert system for forming processes).

CoDeO and DFCA enable to build a reliable model for assessing the feasibility and optimizing both economic and technological sides of a NNS manufacturing chain. CoDeO and DFCA do not redesign the whole manufacturing chain or the component, but only optimise the application of the new NNS process (selected by ProGeMa3) coherently with the existing technological, economic and design constraints.

Similarly to other general models, CoDeO and DFCA are of limited use to non-expert users, (given the work that is needed to identify models and develop their application with algorithms/experiments). In both CoDeO and DFCA, variable and target definition are critical for the optimization and feasibility assessment, however accordingly to NNS view, the minimization of machining time and raw material utilization give a guidance for its definition. Accordingly to the contributions and limitations (Section 8.4) the following recommendations can be made for continuing this research approach in NNS manufacturing:

1. Technological/economic feasibility assessment (DFCA) and process/product design optimization (CoDeO) can be used separately from process selection methodology (ProGeMa3). The first two can be used for every manufacturing process, independently form its nature, in combination with any material and product design. The developed and, in general, every process selection methodology should not be seen as an implementation tool (even if refined with experimental data). However, there is a need to scope a broad range of process (with effective and dynamic tools as ProGeMa3) to identify NNS opportunities (i.e. professional engineer).

2. Every process selection methodology (as ProGeMa3 does) should be developed for use as a non-expert tool. This allows users of every level to scan the NNS possibilities for better options to current practice. However NNS process feasibility assessment (technological and economic) and process/product design optimization need to be implemented by an expert user.

3. Lastly, this work demonstrates also how strong the connection is between modelling and optimization (DFCA link with CoDEO). This can be formalized to facilitate effective implementation and the multi-criteria optimization of NNS processes, depending on the process nature and its academic/industrial development. The process optimiza-

tion modelling is often kept separate for its economic and technological implementation, however this work demonstrates how they can be linked. A correct selection of approaches (between analytical, numerical and experimental) allow the optimization to be the natural successor of process implementation via application of the generated models and data.

Appendix A

Near Net Shape Manufacturing of Metal - Literature Survey

A.1 Theoretical Investigations Analytical

The following papers report analytical models of NNS processes. Chitkara and Bhutta [1995] develop an upper-bound model for predicting forming loads in splined shaft forging (relative to their reduction ratio) and compares the results with experimental trials. Similarly, upper-bound Netto et al. [1996] models have been developed for forging of spur gears Chitkara and Bhutta [1996] and crown gears Chitkara and Kim [2001]. In a slightly different approach, Chitkara and Kim [1996] use upper-bound and velocity field (i.e. various forging rate) for predicting loads in forging of gear coupling. Netto et al. [1996] deploy a turbulent fluid flow, heat transfer and solidification model, investigating the strip casting dynamic and nozzle shape optimization. Kwak and Doumanidis [2002] introduce a closed loop controller for optimizing material deposition in thermally scanned welding, extendable to other welding technologies. Jeon and Kim [1999] compare two different analytic methods for simulating hot isostatic pressing and verifying them through a combination of FEM and previous experimental

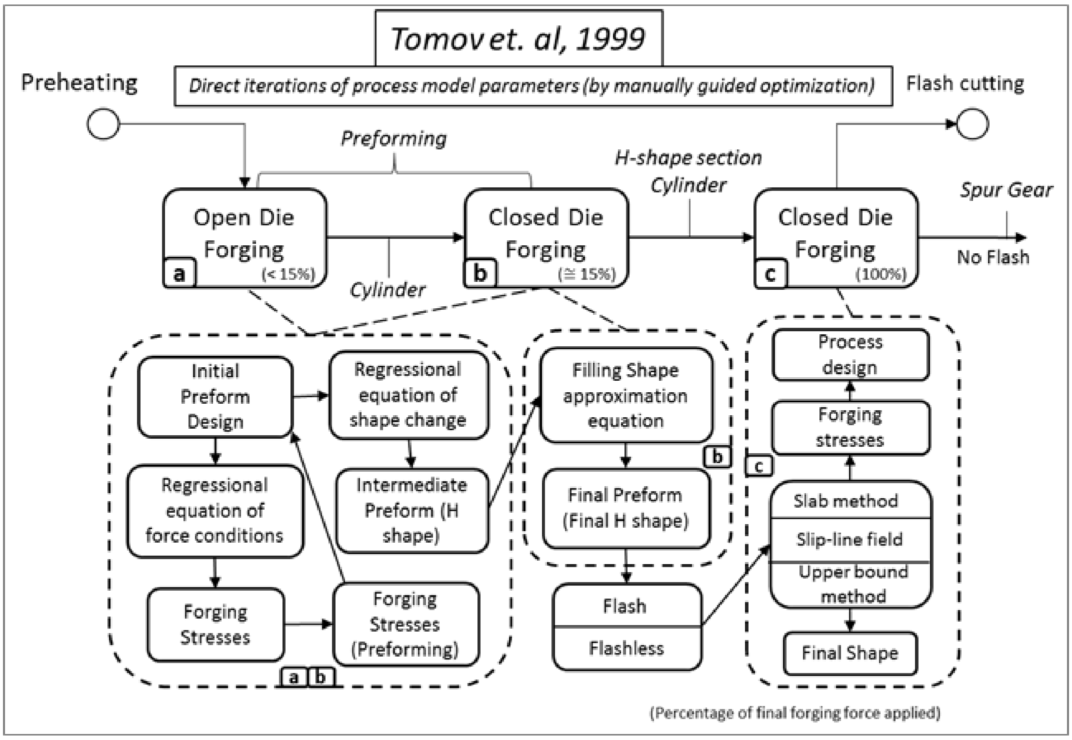


Figure A.1: Schematization of Tomov and Gagov [1999] procedure for analytical optimization of forging process.

trials reported in the literature. Tomov and Gagov [1999] (Figure A.1) optimize the preform design of spur gears. The authors model, analytically, both the preliminary open die forgings operations and the final precision forging, correlating all manufacturing steps with preform dimensioning. Castro et al. [2004] (Figure A.2) apply a genetic algorithm optimization to a numerical model, simulating a hot upset forging process. The evolutionary strategy provides process parameters and preform design optimization (described by a polynomial function). This approach is notable for its linking of process and resource optimization with process parameters and product design.

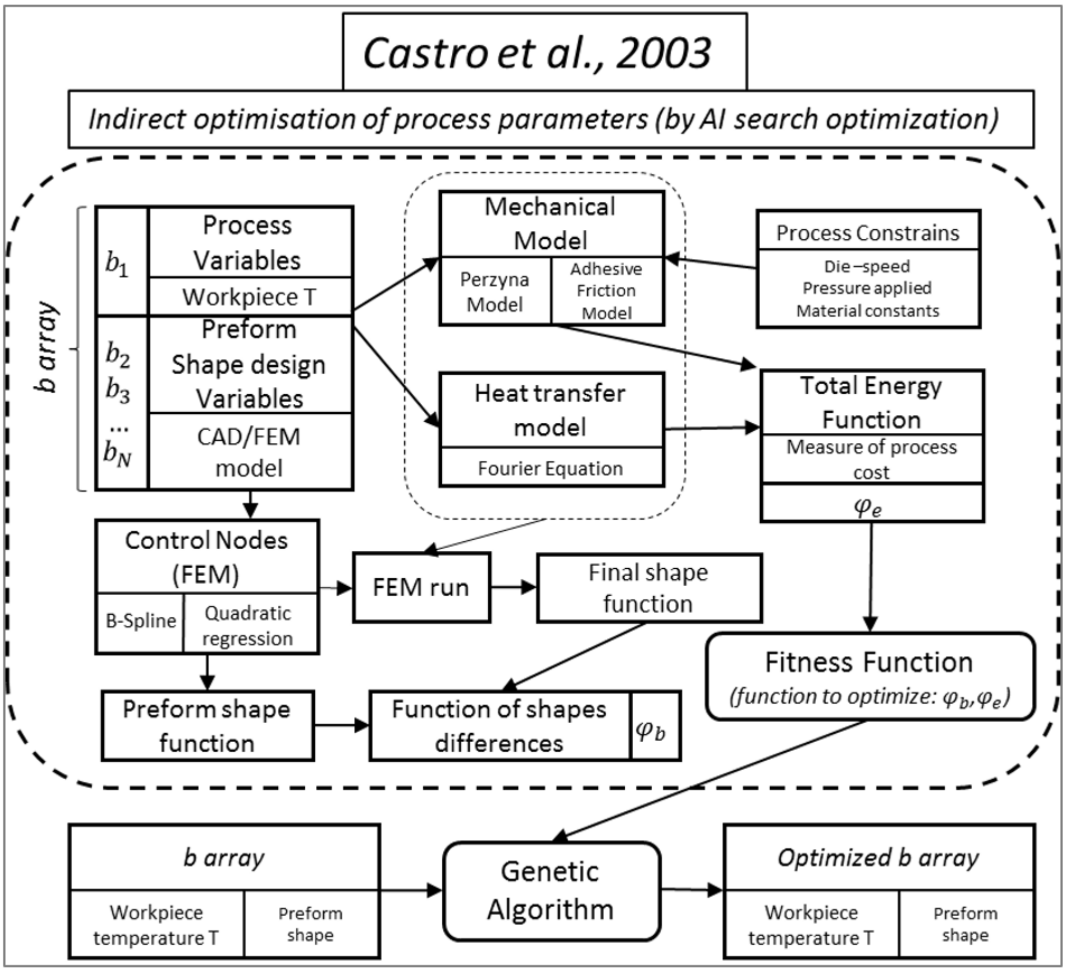


Figure A.2: Schematization of the Castro et al. [2004] Genetic Algorithm for optimizing closed hot die forging process in terms of preform shape and process temperature.

A.2 Theoretical Investigations Numerical

The following papers report numerical models of NNS processes. The emergence of this category of NNS investigation into a practical tools that could support multiphysics models can be seen in the work of Hwang and Stoehr [1988] who develop a solidification model for casting processes that included turbulent viscosity, surface tension and marker reduction scheme of molten metal, combining Lagrangian and Eulerian approaches. Similar complexity of modeling is used in simulating isothermal forging process, Morita et al. [1991] for optimize die design and preform positioning of turbine blade. Comparing to the classic forging process, the authors observe the superior properties of isothermal forged component (in terms of defects, mechanical and material properties and decreasing machining allowance). Li [1995] uses finite elements for modeling the electromagnetic recirculation process during casting. Takemasu et al. [1996] investigate precision forging process of connecting rods. Using material flow simulation, the authors optimized the preform design in this application (volumes definition and the effectiveness of die filling process are critical in precision forming). Initially they optimized the component by parts, dividing the rod in regions, before subsequently proposing a new preform design. Mamalis et al. [1998] compare implicit and explicit approaches to modeling precision die forging. They concluded that implicit code results are more accurate, although that computational cost is higher. Okada et al. [2003] deploy numerical models for forging of semi-solid alloys and validates them with experimental results. The aim is to characterize the Al-Al3Ni flow and deformation in semi-solid state forging. Kim et al. [2005a] investigate numerically a centrifugal casting investment process (or centrifuging casting) of turbocharger rotors (Ti-Al alloy). Simulation provides information about mold filling, which, correlate well with experimental trials and can be used to resolve production problems such as the incomplete filling of dies. Park et al. [2007] develop a bi-dimensional finite element model for characterize multistage forging of automotive parts (joint). The numerical models aim is to develop a reliable forming process chain as well as to establish process parameters and stress analysis for a correct process design. Yuan et al. [2007] (Figure A.3) deploy a model for simulating hot isostatic pressing of axial-symmetric components. The tool design has been tested for obtaining dimensional proprieties of component and again experimental trials show good agreement between predicted and real geometries.

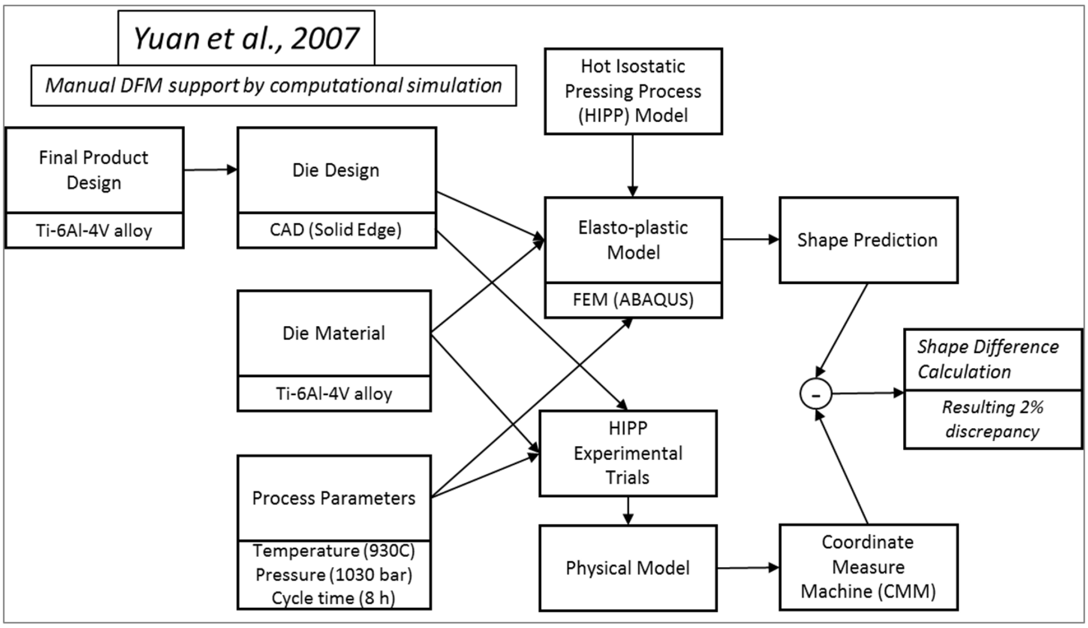


Figure A.3: Yuan et al. [2007] numerical investigation scheme for evaluating hot isostatic pressing final shape prediction through FEM.

A.3 DFM Methodologies

The following papers report Design for X methodologies relevant to NNS processes. Chu et al. [1993] deploy a skeleton-based design analysis to extract topological information from a 3D model (Euler characteristics and connectivity). In this way, product features information are digitalized and computed through a dedicated algorithm. Using a heuristic knowledge base database, product design feasibility can be analysed for different casting and forming technologies. De Sam Lazaro et al. [1993] develop a feature recognition program for sheet metal parts. Program rules are able to represent sheet features and so represent a simple design as a digital object. This allows a knowledge base system to be configured, adapting DFM rules for this specific case. Using this program, multi stage forging of sheet component can be also evaluated and to provide feedback to the designer. Caporalli et al. [1998] (Figure A.4) report a CAD/FEM based Expert System that enables process design optimization for manufacturing by a precision hot forging process. Starting from a part design, the system applies dedicated NNS rules (e.g. minimizing machining allowances, selection of parting line, radii, drafts and fillets selection) and modifies the part design. After this forging sequence (to check the designs preforms) is created using either the jobs similarity with previous routes or generated, according to selected criteria and matched to material, size and geometry of the part. Lastly, a die design is generated, considering preforms geometry, thermal expansion, and the use of standardized tools and inserts. Yin et al. [2001] present a virtual prototyping approach for evaluating the feasibility of mold casting. Framework evaluates geometric mouldability of the component by recognizing and evaluating undercut features. The algorithm is capable of recognizing undercut features and giving multiple interpretations based on volume decomposition. The component volume is decomposed into cells in order to evaluate parting directions and feasibility. Konak et al. [2003] estimate shrinkage in hot isostatic pressing using a neural net approach to create a predictive model based on industrial data (regression analysis). Medellin et al. [2008] develop a decomposition and optimization procedure (OctoTree) from a 3D model, which provides a subdivision of component into different sizes of cube. After stability analysis, an assembly sequence is generated and a robotic cell used to construct the component by collocating and binding the singular cubic volumes. Final component needs to be post-machined in order to obtain curve surfaces. Löwer et al. [2015] review and deploy strategy for substituting conventional material (metal and plastic) and process. They identify and assess the technical, ecological and economic feasibility of this approach and use a systematic approach for matching technical requirements with biological characteristics.

A.4 NNS Reviews

The following papers review NNS processes methodologies and models: Doege and Thalemann [1989] approach NNS by reviewing metal forming technologies for several applications (including squeeze casting and rolling). Existing technologies substitution (mainly machining)

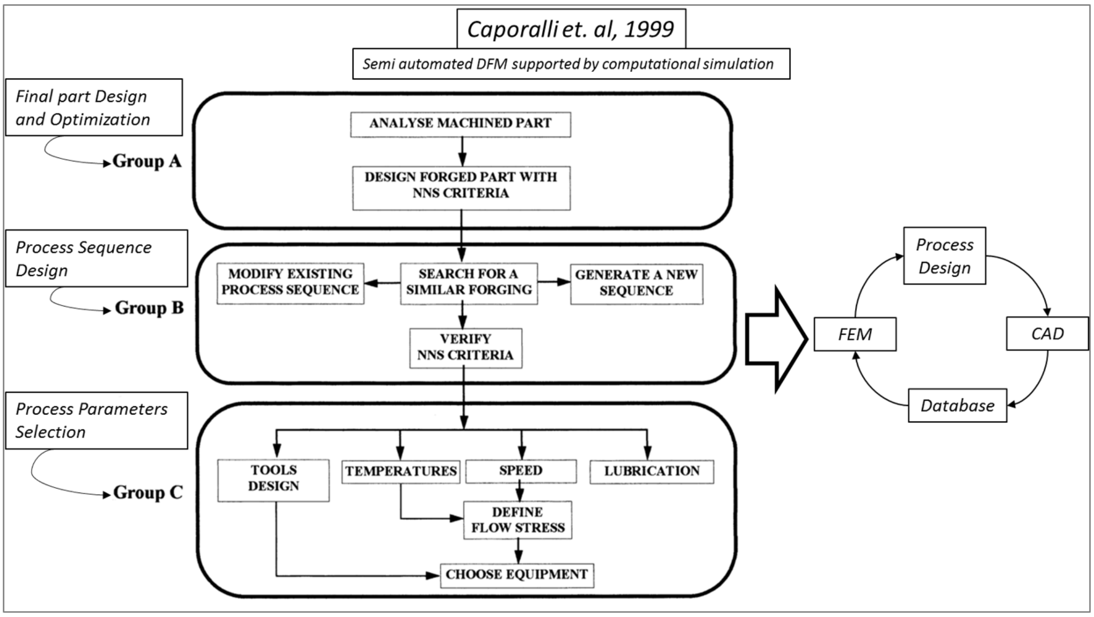


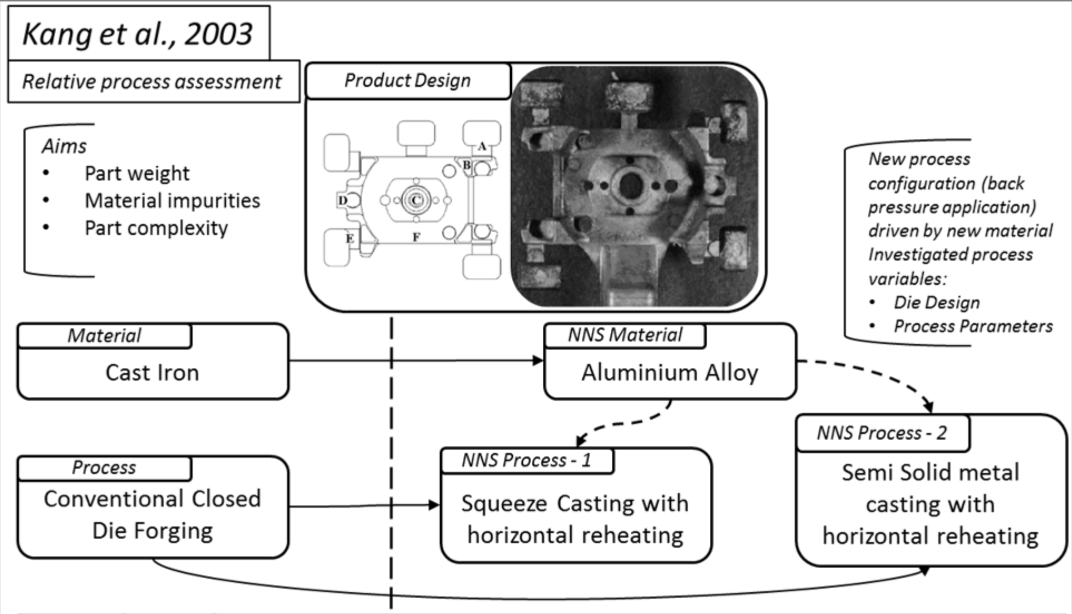
Figure A.4: Caporalli et al. [1998] Expert System flowchart with application to process design components.

are explained and justified by the possibility of obtaining ready-to-install products. Kudo [1990] surveys and summarizes previous industrial approaches and frameworks for quality control, comparing them with NNS approach. The author provides both general models and examples in forming and forging environments. Interaction between process controls (equipment and process parameters), workforce and the process chain workflows design is detailed. Altan and Miller [1990] review previous design-for-forging (hot, cold, warm and sheet forging) and design-for-manufacturing approaches. In the latter the author summarizes design-for-net-shape-methodologies and application, giving fundamental guidelines and definitions. Moriguchi [1992] discusses the impact of cold forging (particularly injection forging) on production of gears and drive train components, including impact of CAE on process output. Similarly, Siegert et al. [1997] summarize approaches for precision forming of aluminum and steel. The authors review die design and process parameter optimization (using FEM) for hot forging of connecting rods and helical gears. Similarly, Yoshimura and Tanaka [2000] review precision forging methods for similar materials and details their possible applications. Kruth et al. [1998] discuss possible future applications of additive layer manufacturing techniques in manufacturing production, presenting them as NNS processes. Doege and Bohnsack [2000] evaluate the impact of innovative equipment and device optimization (particularly closing devices) on hot forging performances (e.g. the reduction of forging loads). Dean [2000] summarizes the benefit of several innovative forming technologies (i.e orbital, precision and closed die-forging) on spur and helical gears. The author reviews the impacts of these new technologies on final product properties and manufacturing chains. Mac Donald and Hashmi [2002] review the impact of bulge-forming on tubes production, including process simulation and optimization. Mudge and Wald [2007] synthesize possible application for freeform technology, including repairing, cladding and components manufacturing. Yamamoto et al. [2010] investigate the potential of the Armstrong process, which provides titanium powders for sintering process. Mechanical properties and final densities obtained by the authors in previous experiments are compared as well as those reported for different powder forming technologies.

A.5 Empirical Investigations - Experimental

The following papers detail experimental investigations into NNS processes: a number of authors have reported investigations into the potential of semi-solid metal casting (SSMC) process for NNS applications: Kapranos et al. [2000] compare SSMC and isothermal forging capabilities for aluminum alloys, mainly in terms of productivity and defects avoidance. Kang et al. [2003] (Figure A.5) examine different reheating methods for the SSMC of aluminum components, comparing the resulting microstructure, mechanical and surface proprieties. Kapranos et al. (Kapranos et al. 2000) optimize a thixoforming die for minimizing defects in the production of end plates for electric motors.

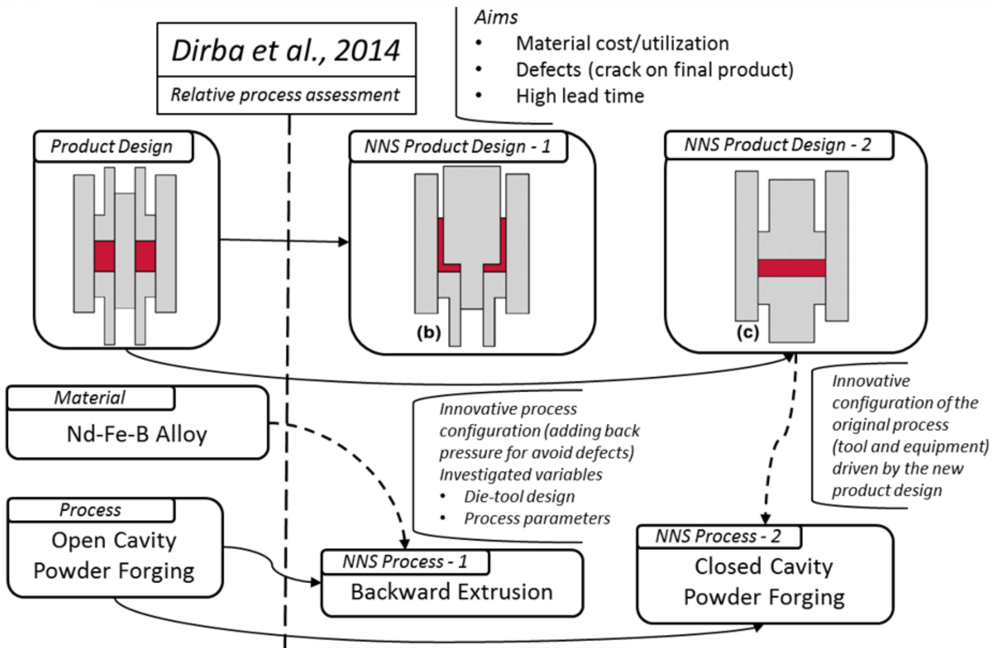
Yin et al. [2010] develop and test horizontal-type induction heating for SSMC. Mechanical properties have been evaluated varying process parameters for a novel reheating method.



NNS process 1	NNS process 2	Comparison Levels between old Process and Near Net Shape Processes ✓, improved; ×, worsen; N, unknown; =, unchanged
N	N	Raw material cost/utilization
✓	✓	Material Microstructure (uniform microstructure, fine grain size and absence of texture)
✓	✓	Mechanical Proprieties (ultimate tensile strength depends on process parameters selection, hardness is highest in semi solid metal casting, wear resistance is highest in squeeze casting)
✓	✓	Design Functionality (weight loss due to lighter material)
N	N	Process Cost
N	N	Process Efficiency
✓	✓	Process Reliability (no defects and cavities with back pressure application)
×	×	Process Complexity

Figure A.5: Schematic representation of Kang et al. [2003] experimental paper on aluminum carter squeeze casting (old process, material, product design and new NNS tested process and material; investigation aims; NNS variables developments and comparison levels between new and old NNS process).

Investigating rheocasting, Curle [2010] report the results of microstructural analysis of Aluminum alloys produced by a number of different processes. Similarly other authors have reported material characteristics for several applications, characterizing materials behaviour, or targeting material properties, through new or existent processes. Gupta and Ling [1999] investigate Al-Si alloy properties (mechanical, thermal and fractural behaviour) and microstructure arising from production of ingots using a disintegrated melt deposition technique. Material properties are also reported during an investigation of the investment casting of automotive components (turbocharger and exhaust valves), in which Sung and Kim [2006] analyse



NNS process 1	NNS process 2	Comparison Levels between old Process and Near Net Shape Processes ✓, improved; ×, worsen; N, unknown; =, unchanged
✓	✓	Raw material cost/utilization (no part to cut due to defects absence)
=	=	Material Microstructure
N	N	Mechanical Proprieties
✓	✓	Design Functionality (increasing of magnetic proprieties of the components)
N	N	Process Cost
N	N	Process Efficiency
✓	✓	Process Reliability (no defects and cavities with back pressure application)
✓	N	Process Complexity

Figure A.6: Schematic representation of Dirba et al. [2014] experimental paper on magnet forging (old process, material, product design and new NNS tested processes and product designs; investigation motives and targets, NNS variables developments; comparison levels between old and NNS process).

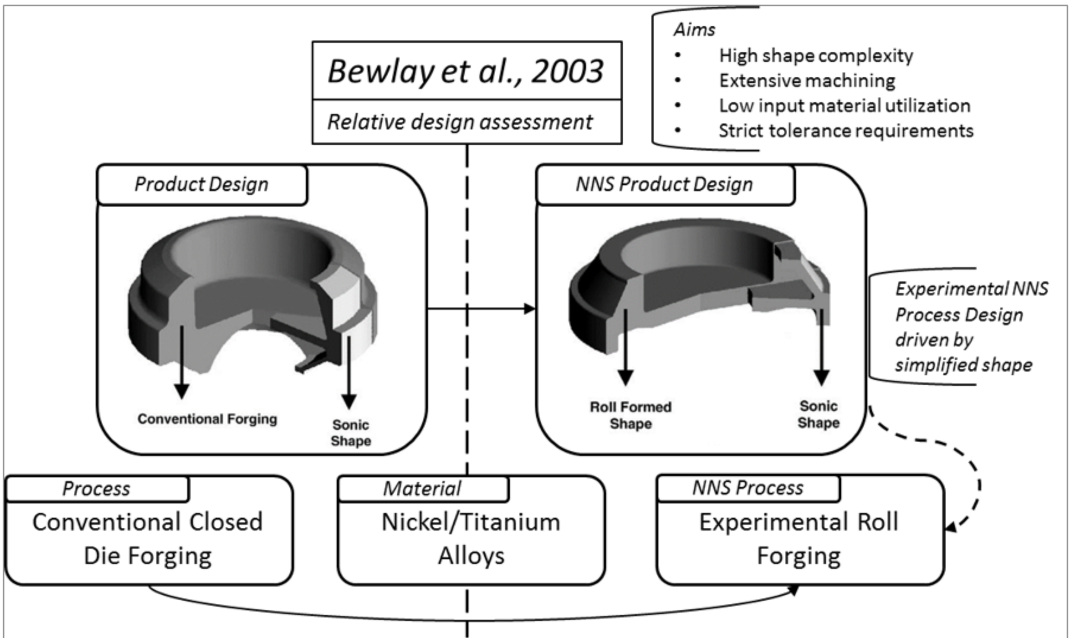
the resulting TiAl microstructure (a-case formation) and fluidity.

For hot rolling, Arribas et al. [2008] investigate dynamic and static recrystallization (dependent on grain size and deformation conditions during the process) as well as particles/precipitates inclusion of Ti alloys. Köhl et al. [2009] develop a variant of MIM (Metal Injection Molding) for producing highly porous NiTi medical implants. Microstructure and mechanical properties control are performed using space-holders techniques (i.e. testing different material powders, injected with the metal and after chemically removed). Qi et al. [2009] study heat treatment effects on microstructure and mechanical properties during a laser deposition process of Inconel alloys. Rapid manufacturing (a.k.a. additive layer manufacturing) technologies have also been investigated by other authors, mainly treating them as NNS processes for defined components geometries or materials. Lewis and Schlienger [2000] summarize the trials for direct light fabrication technology, including final components properties. Milewski et al. [1998] use a 5-axis powder deposition to produce complex geometries from 316 stainless steel direct light fabrication (selective laser melting). Investigating the production of NNS Inconel turbine components, Qi et al. [2009] deploy a Design of Experiments approach for systematically assessing the process parameters in laser net shape manufacturing (melting blown powder technology). Janney et al. [1998] investigates a powder forging process (Gelcast) for producing tool steel and ceramic machinable green parts. Krishna et al. [2007] experiment with LENS system (freeform fabrication) for NiTi alloys, displaying final mechanical and microstructural properties. Taminger and Hafley [2006] investigate Electron Beam Forming process for aerospace components. Working with forming and forging processes, Hartley [1995] investigates hot extrusion for lithium alloys, for aerospace application. The author tested different working condition and assessed the savings for the final machining step. Also Dirba et al. [2014] (Figure 10) use similar technology with low deformable alloys (Nd-Fe-B) for magnet production. Magnetic proprieties have been investigated as well as temperature stability and mechanical characteristics with the aim of enabling material waste reduction. Similar investigation has been conducted by Hinz et al. [2003] for radially oriented magnets. Shi et al. [2007] demonstrate the advantages of isothermal closed die forging for impeller production, using FEM analysis and experimental trials. Julien and Després [2006] develop a novel low pressure metal injection molding (LMIM), process that is economic for low batch sizes. They report the application of the process to production of aerospace turbine blades and investigate the microstructure obtained. Working on strip casting, Liang et al. [1997] investigate edge containment for Zn-10Al alloy. Bewlay et al. [2003] develop roll forming for engine disk, comparing its microstructure, mechanical properties and material wastage with conventional hot forging process (Figure A.7). Park et al. [2009] investigate the machining of turbine blades and report the experimental optimization for tool positioning in the context of NNS production.

A.6 Empirical Investigations - Case study

The following papers report empirical results for NNS processes based on experimental investigations. Onodera and Sawai [1992] (Figure A.8) illustrates two example of NNS applications in automotive industry (for spline shaft and joint productions), and introduce a general production scheme (inspired by Ishikawa trees schematization) that supports quality control functions.

Maegaard [1992] illustrates the difference in process design (die and punch) and final quality for cold forging and backward extrusion, in the context of small batch production. Hirt et al. [1997] investigate potentiality of thixoforming for automotive components weight reduction, developing simulation and production optimization (process parameters). Quality, reliability and potential production volume of components are investigated in an industrial environment (where production is assisted by robotic device). Many authors introduce case studies of rapid prototyping processes as NNS application, for example Schlienger et al. [1998] for LENS, Milewski et al. [2000] and Lewis and Schlienger [2000] for Laser Deposition and Bak [2003] for direct metal casting. Blackwell and Wisbey [2005] compare final properties (mechanical properties and microstructure) using different LENS laser types and power compositions. Similarly, Kottman et al. [2015] assess the feasibility of laser hot wire application for aerospace components (titanium). LaSalle and Zedalis [1999] explain capabilities of MIM for high production volume and low weight component. Groenbaek and Birker [2000] discuss the design about dies containers and the way in which die life-life increases impact on productivity. Dahlman and Escursell [2004] introduce a tool cooling system for turning operation,



NNS process	Comparison Levels between old Process and Near Net Shape Processes ✓, improved; ×, worsen; N, unknown; =, unchanged
✓	Raw material cost/utilization
✓	Material Microstructure (uniform microstructure, fine grain size and absence of texture)
✓	Mechanical Proprieties (no anisotropy, improved tensile strength at low temperature, similar creep behavior)
✓	Design Functionality (10-30% forging weight reduction, increase in signal-to-noise for synthetic flaws of circa 20 dB, lower ultrasonic noise and higher inspectability)
N	Process Cost
N	Process Efficiency and Reliability
N	Machining Cost
×	Process Complexity

Figure A.7: Schematic representation of Bewlay et al. [2003] experimental paper on engine disk roll forging (old process, material, product design and new NNS tested process and product designs, investigation motives and Targets, NNS variables developments, comparison levels between old and NNS process).

which results in an increase in productivity. Douglas and Kuhlmann [2000] illustrate some sensible improvement in material waste and quality, using precision forging processes. Cai et al. [2004] test different die design and lubrication for the precision forging of gears. They examine the influences of different designs on metal flow and load requirements through experiments and finite element simulation. Friction factor has been evaluated experimentally and numerically during all stages of forging process. Friction distribution is shown to have a strong influence on the process of die filling. Klug et al. [2004] synthetize different technologies (forging, forming and casting) for economic production of titanium components and its impact on manufacturing of military equipment.

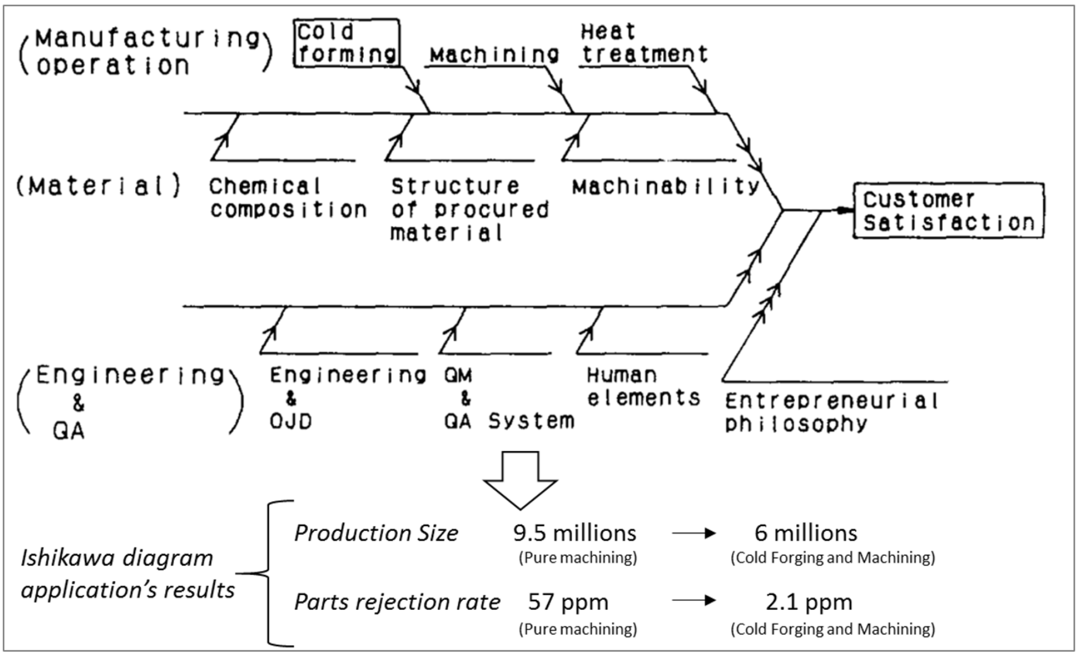
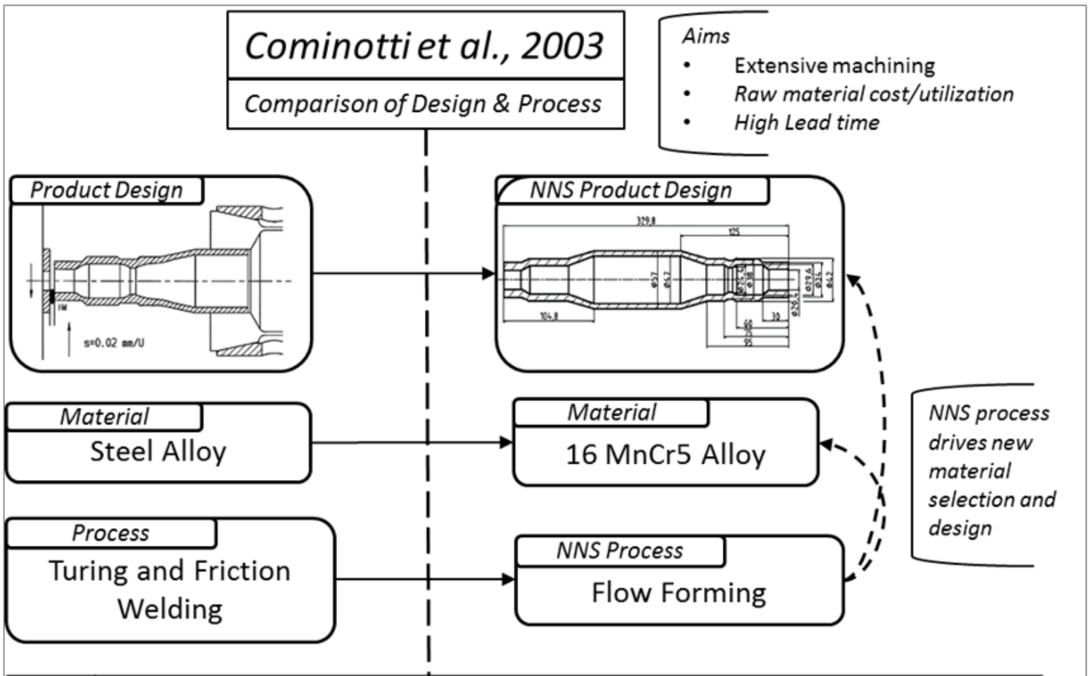


Figure A.8: Onodera and Sawai [1992]'s Ishikawa diagram for cold forging and results of its application

Behrens et al. [2007] and Vilotić et al. [2007] both investigate the impact of precision (crankshafts, rods and gears) and cold forging (roller bearings and cardan joints), respectively for the production of automotive components. Cominotti and Gentili [2008] (Figure A.9) have compared flow forming and classical machining for a shaft production. The authors illustrate the dif-



NNS process	Comparison Levels between old Process and Near Net Shape Processes ✓, improved; ×, worsen; N, unknown; =, unchanged
✓	Raw material cost (-65%) and utilization (almost no material wastage vs 3.5 kg scrap made by machining)
N	Material Microstructure
✓	Mechanical Proprieties (cold plastic deformation)
=	Design Functionality
✓	Process Costs (400,000 part per year production volume: labor cost -68%, set-up cost -21%, labor cost -68%, amortization +37.5%, total cost -33%)
✓	Process Efficiency
✓	Process Reliability (shortening the process chain and avoiding welding process)
✓	Process Complexity (no welding)

Figure A.9: Schematic representation of Cominotti and Gentili [2008] experimental paper (old process, material, product design and new NNS tested process, investigation motives and Targets, NNS variables developments and comparison levels).

ferent process chains (including technological advantages and disadvantages) and detail their impact on the different aspects of cost. A differential cost analysis is presented that considers flow forming as economic alternative to classic machining.

A.7 Empirical Investigations - Quantitative

The following papers report quantitative relationships and data generated by NNS process case studies. Tateno [1984] investigate the differential processes capabilities for casting and forging process in the case of large size part production. Its investigation compares different materials and technological output, generated by different processes. Bhatkal and Hannibal [1999] describes one of the few differential cost analysis and production capabilities mapping, for comparing MIM and Investment casting. Information about several components have been gathered using a technical cost modeling approach. A complete economic evaluation has been made in both cases and its sensitivity has been mapped by varying design and process parameters. Campbell [2000] evaluate casting potentialities for several processes (sand casting, lost foam, lost wax, high pressure and low pressure/gravity casting). The dimensional variability of parts was investigated in relation to process variables, production dimensions and material. The author has been able to rank casting process regarding their potential dimensional accuracy (depending on casting dimensions). Table A.1 summarizes the quantitative approaches methodologies and results.

		Campbell (2000)	Tateno et al. (1985)	Bhatkal et al. (1999)
Investigated Variables	*Materials*	Zinc, Magnesium, Aluminum alloy, Cast Iron, Steel Alloy	Steel, Cast Iron	Pure Nickel
	Processes	Casting processes (pressure die, low pressure/gravity die, high and low tech sand casting, lost foam, lost wax)	Open die Forging, Sand Casting, Ingot manufacturing chain	Metal Injection Molding (MIM), Investment Casting
	Product Designs	Nominal casting sizes (10-1000 mm)	Large sizes component (nuclear and chemical pressure vessels, rotor shafts, water turbine runners)	Lightweight (120 gr) and low thickness (3 mm) components
Tools		Cause- effect matrix, Statistical Survey (variability dependency on casting length	Forging/casting processes chains evolution, process capability mapping, process defects mapping	TCM (Technical cost modelling), Differential cost analysis, process mapping
Investigated Effects		Dimensional variability (mm, %), Casting accuracy (mm,%)	Quality improvements, Process chains (casting and forging) modification impact on equipment, tools and process parameters	Process costs (Direct/Indirect) modelling, Cost sensitivity to production volume, process variables and part weight, Differential impact (%) of voices of cost
Impact on NNS technology		Categorizing casting productions on accuracy and dimensional variability (evaluating and quantifying impact factors)	Identify best casting and forging processes relating to big size components production	At equivalent (or satisfactory) levels of processes' performances, differential costa analysis need to be structured for being a comprehensive and adaptive decision tool
Main Conclusions		Lost wax is the most accurate only for small sizes castings. Pressure die and high quality sand have greatest reproducibility for all dimensions and materials)	Pointing out progress made in mega parts production, including technical details for casting and forging (process chains and parameters) and managerial aspects (R&D)	MIM in convenient over investment casting only for a very high production volume (million pieces magnitude) for the specific product requirements

Table A.1: Quantitative approaches: investigated variables, tools, investigated effects, impact on NNS and conclusions.

Appendix B

Manufacturing Process Review

B.1 Casting

Sand Casting *Process description*: Expandable mold and permanent pattern process. Sand casting consists of (a) placing a pattern (having the shape of the desired casting) in sand to make an imprint, (b) incorporating a gating system, (c) removing the pattern and filling the mold cavity with molten metal, (d) allowing the metal to cool until it solidifies, (e) breaking away the sand mold, and (f) removing the casting [Kalpakjian and Schimd, 2009].
Process variants: Green sand casting (most common and cheapest, although low mold strength), Dry sand (core boxes are used instead of patterns and an oven is used to cure the mould, expensive and time consuming.) Skin-dried sand (the mould is dried to a certain depth. Used in the casting of steels) [Swift and Booker, 2013].
Workable materials: Almost all metals, particularly ferrous and aluminium. Less suitable for lead, tin, zinc and titanium alloys. *Final product characteristic*s: High porosity and inclusions level that lead to poor mechanical characteristics. Poor surface roughness and tolerances. Material exceedance should be provided in pattern design for draft angles, solidification issues (fillet filling, etc.) and machining allowances.

Typical applications: Wide workable range of parts. High complexity parts feasible, although undercuts, bosses and thin walls (small cross-sections) are expensive or unfeasible to produce (engine blocks, manifolds, machine tool bases, pump housings, cylinder heads, crankshaft).

Vacuum Casting (V-Process) *Process description*: A particular pattern (match-plate or a cope and drag pattern) and flasks are used to enable vacuum suction thorough holes. A thin plastic sheet is placed over the casting pattern, where a vacuum suction causes the sheet to adhere to the surface of the pattern. This flask is placed over the casting pattern and filled with sand. Another thin plastic film is placed over the top of the mold and it adhered through vacuum suction form flask holes. The pattern is removed with vacuum pressure from the flask is still on. This causes the plastic film on the top to adhere to the top and the plastic film formerly on the pattern to adhere to the bottom. The procedure is repeated for the other half. The two halves are then assembled for the pouring of the casting. During the pouring of the casting, the molten metal easily burns away the plasti [Schuler, 1998].
Process variants: Vacuum generation system of pattern and flask.
Workable materials: (see *Sand Casting*)
Final product characteristics: No draft required. Tighter tolerances and better surface finish than sand casting. V-process is also slower and more expensive (vacuum generation) even if with lower sand pattern costs. Material utilisation is higher than sand casting.
Typical applications: Same categories of Sand Casting but with higher accuracy requirement.

Permanent Mold Casting This sub-section includes casting processes with permanent mold and permanent pattern, which uses a closed die as chamber for material solidification and external forces for melted metal flowing.

- **Gravity Die Casting**
  - *Process description*: Molten metal is poured under gravity into a pre-heated die,

where it solidifies. The die is then opened and the casting ejected. Also known as permanent mould casting[Swift and Booker, 2013].

- *Process variants*: Low pressure application: (< 1bar) for forcing the metal into the die (common only for wheels production). Slush casting: for creating hollow parts with thin walls without using a core. The molten metal is poured into the metal mold. After the desired thickness of solidified skin is obtained, the mold is inverted (or slung) and the remaining liquid metal is poured out. The mold halves then are opened and the casting is removed. Used for low melting point metal (zinc, tin and lead alloys) for decorative or ornamental parts[Kalpakjian and Schimd, 2009].
- *Workable materials*: Usually non-ferrous metals (usually copper, aluminium, magnesium). Less suitable for cast iron, lead, nickel, tin and zinc alloys. Carbon steel can be cast with graphite dies.
- *Final product characteristics*: Low porosity and inclusions levels. Good surface detail, tolerances and roughness. Good part mechanical properties (better than sand casting but worse than pressure casting processes).
- *Typical applications*: Low complexity parts in nonferrous material with high production volume (cylinder heads, engine connecting rods, pistons, gear and die blanks, gear housings, pipe fittings).

- **Vacuum Permanent Mold Casting**
  - *Process description*: The mold is held with a robot arm and immersed partially into molten metal, held in an induction furnace. The vacuum reduces the air pressure inside the mold to about two-thirds of atmospheric pressure, thus drawing the molten metal into the mold cavities through a gate in the bottom of the mold. Consequently, it begins to solidify within a very short time. After the mold is filled, it is withdrawn from the molten metal.

- *Process variants*: *CLA process* (melted in air), *CLV process* (melted in vacuum)

  Workable materials: Carbon steel, cast iron, magnesium and zinc alloys (CLA process). Reactive metals such as aluminium and titanium alloys (CLV process).

- *Final product characteristics*: Superior mechanical properties and properties uniformity compared to investment, shell mold and sand casting.

- *Typical applications*: Particularly suitable for thin-walled (0.75 mm) complex shapes. Typical parts made are superalloys gas-turbine components with walls as thin as 0.5 mm [Kalpakjian and Schimd, 2009] (marine components, sports equipment components, high voltage electric controls components, automotive components, pressure tight components for medical equipment, pneumatic, gas and hydraulic valves).

• **Pressure Die Casting**

- *Process description*: Molten metal is inserted into a metallic mould under very high pressures (100+ bar), where it solidifies. The die is then opened and the casting ejected [Swift and Booker, 2013]. To improve die life and to aid in rapid metal cooling (thereby reducing cycle time) dies usually are cooled by circulating water or oil through various passageways in the die block.

- *Process variants*: *Hot-chamber die casting*: a piston forces a certain volume of metal (15-35 MPa) into the die cavity through a gooseneck and nozzle. The metal is held under pressure until it solidifies in the die. In *Cold-chamber die casting*, molten metal is poured into the injection cylinder (shot chamber), which is not heated. The metal is forced into the die cavity by pressurization (20-70 MPa, up to 150 MPa). The machines may be horizontal or vertical, in which case the shot chamber is vertical.

- *Workable materials*: Low-melting-point alloys, such as zinc, magnesium, tin, and lead (hot-chamber). High-melting-point alloys of aluminium, magnesium, and copper feasible but less suitable for ferrous metals (cold-chamber).

- *Final product characteristics*: Lowest porosity in small casts, but gas entrapment issues in larger ones. Highest mechanical properties among casting processes. Dimensional accuracy and surface roughness achieved are also high. Low porosity compared with expandable casting processes.
- *Typical applications*: Low complexity part with required high strength and dimensional accuracy (automotive components (aluminium, zinc, magnesium alloys), electrical motor frames and housing, complex shapes with thin walls, parts requiring strength at elevated temperatures (aluminium alloys), plumbing fixtures, bushings (brass), power tools (zinc alloy)).

Shell Mold Casting *Process description*: Expendable mold and permanent pattern process. A heated metal pattern is placed over a box of thermosetting resin-coated sand. The box is inverted for a fixed time to cure the sand. The box is re-inverted and the excess sand falls out. The shell is then removed from the pattern and joined with the other half (previously made). They are supported in a flask by an inert material ready for casting [Swift and Booker, 2013].

Process variants: Pattern material, Composite mold generation (join shell with one mold produced by other processes). Workable materials: All metals except for lead, zinc, magnesium and titanium alloys.

Final product characteristics: Good dimensional accuracy and very high tolerances achievable. Sharper corners, thinner sections, smaller projections than possible with sand casting but undercuts and bosses are difficult.

Typical applications: Alternative to sand casting for high precision components (small mechanical parts, gear housings, cylinder heads, connecting rods, transmission components).

Plaster Mold Casting *Process description*: Expendable mold and permanent pattern process. A precision metal pattern (usually brass) generates the two-part mould, which is made of a gypsum slurry material. The mould is removed from the pattern and baked to remove the moisture. The molten metal is poured into the mould and allowed to cool. The mould is broken to remove the part [Swift and Booker, 2013].

Process variants: Antioch process (mold is dehydrated in an autoclave and then rehydrated in air). Workable materials: Limited to low melting temperature metals (aluminium, copper, zinc and magnesium alloys) due to degradation of the plaster mould at elevated temperatures.

Final product characteristics: Dimensional accuracy and uniform grain structure are superior to sand casting and obtained with less distortion. Good surface finishing and high tolerances. Problem of gas trapping due to non-porosity of the plaster can lead to high porosity.

Typical applications: Alternative to sand casting for more complex geometries and high precision, although it is limited for some alloys. Sharp corners, undercuts and bosses can be cast easily (pump impellers, waveguide components, gear blanks, valve parts, moulds for plastic and rubber processing).

Ceramic Mold Casting *Process description*: A precision pattern generates the mould, which is coated with a ceramic slurry. The mould is dried and baked. The molten metal is then poured into the mould and allowed to solidify. The mould is broken to remove the part.

*Process variant*s: *Shaw process* (the ceramic facings are backed by fireclay to give strength to the mold; the facings then are assembled into a complete mold, ready to be poured), ceramic slurry composition and curing mechanism, pattern materials.

Workable materials: All metals, but to a lesser degree aluminium, magnesium, zinc, tin and copper alloys. Final product characteristics: High dimensional accuracy and high surface finish obtained. Low mechanical properties and moderate porosity can be obtained.

Typical applications: Alternative to plaster mold casting for all alloy (all types of dies and moulds for other casting and forming processes, cutting tool blanks, pump impellers, aerospace and atomic reactor components).

Centrifugal Casting *Process description*: Semi-permanent or expandable mold processes, described in this section, use centrifugal force, as melted material flowings moving force, solidification catalyser and quality enhancing instrument.

Workable materials: Most metals suitable for static casting are suitable for centrifugal casting: all steels, iron, copper, aluminium and nickel alloys.

Process variants: *True-Centrifugal casting*, *Semi-centrifugal casting*, *Centrifuge casting.*

- **True-Centrifugal Casting**
  - *Process description*: Molten metal is poured into a high-speed rotating mould (300 3000 rpm depending on diameter) until solidification takes place. The axis of rotation is usually horizontal, but may be vertical for short work pieces [Swift and Booker, 2013].
  - *Process variants*: Semi-permanent or expendable moulds.
  - *Workable materials*: (see *Centrifugal Casting*).
  - *Final product characteristics*: Castings with good quality, dimensional accuracy, and external surface detail are produced by this process. Properties of castings vary by distance from the axis of rotation. Mechanical properties and grains structure are comparable with forged product ones. Due to centrifugal force increasing at the periphery, inner surface is less dense in molten state and collect all impurities and low density, so it is usually machined away. Lowest porosity among casting processes.
  - *Typical applications*: Cylindrical components with high duty applications. Usually big size component (pipes, flywheel, bearing liners, pressure vessels, bushings,

engine-cylinder liners, bearing rings with or without flanges, and street lampposts).

- **Semi-Centrifugal Casting**
  - *Process description*: Same dynamic as True-Centrifugal casting but used to cast parts with radial symmetry in a vertical axis of rotation at low speeds. In semi-centrifugal casting the mold is filled completely with molten metal, which is supplied to the casting through a central sprue. Castings manufactured by this process will possess rotational symmetry.
  - *Process variants*: Semi-permanent or expendable moulds.
  - *Workable materials*: (see *Centrifugal Casting*).
  - *Final product characteristics*: (see *True-Centrifugal Casting*).
  - *Typical applications*: Axisymmetric component for high duty applications with complex outer surface details (brake drums, pulley wheels, train wheels, flywheel, bearing liners, nozzles, gear blanks).
- **Centrifuge Casting**
  - *Process description*: A number of moulds are arranged radially around a central sprue. Molten metal is poured into the sprue and is forced into the mould cavities by centrifugal force due to high-speed rotation [Kalpakjian and Schimd, 2009].
  - *Process variants*: Expendable or permanent pattern and mold.
  - *Workable materials*: (see *Centrifugal Casting*).
  - *Final product characteristics*: properties of the castings can vary by distance from the axis of rotation, as in True-Centrifugal casting. Used for reducing porosity and increasing strength, surface finish and increasing homogeneity of casted parts.
  - *Typical applications*: Medium to high complexity and small dimensions part with high duty requirements (small gears and mainly parts of intricate detail).

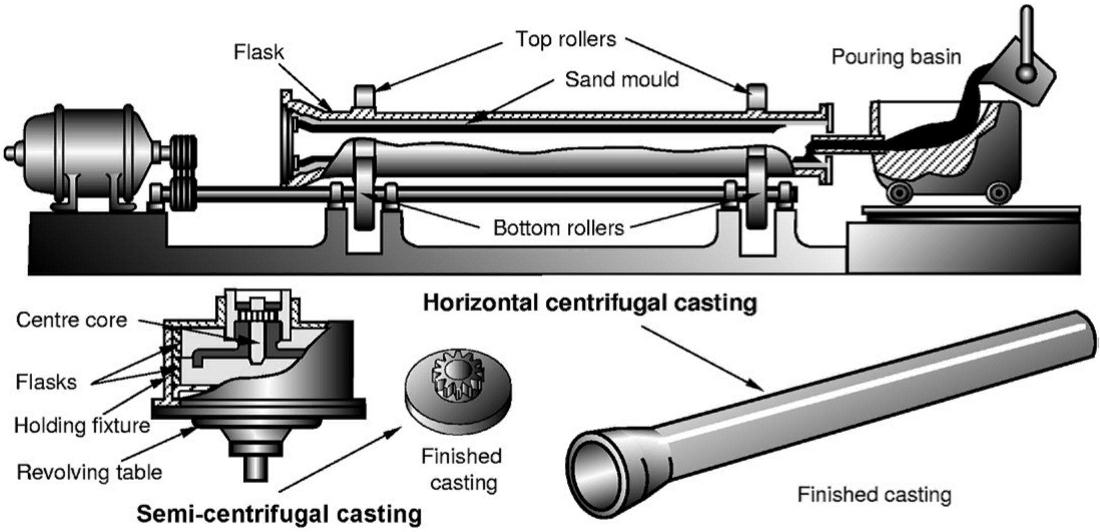


Figure B.1: Schematic of True Centrifugal Casting and Semi-Centrifugal Casting processes [Swift and Booker, 2013].

B.2 Forming

Forging *Process description*: Metal blank is formed into the required shape by the application of pressure or impact forces causing plastic deformation using a press or hammer in a single or a series of dies. Processes can be performed at different temperatures, which defines hot forging (above recrystallization temperature), cold forging (room temperature) and warm forging (intermediate temperatures range). Temperature decision is critical for process parameters design, material selection and product quality.

Workable materials: Forgeability of materials important; must be ductile at forging temperature. Relative forgeability is as follows, with easiest to forge first: aluminium alloys, magnesium alloys, copper alloys, carbon steels, low alloy steels, stainless steels, titanium alloys, high alloy steels, refractory metals and nickel alloys [Swift and Booker, 2013].

Final product characteristics: A balance between hardening (low temperature) and dynamic restoration (high temperature) needs to be assessed. The first one increases formed precision (tolerances), surface roughness and final mechanical properties but decreases applicable strain and its rate. Latter two are enhanced at high temperatures, where complex shape can be easily obtained with a low forging force. Although bigger grain size is developed at high temperature and so low mechanical properties. Die design, lubrication, wear, billet and intermediate step dimensioning have also a great influence on final properties [Douglas and Kuhlmann, 2000]. A proper modelling and dimensioning is fundamental also for evaluating the impact of product design on its own manufacturing process [Schuler, 1998]. Complexity is limited by material flow through dies.

Typical applications: *Cold forging*: carbon steels, low alloy steels, aluminium alloys, magnesium alloys and copper alloys with mainly rotational shapes and low complexity. *Warm forging*: almost any steels with mainly rotational or axial-symmetric shapes and low-medium complexity. *Hot forging*: any steels with medium-high complex shapes [Sheljaskov, 1994].

Process variants: *Open Die-Forging*, *Impression-Die Forging*, *Precision Forging*, *Isothermal Forging*, *Cold Forging*, *Injection Forging (Radial Extrusion)*,

- **Open-Die Forging**
  - *Process description*: material deformed between a flat or shaped punch and die. Open-die forging can be depicted by a solid workpiece placed between two flat dies and reduced in height by compressing it. Shape and dimensions largely controlled by operator.
  - *Process variants*: *Cogging* (flat or slightly contoured die are employed to compress a work piece, reducing its thickness and increasing its length), *Edging* (primary shaping operation with concave surfaces dies).
  - *Workable materials*: (see *Forging*)
  - *Final product characteristics*: Good mechanical proprieties but low production rates. Poor material utilization and low tolerance level.
  - *Typical applications*: Wide range of part size deployable. Sections can be flat, square, round or polygonal but shape must be simple. Parts made by this process

have wide limits and are too long for solid dies (die blocks, large shafts, pressure vessels).

- **Impression-Die Forging**
  - *Process description*: The two dies are brought together and the workpiece undergoes plastic deformation until its enlarged sides touch the side walls of the die. Then, a small amount of material begins to flow outside the die impression forming flash that is gradually thinned. The flash increases resistance to deformation and helps build up pressure inside the bulk of the workpiece that aids material flow into unfilled impressions (Lange 1985)
  - *Process variants*: *Enclosed Impression-Die (Flashless) Forging* (workpiece completely fills the die cavity the forging pressure is very high, and accurate control of the blank volume and proper die design are essential), *Upset forging* (heated metal stock gripped by dies and end pressed into desired shape).
  - Workable materials: (see *Forging*)
  - *Final product characteristics*: Relatively good utilization of material; generally better properties than open-die forgings; good dimensional accuracy; high production rates; High die cost, not economical for small quantities; machining often necessary [Kalpakjian and Schimd, 2009].
  - *Typical applications*: Wide range of product deployable. Complexity dependants on process temperature and number of steps. Symmetrical parts are easier to forge (gear blanks, bearing races, valve seats, shafts, crankshafts, supports, sleeves, bushes).
- **Precision Forging**
  - *Process description*: Precision forging differs from conventional forging for: (a) special and more complex dies, (b) precise control of the blanks volume and shape,

and (c) accurate positioning of the blank in the die cavity. It can be performed at hot temperature for intricate shapes [Douglas and Kuhlmann, 2000]. It can be performed in hot or cold conditions.

- *Process variants*: Dimensioning of dies in order to minimize forging steps and material utilisation.
- *Workable materials*: Aluminium and magnesium alloys are particularly suitable (low forging loads) and temperatures that they require; however, steels and titanium can also be precision forged [Kalpakjian and Schimd, 2009].
- *Final product characteristics*: Highest tolerances and surface roughness in forging operations (relatively to process temperature and part dimension). Draft angles, radii, fillets, die wear, die closure and mismatching of the dies are common cause of defects and low products characteristics.
- *Typical applications*: Spline shafts, constant velocity joints [Onodera and Sawai, 1992] gears, connecting rods, turbine blades.

• **Isothermal Forging**

- *Process description*: Also known as hot-die forging, this process heats the dies to the same temperature as that of the hot workpiece. Because the workpiece remains hot, its flow strength and high ductility are maintained during forging. Also, the forging load is low, and material flow within the die cavity is improved. The dies for hot forging of high-temperature alloys usually are made of nickel or molybdenum alloys (because of their resistance to high temperatures), but steel dies can be used for aluminium alloys [Kalpakjian and Schimd, 2009]. Isothermal forging is usually conducted in a vacuum or highly controlled atmosphere to prevent oxidation.
- *Process variants*: *Near Iso-thermal forging*, *Multi-axial isothermal forging*.

- *Workable materials*: Mainly carbon; low alloy and stainless steels; aluminium; copper; and magnesium alloys. Titanium alloys, nickel alloys, high alloy steels and refractory metals can also be forged [Swift and Booker, 2013].
- *Final product characteristics*: Complex parts with good dimensional accuracy can be isothermally forged to near-net shape by one stroke in a hydraulic press [Schuler, 1998].
- *Typical applications*: Economical for specialized, intricate forgings made of materials such as aluminium, titanium, and superalloys, provided that the quantity required is sufficiently high to justify the die costs.

- **Cold Forming**
  - *Process description*: Various processes under the heading of cold forming tend to combine forward and backward extrusion to produce near-net-shaped components by the application of high pressures and forces [Swift and Booker, 2013].
  - *Process variants*: *Heading*, *Swaging* (gradually shaping and reducing the cross-section of tubes, rods and wire using successive blows from hard dies rotating around the material), *Cold extrusion* (various processes under the heading of cold forming tend to combine forward and backward extrusion to produce near-net-shaped components by the application of high pressures and forces).
  - *Workable materials*: Any ductile material at ambient temperature (aluminium, copper, zinc, lead and tin alloys, and low carbon steels). Also, alloy and stainless steels, nickel and titanium alloys can be performed on limited deformation or several manufacturing steps.
  - *Final product characteristics*: Cold working offers valuable increase in mechanical properties, including extended fatigue life.

- *Typical applications*: Complexity limited. Symmetry of the part is important: concentric, round or square cross-sections typical. Limited asymmetry possible. Undercuts not possible. Draft angles not required. Generally axial-symmetric components with high mechanical characteristics and precision required (gear blanks, sleeves, bushes, collars, bearing races, valve seats; for Swaging: punches, exhaust pipes, closed tubes).

- **Injection Forging (Radial Extrusion)**

  - *Process description*: Injection forging was introduced as a variant of extrusion in which the material, retained in an injection chamber, is injected into a die-cavity in a form which is prescribed by the exit-geometry this process is characterised by combined axial and radial flow of material to fill the die-cavity [Balendra and Qin, 2004]. The mechanisms which affect flow have been shown to depend on the aspect ratio of the primary deformation zone [Balendra, 1993]. Process is usually performed at room temperature.
  - *Process variants*: *Warm injection forging*, combination with other forging process (extrusion, ironing, upsetting).
  - *Workable materials*: Carbon steel, low alloy steel, aluminium alloy, copper alloy.
  - *Final product characteristics*: Strength and hardness increasing due to hardening. Tight tolerances reachable with proper dimensioning of the dies (e.g. fillet radii).
  - *Typical applications*: Usually applied to axisymmetric components. Complex component-forms, particularly components with flanges and multi-branches in radial direction (hollow and solid flanged components, solid and tubular body branched components).

Orbital (Rotary) Forging *Process description*: Plastic deformation of workpiece is performed by inducing compressive pressures to the billet in incremental manner. Workpiece is positioned between upper and lower tool in vertical press machine, in which the axis of the upper tool is slightly tilted for a specific angle. Upper tool performs only rotary motion and lower tool moves upwards. Lower surface of the workpiece is in full contact with the tool, while the contact surface between upper workpiece surface and upper tool is smaller compared to classical forging, due to tilted axis. Contact area between die and workpiece is smaller than in classical forging which results in lower forming load and die pressure [Plancak et al., 2012].

Process variants: Low die movement (stationary, free or driven rotation, forced translation) Upper die movement (driven rotation, forced translation), Upper die rotation (orbital, planetary, spiral, straight) [Plancak et al., 2012, Standring, 2001].

Workable materials: carbon steel, low alloy steejs and titanium alloy are feasible. Commonly aluminium alloy and copper alloy.

Final product characteristics: Compared with traditional forging, lower level of noise and vibration, uniform quality, smooth surface, close tolerance and considerable savings in energy and materials cost characterize this process [Han and Hua, 2009]. Production steps decrease with rotary forging application, even if lead time, process complexity and workability limits are higher [Standring, 2001].

Typical applications: Conical and disk shaped parts, such as gears. Parts with large diameter to height ratio, especially with intricate external shapes, are produced in NNS with only one process, in comparison with forging (gears, clutch shaft, hex flange, cam plate injection pump, toothed rack, coupling rings, differential conical wheel, flange with ball race).

Spinning *Process description*: Spinning is commonly known as a process for transforming flat sheet metal blanks, usually with axisymmetric profiles, into hollow shapes by a tool which forces a blank onto a mandrel. The blanks are clamped rigidly against the mandrel by means of a tailstock and the shape of the mandrel bears the final profile of the desired product. During the process, both the mandrel and blank are rotated while the spinning tool contacts the blank and progressively induces a change in its shape according to the profile of the mandrel [Wong et al., 2003].

Workable materials: Carbon steels, stainless steels, high and low alloys, aluminium alloys, copper alloys and zinc alloys are the most common. Magnesium, tin, lead, titanium and nickel alloys usage is limited. Every material has defined spinnability (micro- and macro-), which defines capability of being deformed without developing defects or exceeding shear resistance limit [Gur and Tirosh, 1982, Hayama and Kudo, 1979a, Davidson et al., 2008, Kalpakcioglu, 1961a].

Process variants: *Spinning*, *Shear forming*, *Flow forming.*

- **Conventional Spinning**
  - *Process description*: Spinning, in conventional terms, is defined as a process whereby the diameter of the blank is deliberately reduced either over the whole length or in defined area without a change in the wall thickness. Conventional spinning is carried out with only one roller.
  - *Process variants*: *Flame spinning* (oxyacetylene flame heats material prior to forming, permits rapid forming of parts with thick sections), *Laser spinning*
  - *Workable materials*: (see *Spinning*)
  - *Final product characteristics*: Grain flow and cold working give good mechanical properties. Anisotropy in microstructure gives better priorities in axial direction.
  - *Typical applications*: Complexity limited to thin-walled, conical, concentric shapes. Typically, the diameter is twice the depth. Thickness must be constant and internal geometry cannot be worked (shaft, pipes).

- **Shear Forming**
  - *Process description*: Part thickness is deliberately reduced while the diameter of the part remains constant, equal to the diameter of the blank. Blank may be either a flat circular or square sheet or a pre-formed shape and is formed in a single pass, typically using a single roller [Music et al., 2010].
  - *Process variants*: *Mandrel-free spinning* (for giving flexibility to the process, without dedicated mandrel necessity; five approaches: spinning pre-formed shells, replacing the mandrel with a roller, spinning with a moving blank holder, spinning with a simple cylindrical mandrel and spinning with a multi-roller tool), *Asymmetric spinning* (for producing non symmetrical parts; four used approaches: using spring-controlled rollers, using a radially offset mandrel, using a radially offset roller and using a feedback control system), *Hot spinning* (component locally heated during process through a laser or directly enclosed in a hot-chamber)[Music et al., 2010].
  - *Workable materials*: (see *Spinning*)
  - *Final product characteristics*: High process flexibility, used in production of broad lightweight items. Good mechanical properties and a very good surface finish.
  - Typical applications: Profile shape of the final component must be axial-symmetrical but can be concave, convex or combination of these two geometries [Wong et al., 2003] (rocket nose cones, gas turbine engine and dish aerials).

- **Flow Forming**
  - *Process description*: tubular or cup blank is fitted into the rotating mandrel and the rollers approach the blank in the axial direction and plasticise the metal under the contact point. In this way, the wall thickness is reduced as material is encouraged to flow mainly in the axial direction, increasing the length of the workpiece

- Process variants: *Hot flow forming* (component locally heated during process through a laser).
- *Workable materials*: (see *Spinning*)
- *Final product characteristics*: Increase in hardness and ultimate strength due to cold work and better surface finish couples with simple tool design and tooling cost [Sivanandini et al., 2012]. Internal roughness and precision is excellent. External roughness and tolerances are strictly dependant on process parameters and worked material.
- *Typical applications*: Sectional changes can be easily deployed. Precision thin-walled plain and sectional tubes or small pipes (precision hydraulic cylinders, and cylindrical hollow parts with different stepped sections, jet-engine parts, pressure vessels, and automotive components, such as car and truck wheels).

Tube Hydroforming *Process description*: A tubular or solid blank is firstly placed between the two die halves and then filled with high-pressure liquid through holes in the plungers to remove any air bubbles trapped inside. The tube is then forced to adopt the inner contour of the tool by application of internal pressure (via high pressure liquid) and two axial forces (via plungers) simultaneously [Alaswad et al., 2012].
Process variants: *Rubber forming Guerin process* (internal pressure can be transmitted via an elastomer or a soft metal).
Workable materials: Carbon steel, low and high alloy, copper alloys, titanium alloys. Final product characteristics: Close control of the part during forming that prevents wrinkling or tearing. Deeper draws are obtained than in conventional deep drawing. Tight tolerances and high surface finishing reachable.
Typical applications: used for the manufacture of geometrically highly complex hollow bodies from tubular or preforms.

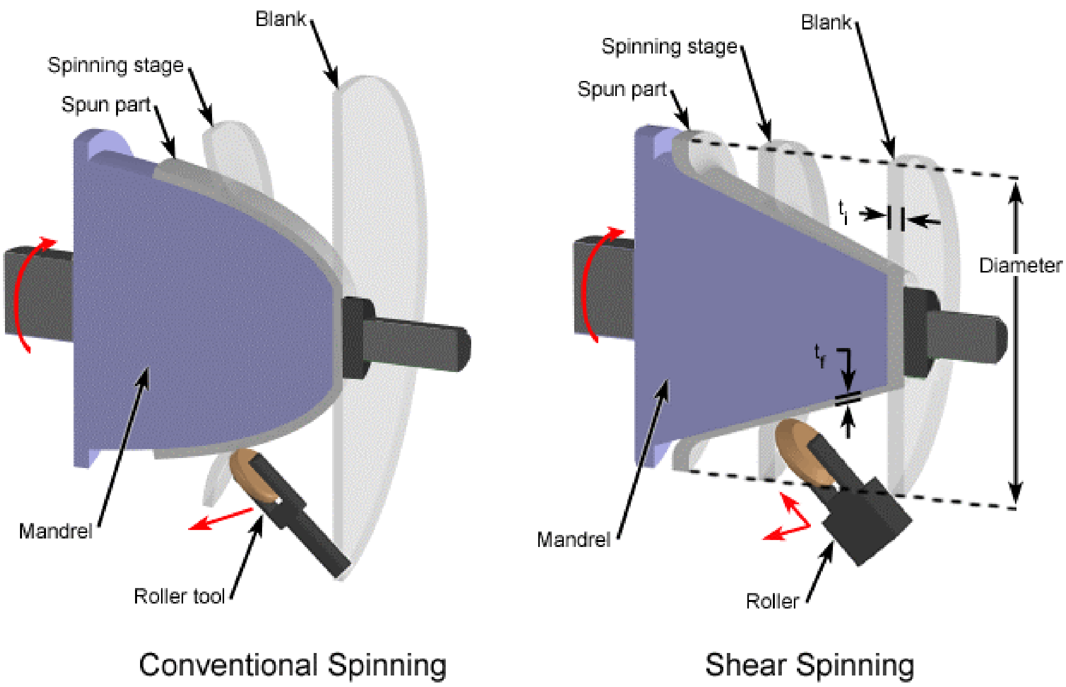


Figure B.2: Schematic of Conventional Spinning and Shear Forming processes [Sivanandini et al., 2012].

[Schuler, 1998] (Automotive industry: cross members, side members, manifolds, roof rails, spoilers, gear shafts, seat frame components, pillars, roof frame profiles, steering column with compensation. Oil, gas, chemical, power industries: tank components, pipe fittings, T-fittings, reducers, housings, panelling, intake pipes).

Powder Metallurgy Powder Metallurgy

- *Process description*: part produced from compaction and sintering serves as the preform in a forging operation. These products are almost fully dense and have a good surface finish, good dimensional tolerances, and a uniform and fine grain size. The superior properties obtained make forging particularly suitable for such applications as highly stressed automotive (such as connecting rods) and jet-engine components [Swift and Booker, 2013].

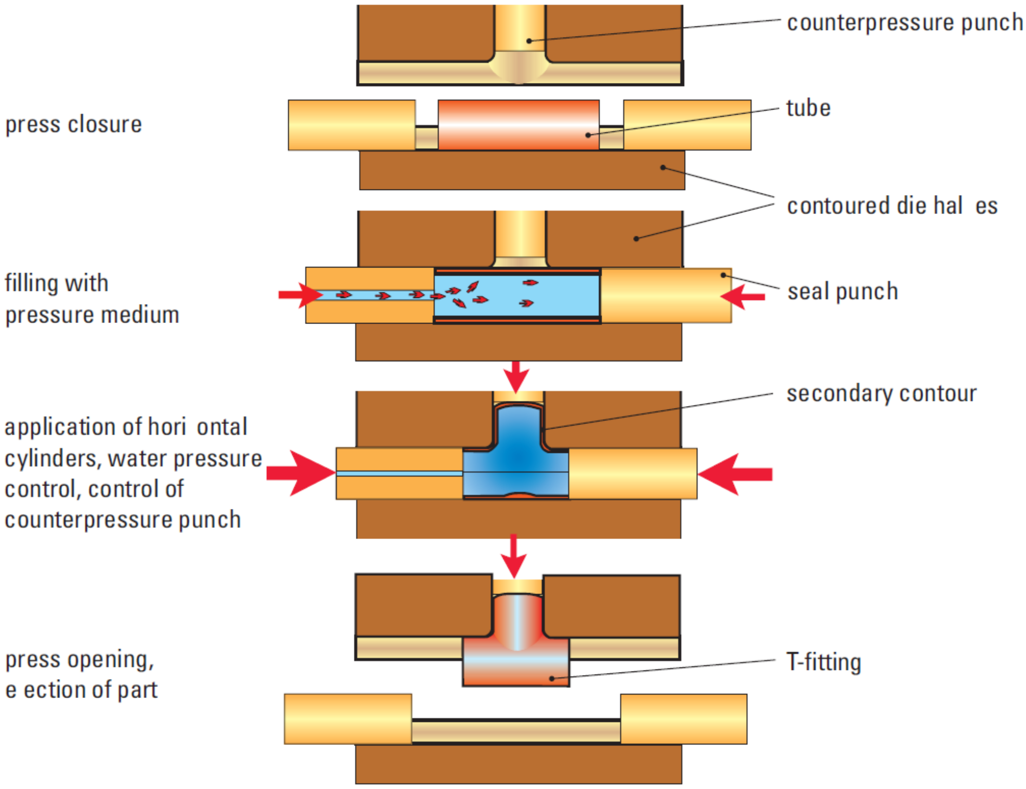


Figure B.3: Schematic of a Tube hydroforming process [Schuler, 1998].

- *Process variants*: *Hot powder forging* (deformation of reheated, sintered compact to final density and shape) *Cold powder forging* (performed at room temperature, producing high-porosity and low-strength parts), *Spark Sintering* (sample is heated by a pulsed electric current which flows through the punch-die-sample-assembly using a high current and low voltage).

- *Workable materials*: All materials, typically metals and ceramics. Iron, copper alloys and refractory metals most common.

- Final product characteristics: High porosity that can be eliminated by hot process or heat treatments. Strength proportional to powder size and process parameters. Generally low mechanical characteristics.

- *Typical applications*: Preferable symmetric shapes. Complexity and part size limited by powder flow through die space (powders do not follow hydrodynamic laws) and pressing action. Complex only on one side [Swift and Booker, 2013] (filters (porous), machine parts (ratchets, pawls, cams, gears)).

Isostatic Pressing

- *Process description*: Compaction of powder in a membrane using pressurised fluid (oil, water) or gas. Permits more uniform compaction and near-net shapes [Swift and Booker, 2013].

- *Process variants*: *Hot isostatic pressing* (capsules are placed in a hot isostatic press where they are subjected to high pressure and temperatures).

- *Workable materials*: Stainless steel, high alloys, titanium alloys, super alloys.

- *Final product characteristics*: pressure applied from all directions decrease porosity levels and increase mechanical proprieties. Strength remains the lowest in forging process applications.

- *Typical applications*: Undercuts and reverse tapers possible, but not transverse holes. Same applications of *Powder forging* but for less complex parts.

Metal Injection Moulding (MIM) *Process description*: Fine metal powder mixed with a binder is injected into a mould under high pressure, similar to plastic injection moulding, to create a brittle green compact part. The binder is stripped from the green part with solvents and/or heat and then sintered at temperatures below the melting temperature of the parent material to bond the powder particles, known as a brown part. Process is essentially a combination of powder metallurgy and injection moulding [Swift and Booker, 2013]. *Process variants*: Binder choice (natural waxes, thermoplastics polyacetals and water/agar), powder production (gas and water atomisation, electrolysis and chemical reduction methods), post process operation (cold forming operations such as sizing and coining).

Workable materials: Powder form (micron-sized) of plain and low alloy steels, stainless steels, high-speed steels, copper alloys, nickel superalloys, titanium. Non-castable alloys deployable. Final product characteristics: fine surface roughness (better than investment casting, also with non-castable materials (dependent on powder particle size). More complex design can be developed, comparing to die-casting and powder forming. Tolerances are proportional to part size, giving imprecision in bigger components. High density and connected performances (e.g. corrosion and fatigue resistance, thermal expansion).

Typical applications: complex shape, thin walls and fine details parts but limited to small and light components (below 250 gr.) with high volume production (small valves and pumps, cogs and gears, rotors, hydraulic fittings, gas manifolds, fuel nozzles, power and hand tools, electronics enclosures, connectors, heat sinks).

B.3 Additive Layer Manufacturing

Processes Involving Discrete Particles

Metal Power Beds Processes Selective Laser Sintering (SLS)

- *Process description*:A high-power laser beam directed by a mirror is used to sinter powdered material in thin 2D cross-sections. The build platform is lowered down an amount equal to the thickness of the sintered layer. A roller replenishes the layer of powder from adjacent powder supply chambers, the laser traces out the next 2D cross-section, and the process is repeated until a 3D structure is built up. Excess powder not sintered on each layer acts as a support for the part being built. The part is removed and excess powder is removed by brushing or vacuuming [Swift and Booker, 2013].

- *Process variants*: Laser types (Yb-fibre, CO2 up to 100 W in power).

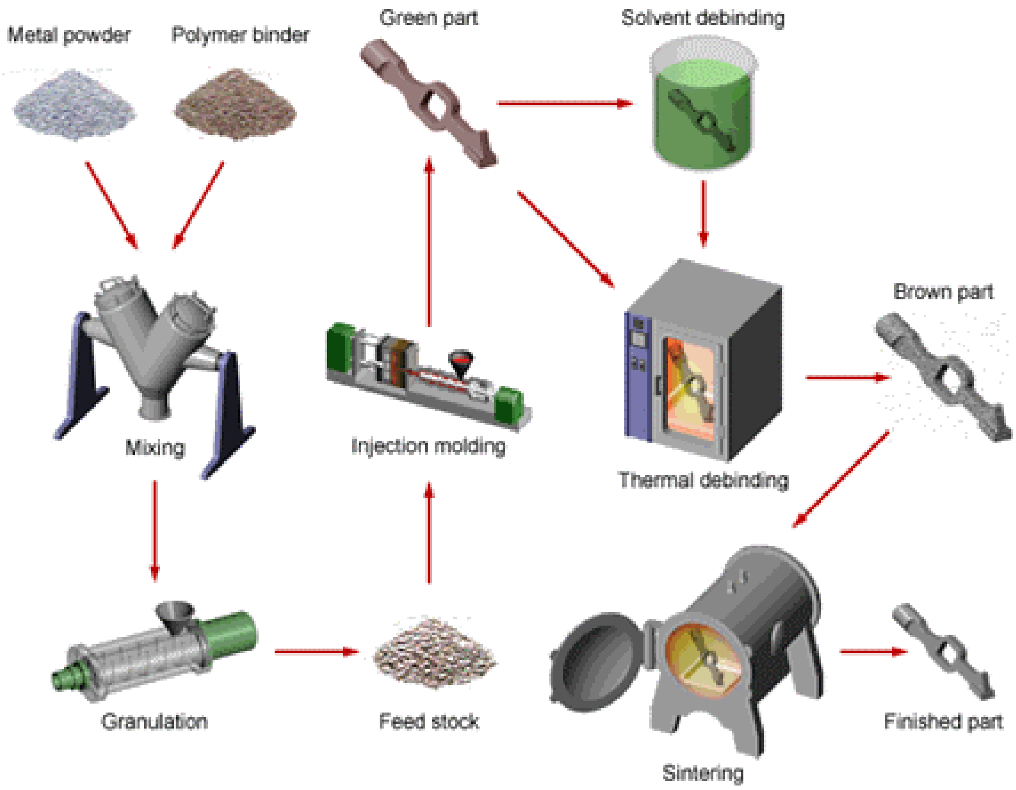


Figure B.4: Schematic of a Metal Injection Molding process [Swift and Booker, 2013].

- Workable materials: Metals and ceramic powders. Particularly stainless steel, tools and alloy steels, titanium, tungsten, copper alloy, aluminium and nickel super alloys.
- *Final product characteristics*: Anisotropy in material properties (less strength in built direction). Low to moderate tensile strength. Moderate surface finishing but fine tolerances achievable.
- *Typical applications*: Complex geometry and low-moderate production volume functional components. Undercuts, void and all internal geometries are feasible (turbine blades, impellers, fuel nozzles for aerospace sector. Patterns, moulds and cores for casting and moulding).

Selective Laser Melting (SLM)

- *Process description*: Alternative process to SLS that use similar dynamic. Power of laser is raised up for reaching melting temperature of the powder. A controlled atmosphere of inert gas, either argon or nitrogen is necessary for preventing oxidation.

- *Process variants*: Laser type (Nd-YAG, Argon Up to 200 W in power).
- *Workable materials*: (see *SLS*).
- *Final product characteristics*: Less anisotropy than SLS. Tensile strength higher than SLS. Even if lower surface roughness and tolerance achievable.
- *Typical applications*: Similar to *SLS* but available also for larger production volumes.

DMLS - Direct Metal Laser Sintering (DMLS)

- *Process description*: DMLS process uses a powder mixture, consisting of metals with different melting points. Several powder mixtures are available from EOS. The bronze based powders can be processes in air whereas the steel based powders need an inert gas atmosphere during processing [Niebling et al., 2002]
- Process variants: *ILMS - Indirect Metal Laser Sintering* (uses polymer binders, which are burned out in following oven processes and the porous material is infiltrated with metal [Niebling et al., 2002]), *DMLM - Direct Metal Laser Melting* (as for SLM, metal powder is directly melted by a more powerful laser beam)
- Workable materials: (see *SLS*) Particularly suitable for high alloys, special alloys (Maraging), stainless and titanium alloys. Binding powders can be brass,
- *Final product characteristics*: Tensile strength, tolerance level and surface roughness superior to SLS and SLM. Lower variability in properties. Surface details and sharp details are better reproduced
- *Typical applications*: (see *SLS*) High duty applications can be carried out by DMLS. External surface complexity can be raised too.

Electron Beam Melting (EBM)

- *Process description*: Electron beam that generates the energy needed for high melting capacity and high productivity. The electron beam is managed by electromagnetic coils providing extremely fast and accurate beam control that allows several melt pools to be maintained simultaneously [Gibson et al., 2010].
- *Process variants*: *Arcam MultiBeam™* (more than one electron arrive on the surface simultaneously).
- *Workable materials*: All metals, also reactive and refractor alloys (due to vacuum). Mainly used for titanium alloys.
- *Final product characteristics*: High density and a very fine microstructure properties. Because of this built microstructure, yield stress and UTS are quite high, whilst elongation at fracture is quite low [Facchini et al., 2009]. Parts are free from residual stresses [Gibson et al., 2010].
- *Typical applications*: (see *SLS*).

Gas Phase Deposition (GPD)

- *Process description*: Molecules of a reactive gas are decomposed using either light or heat to leave a solid. The solid result of the decomposition then adheres to the substrate to form the part [Pham and Gault, 1998].
- *Process variants*: *SALD - Selective Area Laser Deposition*, *SALDVI - Selective Area Laser Deposition Vapour Infiltration*, *SLRS - Selective Laser Reactive Sintering.*
- *Workable materials*: Reactive gas leaving solid particles.
- *Final product characteristics*: Unknown. Hypothetical high resolution for layer thickness.

- *Typical applications*: Not commercially available.

Tri-dimensional Printing (3DP)

- *Process description*: A printing head (similar to those found in inkjet printers) deposits a liquid binder on to a powder in a build chamber. The powder particles become bonded together and the build platform is lowered down an amount equal to the thickness of the layer created. The powder is replenished in the build chamber from a similar powder supply chamber adjacent to it, compacted and levelled on top of the last bonded layer using a roller. The process is repeated, building up a 3D part. The completed part is cleaned of excess powder and typically impregnated with a sealant [Swift and Booker, 2013]. Obtained product is usually post-processed by heat treatments of curing (low temperature) and firing (high temperature). Binder is usually in liquid form (wax, epoxy resin, elastomer and polyurethane).

- *Process variants*: *Thermal Phase Change Inkjet Printing* (two separate printing heads, one dispensing a thermoplastic melt and the other hot wax support material, create a 2D layer that hardens on contact. A milling tool machines the surface level and the wax is dissolved or melted out)

- *Workable materials*: Powder form of stainless steel, bronze, ceramics, moulding sand, plaster and starch.

- Final product characteristics: Very coarse roughness but good tolerances achievable. Parts structure is anisotropic and fragile. Accuracy is high, even if dependant on powder and binder droplet sizes

- *Typical applications*: Complex and intricate with small-medium dimension (Non-functional prototypes, patterns and cores for casting processes).

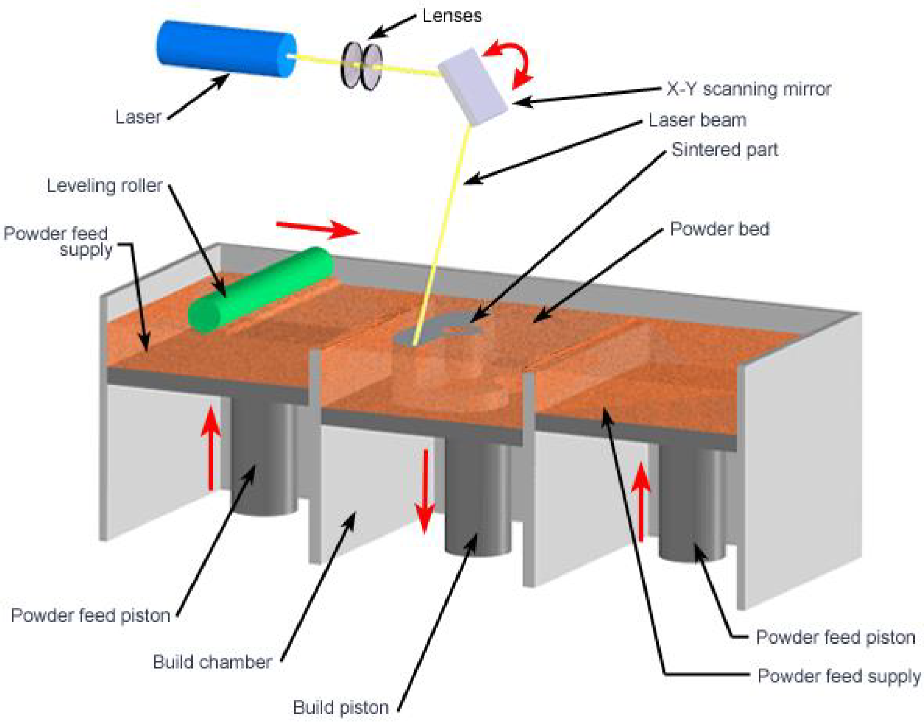


Figure B.5: Schematic of Direct Metal Laser Sintering process [Esmaeilian et al., 2016].

Blown Metal Powder Processes Laser Based Metal Deposition (LBMD)

- *Process description*: *Directed Energy Deposition (DED)* or *Direct Metal Deposition Process (DMD)*. DED processes use a focused heat source (typically a laser or electron beam) to melt the feedstock material and build up three-dimensional objects in a manner similar to the extrusion-based processes. DED processes direct energy into a narrow, focused region to heat a substrate, melting the substrate and simultaneously melting material that is being deposited into the substrates melt pool [Gibson et al., 2010].

- *Process variants*: Changes in laser power, laser spot size, laser type, powder delivery method, inert gas delivery method, feedback control scheme, and/or the type of motion control: *Laser Engineered Net Shaping (LENS), Directed Light Fabrication (DLF), Di-*

rect Metal Deposition (DMD), 3D Laser Cladding, Laser Generation, Laser Freeform Fabrication (LFF), Laser Direct Casting and other [Gibson et al., 2010].

- *Workable materials*: Any powder material or powder mixture which is stable in a molten pool. Mainly used for high steel alloys, stainless steel, titanium alloys.

- *Final product characteristics*: Good accuracy and good surface roughness. To achieve better accuracies, small beam sizes and deposition rates are required. Conversely, to achieve rapid deposition rates, degradation of resolution and surface finish result [Gibson et al., 2010]. Trade-off solution is required in this case.

- *Typical applications*: Freeform manufacturing allowed also for large size part. Part less complex than bed metal powder systems (weld repairs and modifications to tools and dies, coating, cladding, aerospace, aircraft, hollow stem engine valves).

Electron Beam Based Metal Deposition (EBMD)

- *Process description*: *Directed Energy Deposition (DED)* or *Direct Metal Deposition Process (DMD)*. Using an electron beam as a thermal source and a wire feeder, this process is capable of rapid deposition under high current flows, or more accurate depositions using slower deposition rates than LBMD. Performed in vacuum.

- *Process variants*: *Electron Beam Freeform Fabrication (EBF)*, *Electron Beam Additive Manufacturing(EBAM)* (wire-fed variant of the process)

- *Workable materials*: Any powder material or powder mixture which is stable in a molten pool. Mainly titanium alloys.

- *Final product characteristics*: (see *LBMD*)

- Typical applications: Similar to *LBMD*. Large and solid components with rib-on-plate structures and other kind of deposits (aerospace components).

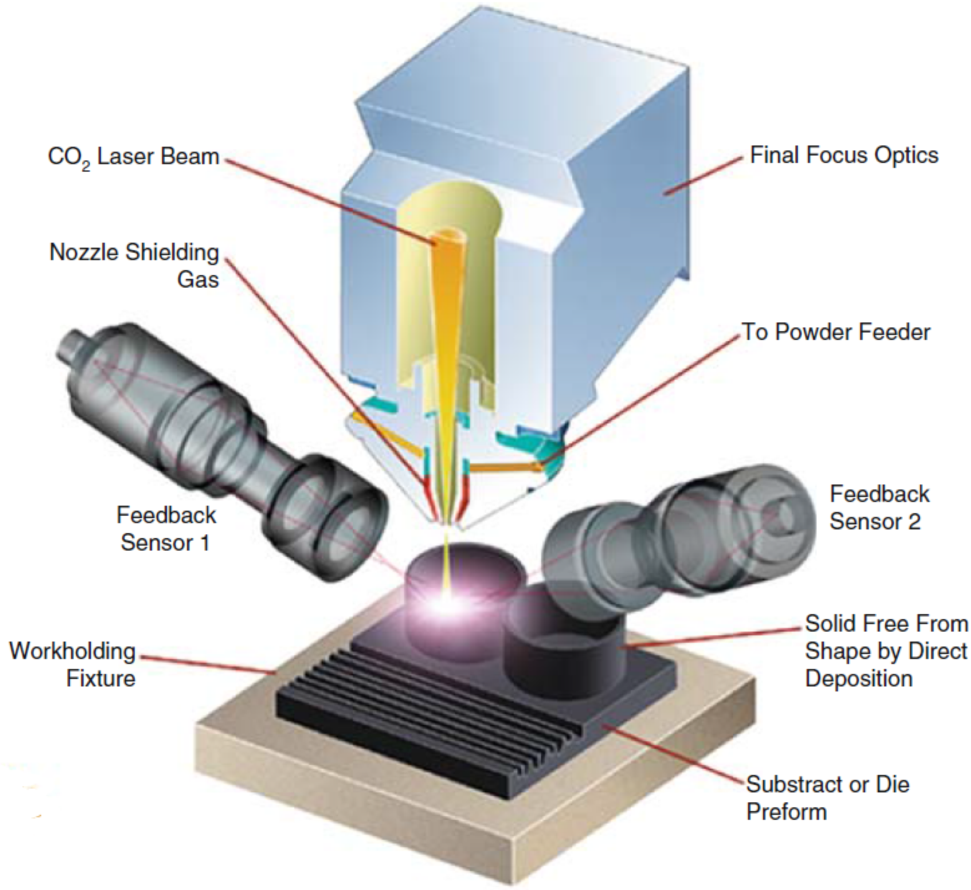


Figure B.6: Schematic of a Direct Energy Deposition process [Esmaeilian et al., 2016].

Plasma Deposition Manufacturing (PDM)

- *Process description*: *Directed Energy Deposition (DED)* or *Direct Metal Deposition Process (DMD)*. Nozzle supplies a continuous powder feed to the plasma-melting zone where the powder is melted and re-solidifies in the wake of the molten pool as the plasma beam scans across deposited layer. Processing is performed usually in inert gas argon, helium, nitrogen environments, typically to reduce oxidation [Zhang et al., 2002].

- *Process variants*: Changes in powder delivery method, inert gas delivery method, feedback control scheme, and/or the type of motion control.

- *Workable materials*: Almost all metals, also reactive and refractory.
- *Final product characteristics*: Fair mechanical characteristics (strength and hardness) and microstructural homogeneity. Usually low accuracy and consequently low surface roughness and tolerances. Fastest process in its category. Accuracy can be set as high by severely slowing down the process.
- *Typical applications*: (see *LBMD*)

B.3.1 Processes Involving Solidification of Molten Metal

Fuse Deposition Modelling (FDM)

- *Process description*: Solid material, usually in filament form, is melted and extruded through a heated nozzle to create a molten bead of build material. The build chamber is maintained at a temperature just below the melting point of the build material. The controllable nozzle is moved in the horizontal plane, depositing the molten bead to create a thin layer of the required 2D profile. The molten bead solidifies and effectively cold welds on contact with the previous layer. The build platform is lowered down an amount equal to the thickness of the solidified layer, and the process is repeated, building up a 3D part. Additional support material for overhangs and undercuts is simultaneously deposited during the build process using a second nozzle. The support material can be dissolved away after the part is removed from the build chamber [Swift and Booker, 2013].
- *Process variants*: *FDMm - Fused Deposition Modelling of Metals* (new process configuration for higher melting point alloys, still in experimental phase)
- *Workable materials*: Metals that can be produced as a wire. Tin, zinc, lead, other low melting point alloys and thermoplastics. Copper is most suitable alloy.

- Final product characteristics: Anisotropy in material properties exist due additive layer method. Strength weakest in vertical build direction. Reduction of strength compared injection molding.
- *Typical applications*: Complex and intricate parts with medium dimensions and small production volume (patterns and cores for casting processes).

Shape Deposition Manufacturing (SDM)

- *Process description*: A nozzle spraying molten metal in NNS onto a substrate, then removing unwanted material via NC operations. Support material is added in the same way either before or after the prototype material depending on whether the layer contains undercut features [Pham and Gault, 1998].
- *Process variants*: different droplets trajectory control system and temperature droplets control system.
- *Workable materials*: stainless steel, high alloy and with supported copper (need to be removed in nitric acid)
- *Final product characteristics*: Same structure of casted or welded parts [Merz et al., 1994].
- *Typical applications*: Mainly micro-casting and micro-manufacturing of precision parts.

Ballistic Particle Manufacturing (BPM)

- *Process description*: A stream of molten material is ejected from a nozzle. It separates into droplets which hit the substrate and immediately cold weld to form the part. If the substrate is rough, thermal contact between it and the part is increased which will reduce stresses within the part [Pham and Gault, 1998].

- Process variants: *BPM1* (drop-on-demand jet to eject the molten material), *BPM2* (direction of the jet is perpendicular to the normal of the surface and should eliminate steps in the build direction)
- Workable materials: All low melting point metals.
- Final product characteristics: Low accuracy. Poor surface roughness and tolerances. Produced parts have low strength and durability. Consequently they cannot be used as functional components.
- Typical applications: No size constrains and medium complexity. Used mainly for non-functional prototypes.

Spatial Forming (SF)

- *Process description*: A negative of each layer is printed onto a ceramic substrate with a ceramic pigmented organic ink. The layer is then cured with UV light and the process repeated. After approximately 30 layers, the positive space left by the printing, which corresponds to the part cross section, is filled using another ink which contains metal particles. This is then cured and milled flat. The process continues until the whole part is finished. Once the prototype is complete, it is heated in a nitrogen atmosphere to remove the binders in both the positive and negative inks and to sinter the metal particles. The ceramic negative can then be removed in an ultrasonic bath to reveal the final piece, which is infiltrated with liquid metal to produce the metal prototype [Gibson et al., 2010].
- *Process variants*: Ink selection and deposition mechanisms.
- *Workable materials*: All metals. Mainly titanium alloys.
- *Final product characteristics*: Very high precision and tight tolerances. Surface roughness can be controlled. High roughness and hardness.

- *Typical applications*: High level biomedical and robotic application. Used also in micro-manufacturing.

B.3.2 Processes Involving Solid Sheets

Laminated Object Manufacturing (LOM)

- *Process description*: Sheet material coated with an adhesive is moved into the build area using a feed roll and pressure is applied using a heated roller to bond to the layer below. The sheet is cut using a CO2 laser beam directed by a mirror and optic heads to create the required 2D profile. The build platform is lowered down an amount equal to the thickness of the layer created and the process is repeated, building up a 3D part. Excess sheet surrounding the 2D profile is cross-hatched with the laser for easier removal (chopped away in sections later) and the remaining sheet is moved away on a waste take-up roll. The finished part is removed and is typically sanded down to improve the surface finish and then sealed [Swift and Booker, 2013].
- *Process variants*: *UC Ultrasonic Consolidation* (a solid-state process that involves the use of high frequency, low amplitude, mechanical vibrations to bond metal foils in a layer-by-layer method [Kong et al., 2004])
- *Workable materials*: Thin sheet form of metal foils and ceramics.
- *Final product characteristics*: Not enough strength for being used as functional component, particularly in building direction. Dimensional tolerances are good, although surface roughens is poor compared with rapid prototyping process.
- *Typical applications*: Complex, large and solid component. Undercuts difficult to create (product concept models, patterns and cores for casting processes, rapid tooling).

Appendix C

Fuzzy Logic Application to Case Studies

C.1 Fuzzy Logic Calculations for Case Studies IA, IB, II and III

Hot Closed-die Forging	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibilty	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.20	0.80	1.00	2.00	0.3	0.08	0.92	0.50	0.92	4	0.11
Axial Tolerance [±mm]	0.10	0.50	1.00	2.00	0.3	0.38	0.63	0.50	0.92	4	0.11
Surface Roughness [Ra]	1.6	3.2	6.4	12.5	1.6	0.00	1.00	0.50	0.92	4	0.11
Workable Section Thickness [mm]	0	10	100	200	45	1.00	1.00	1.00	1.00	5	0.14
Workable Weight [kg]	0.30	2.00	100.00	500.00	2.7	1.00	1.00	1.00	1.00	5	0.14
Resulting Mechanical Propieties	2	3	4	5	≥4	1.00	1.00	1.00	1.00	4	0.11
Tooling Cost	2	3	3	4	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	3	4	4	5	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	2	3	3	4	≤4	1	1	1	1.00	3	0.09
Optimism Level (β)	0.5					**Total Compatibility**		0.79			

Table C.1: Fuzzy logic compatibility analysis between Hot-Closed Die Forging and Case Study IA.

Hot Precision Forging	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibilty	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.10	0.20	0.50	0.80	0.3	1.00	1.00	1.00	1.00	4	0.11
Axial Tolerance [±mm]	0.08	0.1	0.3	0.5	0.3	1.00	1.00	1.00	1.00	4	0.11
Surface Roughness [Ra]	0.40	0.80	1.60	3.20	1.6	1.00	1.00	1.00	1.00	4	0.11
Workable Section Thickness [mm]	3	8	40	100	45	0.92	0.08	0.50	0.91	5	0.14
Workable Weight [kg]	0.10	0.50	20.00	250.00	2.7	1.00	1.00	1.00	1.00	5	0.14
Resulting Mechanical Propieties	2	3	4	5	≥4	1	1	1.00	1.00	4	0.11
Tooling Cost	5	5	5	5	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	3	4	4	5	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	3	4	4	5	≤4	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.5					Total Compatibility		0.91			

Table C.2: Fuzzy logic compatibility analysis between Hot-Precision Forging and Case Study IA.

Hot Injection Forging	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibilty	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.20	1.00	1.50	2.00	0.3	0.06	0.94	0.50	0.92	4	0.11
Axial Tolerance [±mm]	0.10	0.50	1.00	2.00	0.3	0.38	0.63	0.50	0.92	4	0.11
Surface Roughness [Ra]	0.40	0.80	1.60	3.20	1.6	1.00	0.00	0.50	0.92	4	0.11
Workable Section Thickness [mm]	5	10	50	100	45	1.00	1.00	1.00	1.00	5	0.14
Workable Weight [kg]	0.10	0.50	20.00	250.00	2.7	1.00	1.00	1.00	1.00	5	0.14
Resulting Mechanical Propieties	2	3	4	5	≥4	1.00	1.00	1.00	1.00	4	0.11
Tooling Cost	2	3	3	4	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	5	5	5	5	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	1	2	3	4	≤4	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.5					Total Compatibility		0.79			

Table C.3: Fuzzy logic compatibility analysis between Hot-Injection Forging and Case Study IA.

Rotary Forging	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibilty	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.04	0.10	0.20	0.50	0.3	0.83	0.17	0.50	0.92	4	0.11
Axial Tolerance [±mm]	0.08	0.15	0.5	0.8	0.3	1.00	1.00	1.00	1.00	4	0.11
Surface Roughness [Ra]	0.40	1.20	1.60	3.20	1.6	1.00	1.00	1.00	1.00	4	0.11
Workable Section Thickness [mm]	1.0	10.0	30.0	50.0	45.0	0.25	0.75	0.50	0.91	5	0.14
Workable Weight [kg]	0.20	3.00	10.00	50.00	2.7	0.89	0.11	0.50	0.91	5	0.14
Resulting Mechanical Propieties	3	4	4	5	≥4	1.00	1.00	1.00	1.00	4	0.11
Tooling Cost	2	3	3	4	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	4	5	5	5	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	1	2	3	4	≤4	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.5					Total Compatibility		0.76			

Table C.4: Fuzzy logic compatibility analysis between Rotary Forging and Case Study IA.

Flow Forming	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibilty	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.05	0.10	0.30	0.50	0.3	1.00	1.00	1.00	1.00	4	0.11
Axial Tolerance [±mm]	0.1	0.2	0.5	0.8	0.3	1.00	1.00	1.00	1.00	4	0.11
Surface Roughness [Ra]	0.40	0.80	1.60	3.20	1.6	1.00	1.00	1.00	1.00	4	0.11
Workable Section Thickness [mm]	0.5	1.0	10.0	75.0	45.0	0.46	0.54	0.50	0.91	5	0.14
Workable Weight [kg]	1.00	5.00	300.00	5000.00	2.7	0.43	0.58	0.50	0.91	5	0.14
Resulting Mechanical Propieties	3	4	4	5	≥4	1.00	1.00	1.00	1.00	4	0.11
Tooling Cost	1	2	2	3	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	2	3	4	5	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	2	3	4	5	≤4	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.5					Total Compatibility		0.82			

Table C.5: Fuzzy logic compatibility analysis between Flow Forging and Case Study IA.

Centrifugal Casting	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibilty	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.10	0.20	0.50	1.00	0.3	1.00	1.00	1.00	1.00	4	0.11
Axial Tolerance [±mm]	0.1	0.5	0.8	1.5	0.3	0.38	0.63	0.50	0.92	4	0.11
Surface Roughness [Ra]	0.80	1.60	3.20	6.40	1.6	1.00	1.00	1.00	1.00	4	0.11
Workable Section Thickness [mm]	10.0	50.0	100.0	200.0	45.0	1.00	0.13	0.56	0.92	5	0.14
Workable Weight [kg]	1.00	10.00	5000.00	10000.00	2.7	0.19	0.81	0.50	0.91	5	0.14
Resulting Mechanical Propieties	2	3	4	5	≥4	1.00	1.00	1.00	1.00	4	0.11
Tooling Cost	2	3	3	4	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	2	3	3	4	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	1	2	2	3	≤4	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.5					Total Compatibility		0.77			

Table C.6: Fuzzy logic compatibility analysis between Centrifugal Casting and Case Study IA.

Sand Casting	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibilty	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.65	1.50	3.50	5.00	0.3	0.00	0.00	0.00	0.00	4	0.11
Axial Tolerance [±mm]	0.65	1.50	3.50	5.00	0.3	0.00	0.00	0.00	0.00	4	0.11
Surface Roughness [Ra]	6.30	12.50	25.00	50.00	1.6	0.00	0.00	0.00	0.00	4	0.11
Workable Section Thickness [mm]	2.5	No Limit	No Limit	No Limit	45.0	1.00	1.00	1.00	1.00	5	0.14
Workable Weight [kg]	0.05	No Limit	No Limit	No Limit	2.7	1.00	1.00	1.00	1.00	5	0.14
Resulting Mechanical Propieties	1	1	1	1	≥4	0.00	0.00	0.00	0.00	4	0.11
Tooling Cost	1	1	1	2	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	1	1	1	1	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	1	2	2	3	≤4	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.5					Total Compatibility		0.00			

Table C.7: Fuzzy logic compatibility analysis between Sand Casting and Case Study IA.

Shell Moulding	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibilty	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.20	0.30	0.80	1.00	0.3	0.50	0.50	0.50	0.92	4	0.11
Axial Tolerance [±mm]	0.20	0.30	0.80	1.00	0.3	0.50	0.50	0.50	0.92	4	0.11
Surface Roughness [Ra]	0.80	3.20	6.30	12.50	1.6	0.33	0.67	0.50	0.92	4	0.11
Workable Section Thickness [mm]	1.5	10.0	30.0	50.0	45.0	0.25	0.75	0.50	0.91	5	0.14
Workable Weight [kg]	0.05	1.00	20.00	100.00	2.7	1.00	1.00	1.00	1.00	5	0.14
Resulting Mechanical Propieties	2	3	3	4	≥4	0.00	1.00	0.50	0.92	4	0.11
Tooling Cost	1	2	2	3	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	3	4	4	5	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	1	2	2	3	≤4	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.5					Total Compatibility		0.66			

Table C.8: Fuzzy logic compatibility analysis between Shell Molding and Case Study IA.

Investment Casting	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibilty	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.08	0.15	0.30	0.50	0.3	1.00	1.00	1.00	1.00	4	0.11
Axial Tolerance [±mm]	0.08	0.15	0.30	0.50	0.3	1.00	1.00	1.00	1.00	4	0.11
Surface Roughness [Ra]	0.8	1.6	3.2	6.3	1.6	1.00	1.00	1.00	1.00	4	0.11
Workable Section Thickness [mm]	1.0	10.0	30.0	75.0	45.0	0.67	0.33	0.50	0.91	5	0.14
Workable Weight [kg]	0.01	0.50	5.00	100.00	2.7	1.00	1.00	1.00	1.00	5	0.14
Resulting Mechanical Propieties	2	3	3	4	≥4	0.00	1.00	0.50	0.92	4	0.11
Tooling Cost	3	4	4	5	≤3	0.00	1.00	0.50	0.94	3	0.09
Equipment Cost	1	2	2	3	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	5	5	5	5	≤4	0	0	0.00	0.00	3	0.09
Optimism Level (β)	0.5					Total Compatibility		0.00			

Table C.9: Fuzzy logic compatibility analysis between Investment Casting and Case Study IA.

Lost Foam Casting	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibility	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.50	1.00	2.00	3.00	0.3	0.00	0.00	0.00	0.00	4	0.11
Axial Tolerance [±mm]	0.50	1.00	2.00	3.00	0.3	0.00	0.00	0.00	0.00	4	0.11
Surface Roughness [Ra]	3.20	6.30	12.50	25.00	1.6	0.00	0.00	0.00	0.00	4	0.11
Workable Section Thickness [mm]	2.5	No Limit	No Limit	No Limit	45.0	1.00	1.00	1.00	1.00	5	0.14
Workable Weight [kg]	0.05	20.00	20.00	100.00	2.7	1.00	1.00	1.00	1.00	5	0.14
Resulting Mechanical Proprieties	1	2	2	3	≥4	0.00	0.00	0.00	0.00	4	0.11
Tooling Cost	1	2	2	3	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	2	3	3	4	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	3	4	4	5	≤4	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.5					**Total Compatibility**		0.000			

Table C.10: Fuzzy logic compatibility analysis between Lost Foam Casting and Case Study IA.

Flow Forming	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibility	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.05	0.10	0.30	0.50	0.25	1.00	1.00	1.00	1.00	4	0.11
Axial Tolerance [±mm]	0.1	0.2	0.5	0.8	0.25	1.00	1.00	1.00	1.00	4	0.11
Surface Roughness [Ra]	0.80	1.60	3.20	6.3	3.2	1.00	1.00	1.00	1.00	4	0.11
Workable Section Thickness [mm]	0.5	1.0	10.0	75.0	33.0	0.65	0.35	0.50	0.91	5	0.14
Workable Weight [kg]	1	5	300	2500	1300	0.55	0.45	0.50	0.91	5	0.14
Resulting Mechanical Proprieties	3	4	4	5	≥4	1.00	1.00	1.00	1.00	4	0.11
Tooling Cost	1	2	2	3	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	2	3	4	5	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	2	3	4	5	≤4	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.4					**Total Compatibility**		0.82			

Table C.11: Fuzzy logic compatibility analysis between flow forming and Case Study IB.

Centrifugal Casting	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibility	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.10	0.20	0.50	1.00	0.25	1.00	1.00	1.00	1.00	4	0.11
Axial Tolerance [±mm]	0.1	0.5	0.8	1.5	0.25	0.38	0.63	0.50	0.92	4	0.11
Surface Roughness [Ra]	0.8	1.6	3.2	6.3	3.2	1.00	1.00	1.00	1.00	4	0.11
Workable Section Thickness [mm]	10.0	50.0	100.0	200.0	33.0	0.58	0.58	0.58	0.92	5	0.14
Workable Weight [kg]	1	10	5000	10000	1300	1.00	1.00	1.00	1.00	5	0.14
Resulting Mechanical Proprieties	2	3	4	5	≥4	1.00	1.00	1.00	1.00	4	0.11
Tooling Cost	2	3	3	4	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	2	3	3	4	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	1	2	2	3	≤4	1	1	1	1	3	0.09
Optimism Level (β)	0.5					**Total Compatibility**		0.85			

Table C.12: Fuzzy logic compatibility analysis between centrifugal casting and Case Study IB.

Ceramic Moulding	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibility	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.05	0.10	0.50	0.80	0.25	1.00	1.00	1.00	1.00	4	0.11
Axial Tolerance [±mm]	0.05	0.10	0.50	0.80	0.25	1.00	1.00	1.00	1.00	4	0.11
Surface Roughness [Ra]	0.4	0.8	1.6	3.2	3.2	0.00	1.00	0.50	0.92	4	0.11
Workable Section Thickness [mm]	0.6	1.2	50.0	100.0	33.0	1.00	1.00	1.00	1.00	5	0.14
Workable Weight [kg]	0	1	50	3000	1300	0.58	0.42	0.50	0.91	5	0.14
Resulting Mechanical Proprieties	2	3	3	4	≥4	0.00	1.00	0.50	0.92	4	0.11
Tooling Cost	3	4	4	5	≤3	0.00	1.00	0.50	0.94	3	0.09
Equipment Cost	3	4	4	5	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	3	4	4	5	≤4	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.4					**Total Compatibility**		0.73			

Table C.13: Fuzzy logic compatibility analysis between ceramic moulding and Case Study IB.

Sand Casting	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibility	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.65	1.50	3.50	5.00	0.25	0.00	0.00	0.00	0.00	4	0.11
Axial Tolerance [±mm]	0.65	1.50	3.50	5.00	0.25	0.00	0.00	0.00	0.00	4	0.11
Surface Roughness [Ra]	6.30	12.50	25.00	50.00	3.2	0.00	0.00	0.00	0.00	4	0.11
Workable Section Thickness [mm]	2.5	No Limit	No Limit	No Limit	33	1.00	1.00	1.00	1.00	5	0.14
Workable Weight [kg]	0.05	No Limit	No Limit	No Limit	1300	1.00	1.00	1.00	1.00	5	0.14
Resulting Mechanical Proprieties	1	1	1	1	≥4	0.00	0.00	0.00	0.00	4	0.11
Tooling Cost	1	1	1	2	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	1	1	1	1	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	1	2	2	3	≤4	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.4					**Total Compatibility**		0.00			

Table C.14: Fuzzy logic compatibility analysis between sand casting and Case Study IB.

Lost Foam Casting	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibility	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.50	1.00	2.00	3.00	0.25	0.00	0.00	0.00	0.00	4	0.11
Axial Tolerance [±mm]	0.50	1.00	2.00	3.00	0.25	0.00	0.00	0.00	0.00	4	0.11
Surface Roughness [Ra]	3.20	6.30	12.50	25.00	3.2	0.00	0.00	0.00	0.00	4	0.11
Workable Section Thickness [mm]	2.5	No Limit	No Limit	No Limit	33	1.00	1.00	1.00	1.00	5	0.14
Workable Weight [kg]	0.05	20.00	20.00	100.00	1300	1.00	1.00	1.00	1.00	5	0.14
Resulting Mechanical Proprieties	1	2	2	3	≥4	0.00	0.00	0.00	0.00	4	0.11
Tooling Cost	1	2	2	3	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	2	3	3	4	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	3	4	4	5	≤4	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.4					**Total Compatibility**		0.00			

Table C.15: Fuzzy logic compatibility analysis between lost foam and Case Study IB.

Investment Casting	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibility	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.08	0.15	0.30	0.50	0.25	1.00	1.00	1.00	1.00	4	0.11
Axial Tolerance [±mm]	0.08	0.15	0.30	0.50	0.25	1.00	1.00	1.00	1.00	4	0.11
Surface Roughness [Ra]	0.8	1.6	3.2	6.3	3.2	1.00	1.00	1.00	1.00	4	0.11
Workable Section Thickness [mm]	1	10	50	75	33	1.00	1.00	1.00	1.00	5	0.14
Workable Weight [kg]	0.01	0.50	5.00	75.00	1300	0.00	0.00	0.00	0.00	5	0.14
Resulting Mechanical Proprieties	2	3	3	4	≥4	1.00	1.00	1.00	1.00	4	0.11
Tooling Cost	3	4	4	5	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	1	2	2	3	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	5	5	5	5	≤4	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.4					**Total Compatibility**		0.00			

Table C.16: Fuzzy logic compatibility analysis between investment casting and Case Study IB.

Flow Forming	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibilty	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.05	0.10	0.30	0.50	0.25	1.00	1.00	1.00	1.00	4	0.12
Axial Tolerance [±mm]	0.1	0.2	0.5	0.8	0.25	1.00	1.00	1.00	1.00	4	0.12
Surface Roughness [Ra]	0.80	1.60	3.20	6.40	1.6	1.00	1.00	1.00	1.00	4	0.12
Workable Section Thickness [mm]	0.5	1.0	10.0	80	80	0.00	1.00	0.50	0.90	5	0.15
Workable Weight [kg]	1.00	5.00	300.00	5000.00	360	0.99	0.01	0.50	0.90	5	0.15
Resulting Mechanical Propieties	3	5	4	5	≥2	1.00	1.00	1.00	1.00	3	0.09
Tooling Cost	1	2	2	3	≤3	0.00	1.00	0.50	0.94	3	0.09
Equipment Cost	2	3	4	5	≤3	1	1	1.00	1.00	3	0.09
Labour Cost	2	3	4	5	≤3	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.5					**Total Compatibility**		0.77			

Table C.17: Fuzzy logic compatibility analysis between flow forming and Case Study II.

Centrifugal Casting	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibilty	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.20	0.20	0.50	1.00	0.25	1.00	1.00	1.00	1.00	4	0.12
Axial Tolerance [±mm]	0.1	0.5	0.8	1.5	0.25	0.38	0.63	0.50	0.92	4	0.12
Surface Roughness [Ra]	0.80	1.60	3.20	6.40	1.6	1.00	1.00	1.00	1.00	4	0.12
Workable Section Thickness [mm]	10	50	100	200	80	1.00	1.00	1.00	1.00	5	0.15
Workable Weight [kg]	1.00	10.00	5000.00	10000.000	360	1.00	1.00	1.00	1.00	5	0.15
Resulting Mechanical Propieties	2	3	4	5	≥2	1.00	1.00	1.00	1.00	3	0.09
Tooling Cost	2	3	3	4	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	2	3	3	4	≤3	1	1	1.00	1.00	3	0.09
Labour Cost	1	2	2	3	≤3	1	1	1	1	3	0.09
Optimism Level (β)	0.5					**Total Compatibility**		0.92			

Table C.18: Fuzzy logic compatibility analysis between centrifugal casting and Case Study II.

Ceramic Moulding	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibilty	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.05	0.10	0.50	0.80	0.25	1.00	1.00	1.00	1.00	4	0.12
Axial Tolerance [±mm]	0.05	0.10	0.50	0.80	0.25	1.00	1.00	1.00	1.00	4	0.12
Surface Roughness [Ra]	0.4	0.8	1.6	3.2	1.6	1.00	1.00	1.00	1.00	4	0.12
Workable Section Thickness [mm]	1	1	50	100	80	0.40	0.60	0.50	0.90	5	0.15
Workable Weight [kg]	0.10	1.00	50.00	3500.00	360	0.91	0.09	0.50	0.90	5	0.15
Resulting Mechanical Propieties	2	3	3	4	≥2	1.00	1.00	1.00	1.00	3	0.09
Tooling Cost	3	4	4	5	≤3	0.00	1.00	0.50	0.94	3	0.09
Equipment Cost	3	4	4	5	≤3	0.00	1.00	0.50	0.94	3	0.09
Labour Cost	3	4	4	5	≤3	0.00	1.00	0.50	0.94	3	0.09
Optimism Level (β)	0.5					**Total Compatibility**		0.68			

Table C.19: Fuzzy logic compatibility analysis between ceramic moulding and Case Study II.

Sand Casting	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibilty	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.65	1.50	3.50	5.00	0.25	0.00	0.00	0.00	0.00	4	0.12
Axial Tolerance [±mm]	0.65	1.50	3.50	5.00	0.25	0.00	0.00	0.00	0.00	4	0.12
Surface Roughness [Ra]	6.30	12.50	25.00	50.00	1.6	0.00	0.00	0.00	0.00	4	0.12
Workable Section Thickness [mm]	2.50	No Limit	No Limit	No Limit	80	1.00	1.00	1.00	1.00	5	0.15
Workable Weight [kg]	0.05	No Limit	No Limit	No Limit	360	1.00	1.00	1.00	1.00	5	0.15
Resulting Mechanical Propieties	1	1	1	1	≥2	0.00	0.00	0.00	0.00	3	0.09
Tooling Cost	1	1	1	2	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	1	1	1	1	≤3	1	1	1.00	1.00	3	0.09
Labour Cost	1	2	2	3	≤3	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.5					**Total Compatibility**		0.00			

Table C.20: Fuzzy logic compatibility analysis between sand casting and Case Study II.

Loast Foam Casting	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibilty	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.50	1.00	2.00	3.00	0.25	0.00	0.00	0.00	0.00	4	0.12
Axial Tolerance [±mm]	0.50	1.00	2.00	3.00	0.25	0.00	0.00	0.00	0.00	4	0.12
Surface Roughness [Ra]	3.20	6.30	12.50	25.00	1.6	0.00	0.00	0.00	0.00	4	0.12
Workable Section Thickness [mm]	2.50	No Limit	No Limit		80	1.00	1.00	1.00	1.00	5	0.15
Workable Weight [kg]	0.05	20.00	20.00	100.00	360	1.00	1.00	1.00	1.00	5	0.15
Resulting Mechanical Propieties	1	2	2	3	≥2	0.00	0.00	0.00	0.00	3	0.09
Tooling Cost	1	2	2	3	≤3	1	1	1.00	1.00	3	0.09
Equipment Cost	2	3	3	4	≤3	1	1	1.00	1.00	3	0.09
Labour Cost	3	4	4	5	≤3	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.5					**Total Compatibility**		0.00			

Table C.21: Fuzzy logic compatibility analysis between lost foam casting and Case Study II.

Investment Casting	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility	Ranked Compatibilty	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.08	0.15	0.30	0.50	0.25	1.00	1.00	1.00	1.00	4	0.12
Axial Tolerance [±mm]	0.08	0.15	0.30	0.50	0.25	1.00	1.00	1.00	1.00	4	0.12
Surface Roughness [Ra]	0.8	1.6	3.2	6.3	1.6	1.00	1.00	1.00	1.00	4	0.12
Workable Section Thickness [mm]	1.0	10.0	30.0	75.0	80	0.00	0.00	0.00	0.00	5	0.15
Workable Weight [kg]	0.01	0.50	5.00	800.00	360	1.00	1.00	1.00	1.00	5	0.15
Resulting Mechanical Propieties	2	3	3	4	≥2	1.00	1.00	1.00	1.00	3	0.09
Tooling Cost	3	4	4	5	≤3	0	0	0.00	0.00	3	0.09
Equipment Cost	1	2	2	3	≤3	1	1	1.00	1.00	3	0.09
Labour Cost	5	5	5	5	≤3	0	0	0.00	0.00	3	0.09
Optimism Level (β)	0.5					**Total Compatibility**		0.00			

Table C.22: Fuzzy logic compatibility analysis between investment casting and Case Study II.

Hot Closed-die Forging	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility*	Ranked compatibility	Weight (1/5)**	Ranked Weight
Radial Tolerance [±mm]	0.20	0.50	1.00	2.00	0.25	0.17	0.83	0.50	0.94	3	0.09
Axial Tolerance [±mm]	0.10	0.50	1.00	2.00	0.25	0.38	0.63	0.50	0.94	3	0.09
Surface Roughness [Ra]	0.8	1.6	3.2	6.4	3.2	1.00	1.00	1.00	1.00	3	0.09
Workable Section Thickness [mm]	0.10	No Limit	No Limit	No Limit	60	1.00	1.00	1.00	1.00	5	0.16
Workable Weight [kg]	0.30	2.00	100.00	500.00	32	1.00	1.00	1.00	1.00	5	0.16
Resulting Mechanical Proprieties	2	3	4	5	≥4	1.00	1.00	1.00	1.00	4	0.13
Tooling Cost	2	3	3	4	≤4	1	1	1.00	1.00	3	0.09
Equipment Cost	3	4	4	5	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	2	3	3	4	≤4	1.00	1.00	1	1	3	0.09
Optimism Level (β)	0.5					**Total Compatibility**		0.88			

Table C.23: Fuzzy logic compatibility analysis between hot closed-die forging and Case Study III.

Hot Open-Die Forging	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility*	Ranked compatibility	Weight (1/5)**	Ranked Weight
Radial Tolerance [±mm]	0.20	0.80	1.00	2.00	0.25	0.08	0.92	0.50	0.94	3	0.09
Axial Tolerance [±mm]	0.20	0.80	1.00	2.00	0.25	0.08	0.92	0.50	0.94	3	0.09
Surface Roughness [Ra]	1.6	3.2	6.4	12.5	3.2	1.00	1.00	1.00	1.00	3	0.09
Workable Section Thickness [mm]	0.10	No Limit	No Limit	No Limit	60	1.00	1.00	1.00	1.00	5	0.16
Workable Weight [kg]	0.30	2.00	100.00	500.00	32	1.00	1.00	1.00	1.00	5	0.16
Resulting Mechanical Proprieties	2	3	4	5	≥4	1.00	1.00	1.00	1.00	4	0.13
Tooling Cost	2	3	3	4	≤4	1	1	1.00	1.00	3	0.09
Equipment Cost	3	4	4	5	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	3	4	4	5	≤4	1.00	1.00	1	1	3	0.09
Optimism Level (β)	0.5					**Total Compatibility**		0.88			

Table C.24: Fuzzy logic compatibility analysis between hot open-die forging and Case Study III.

Centrifugal Casting	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility*	Ranked compatibility	Weight (1/5)**	Ranked Weight
Radial Tolerance [±mm]	0.20	0.30	0.50	1.00	0.25	0.50	0.50	0.50	0.94	3	0.09
Axial Tolerance [±mm]	0.1	0.5	0.8	1.5	0.25	0.38	0.63	0.50	0.94	3	0.09
Surface Roughness [Ra]	0.80	1.60	3.20	6.40	3.2	1.00	1.00	1.00	1.00	3	0.09
Workable Section Thickness [mm]	10.00	50.00	100.00	200.00	60	1.00	1.00	1.00	1.00	5	0.16
Workable Weight [kg]	1	10	5000	10000	32	1.00	1.00	1.00	1.00	5	0.16
Resulting Mechanical Proprieties	2	3	3	4	≥4	0.00	1.00	0.50	0.92	4	0.13
Tooling Cost	2	3	3	4	≤4	1	1	1.00	1.00	3	0.09
Equipment Cost	2	3	3	4	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	1	2	2	3	≤4	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.5					**Total Compatibility**		0.81			

Table C.25: Fuzzy logic compatibility analysis between centrifugal casting and Case Study III.

Ceramic Moulding	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility*	Ranked compatibility	Weight (1/5)**	Ranked Weight
Radial Tolerance [±mm]	0.05	0.10	0.50	0.80	0.25	1.00	1.00	1.00	1.00	3	0.09
Axial Tolerance [±mm]	0.05	0.10	0.50	0.80	0.25	1.00	1.00	1.00	1.00	3	0.09
Surface Roughness [Ra]	0.4	0.8	1.6	3.2	3.2	0.00	1.00	0.50	0.94	3	0.09
Workable Section Thickness [mm]	0.60	1.20	50.00	100.00	60	0.80	0.20	0.50	0.90	5	0.16
Workable Weight [kg]	0.10	1.00	50.00	3500.00	32	1.00	1.00	1.00	1.00	5	0.16
Resulting Mechanical Proprieties	2	3	3	4	≥4	0.00	1.00	0.50	0.92	4	0.13
Tooling Cost	3	4	4	5	≤4	1	1	1.00	1.00	3	0.09
Equipment Cost	3	4	4	5	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	3	4	4	5	≤4	1.00	0.00	0.50	0.94	3	0.09
Optimism Level (β)	0.5					**Total Compatibility**		0.72			

Table C.26: Fuzzy logic compatibility analysis between ceramic moulding and Case Study III.

Sand Casting	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility*	Ranked compatibility	Weight (1/5)**	Ranked Weight
Radial Tolerance [±mm]	0.65	1.50	3.50	5.00	0.25	0.00	0.00	0.00	0.00	3	0.09
Axial Tolerance [±mm]	0.65	1.50	3.50	5.00	0.25	0.00	0.00	0.00	0.00	3	0.09
Surface Roughness [Ra]	6.30	12.50	25.00	50.00	3.2	0.00	0.00	0.00	0.00	3	0.09
Workable Section Thickness [mm]	2.50	No Limit	No Limit	No Limit	60	1.00	1.00	1.00	1.00	5	0.16
Workable Weight [kg]	0.05	No Limit	No Limit	No Limit	32	1.00	1.00	1.00	1.00	5	0.16
Resulting Mechanical Proprieties	1	1	1	1	≥4	0.00	0.00	0.00	0.00	4	0.13
Tooling Cost	1	1	1	2	≤4	1	1	1.00	1.00	3	0.09
Equipment Cost	1	1	1	1	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	1	2	2	3	≤4	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.5					**Total Compatibility**		0.00			

Table C.27: Fuzzy logic compatibility analysis between sand casting and Case Study III.

Lost Foam Casting	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility*	Ranked compatibility	Weight (1/5)**	Ranked Weight
Radial Tolerance [±mm]	0.50	1.00	2.00	3.00	0.25	0.00	0.00	0.00	0.00	3	0.09
Axial Tolerance [±mm]	0.50	1.00	2.00	3.00	0.25	0.00	0.00	0.00	0.00	3	0.09
Surface Roughness [Ra]	3.20	6.30	12.50	25.00	3.2	1.00	1.00	1.00	1.00	3	0.09
Workable Section Thickness [mm]	2.50	No Limit	No Limit	No Limit	60	1.00	1.00	1.00	1.00	5	0.16
Workable Weight [kg]	0.05	20.00	20.00	100.00	32	0.00	0.00	0.00	0.00	5	0.16
Resulting Mechanical Proprieties	1	2	2	3	≥4	1	1	1.00	1.00	4	0.13
Tooling Cost	1	2	2	3	≤4	1	1	1.00	1.00	3	0.09
Equipment Cost	2	3	3	4	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	3	4	4	5	≤4	1	1	1.00	1.00	3	0.09
Optimism Level (β)	0.5					**Total Compatibility**		0.00			

Table C.28: Fuzzy logic compatibility analysis between lost foam casting and Case Study III.

Investment Casting	Level 1	Level 2	Level 3	Level 4	Request	Possibility	Necessity	Compatibility*	Ranked compatibility	Weight (1/5)**	Ranked Weight
Radial Tolerance [±mm]	0.08	0.15	0.30	0.50	0.25	1.00	1.00	1.00	1.00	3	0.09
Axial Tolerance [±mm]	0.08	0.15	0.30	0.50	0.25	1.00	1.00	1.00	1.00	3	0.09
Surface Roughness [Ra]	0.8	1.6	3.2	6.3	3.2	1.00	1.00	1.00	1.00	3	0.09
Workable Section Thickness [mm]	1.00	10.00	30.00	75.00	60	1.00	1.00	1.00	1.00	5	0.16
Workable Weight [kg]	0.01	0.50	5.00	800.00	32	0.97	0.03	0.50	0.90	5	0.16
Resulting Mechanical Proprieties	2	3	3	4	≥4	1.00	1.00	1.00	1.00	4	0.13
Tooling Cost	3	4	4	5	≤4	1	1	1.00	1.00	3	0.09
Equipment Cost	1	2	2	3	≤4	1	1	1.00	1.00	3	0.09
Labour Cost	5	5	5	5	≤4	0	0	0.00	0.00	3	0.09
Optimism Level (β)	0.5					**Total Compatibility**		0.00			

Table C.29: Fuzzy logic compatibility analysis between investment casting and Case Study III.

Appendix D

Systematic Literature Review of Manufacturing Processes: Case Studies

D.1 Flow Forming - Case Study IA and IB

D.1.1 Process Nomenclature

Flow forming, shear forming and conventional spinning have several common traits that can make it difficult for newcomers to clearly distinguish between different members of the family of rotational forming processes. As explained in Runge [1994], the term 'spinning' refers to all process for the production of rotating, symmetrical, hollow components. Spinning is generally defined by workpiece rotation through a mandrel where the component is clamped usually by tailstocks and is deformed into the required shape by spinning tools.

The essential difference between flow forming and spinning is that, metal spinning utilizes a relatively thinner piece of starting material than flow forming and produces the shape of the finished part from a starting blank whose diameter is bigger than the largest diameter of the finished part. This is similar to deep drawing, in which no reduction of the wall thickness occurs. Flow forming, on the other hand, is based upon a precise, pre-determined reduction of the thickness of the starting blank, or preform. reduction [Sivanandini et al., 2012].

A form of spinning that both forms sheets on to a mandrel and creates changes in material thickness is known as shear forming. Essentially flow forming and shear forming vary in the degree of the deformation mechanisms employed (e.g. reduction ratio) and the geometry of the billet (i.e. sheet for shear or tube for flow). Gur and Tirosh [1982] differentiate between these two processes by describing flow forming as being a combination of extrusion and rolling processes. Kalpakcioglu [1961b] developed a 'sine law' for shear forming, which define the angle of available deformation of the piece through the mandrel inclination without defects. This determines the spinnability of the metal undergoing these working conditions. With this hypothesis, Kalpakcioglu [1961a] defines the metal flow conditions for shear forming and conclude that it is distinctly different from the flow forming process. As in Gur and Tirosh [1982], Kalpakcioglu [1964] defines the deformation mode of flow forming as being similar to extrusion. These observations suggest that while similar shear forming and flow forming are based on different deformation mechanism and should be treated separately (Music et al. 2010). It is also interesting to note that considerable effort was expended by researchers in the investigation of shear spinning of cones during early '60s, which achieved both practical and theoretical success. However as Nagarajan et al. [1981] points out, these models are not able to predict flow forming process behaviour correctly.

Given the similarities, and differences, of the various rotational forming processes it is not surprising that there have been a number of proposals for criteria to produce an unambiguous classification. The only standard classification of spinning processes is the DIN 8582 standard which classifies processes by means of the stresses generated during spinning operation. Using this criterion DIN 8584 classifies conventional spinning as processes where plastic deformations are caused by application of tri-axial compressive and tensile stresses. Similarly flow and shear forming are defined (DIN 8583) as processes that applies only compressive stresses. Using this classification DIN 8583 makes no distinction between flow and shear forming. However is clear that while similar in the deformation force applied, flow and shear forming differ in the nature of preforms and mandrels used.

But the DIN standard does not represent a consensus view, Lange [1985], for example, groups flow forming and conventional forming with other sheet forming processes (such as deep drawing), and classifies them as tensile-compressive. Shear forming process are grouped with bulk-forming processes such as rolling, due to the compressive stresses applied to the workpiece. Similarly Kalpakjian and Schimd [2009] develops a wide classification of these manufacturing processes and divides them in bulk and sheet forming, placing all the spinning processes in the latter one. Slightly different is the definition of Music et al. [2010]. They associate metal spinning with a group of forming processes' group, where the common mechanism is a plastic deformation on a mandrel through single or multiple rollers in one or more stages.

In 1989, Wang, Z.R., Lu [1989] proposed a standard nomenclature for all spinning process, but as Music et al. [2010] pointed out in 2010, it has not been widely adopted in industrial or research environment. In summary, there is no universally accepted definition, or taxonomy, for rotational manufacturing processes. Manufacturers and researchers use different terminology for similar equipment and working techniques, especially for the ones which involve reduction of thickness. For example the process of tube spinning, flow forming, shear forming and power spinning are all simply classified as "tube forming process". The following sections reviews the experimental and analytical methodologies adopted by flow forming researchers. Some conventional spinning articles are presented when their findings, or theories, have also been shown to be valid for flow forming.

D.1.2 Theoretical Investigations - Analytical and Numerical

Theoretical methodologies are able to investigate the tension and displacement states and their evolution in the deformed blank during the flow forming process. A combination of this knowledge with failure or deformation models and criteria can predict the failure, damage accumulation and final characteristics of the worked piece.

Analytical

The main focus of analytical research is to develop a model of the flow of the metal during the flow forming process. This would provide the means to quantify the working energies and the forces required to form a specific geometry from a given billet. This can also give general feasibility boundaries for the process (e.g. maximum reduction ratio achievable in one pass for a certain kind of process and metals). All the models start with the assumption of 'conservation of volume' and consequently evaluate its distribution between axial growing and radial reduction.

Mohan and Misra [1970], use a grid-lines model in order to evaluate the tri-axial state of strain during flow forming process. Their energy based calculations of plastic work are grounded on a linear deformation hypothesis. Calculations of the displacement and knowledge of the material proprieties make it possible to evaluate the strain tensor. The main problem of this theory is the necessity of point-to-point calculation of all displacements values during the process. Using their own metal flow schematization and volume exchanging parameters, Hayama and Kudo [1979b] develop an energy model in order to predict the working forces and their relation with the reduction ratio. They divide the energy exchange in the process into four main parts: plastic deformation energy (under the roller), velocity discontinuity energy consumption (due to the metal flow velocity discontinuities in the various worked zones), frictional energy (contacts between mandrel/piece and piece/rollers), and blocking energy (mandrel constrains). They are able to make a unified theory for backward and forward spinning by identifying the position of the neutral line of plastic flow. This zone identifies the volume of material that passes from the front of the roller to the growing zone of the worked piece. For the backward process, this zone is located at a certain distance from the roller on the feed axis. In contrast, the forward process has this point exactly under the contact point between roller/piece. Singhal et al. [1990] simplify the Hayama and Kudo [1979b] approach for stainless steels, excluding diametral growth, which is negligible for hard materials. They evaluate power absorbance by friction and velocity, and make the conclusion that the first (i.e. friction) has no influence. Jolly and Bedi (Jolly & Bedi 2010) apply the same model but with a different reference system. They use a polar coordinates system and a circumferential force. The authors define the contact zone between rotating tools and workpiece as a circular sector of the roller (14°), which is consider infinitely rigid. Regarding aluminium alloys, another application of the Hayama's model is described by Molladavoudi and Djavanroodi [2010], including diametral growth and plasticity parameters. The authors include microstructural analysis and defects correlation with process parameters, and reach conclusions similar to other experimental evaluations.

Gur and Tirosh [1982] use an upper-bound method for analysing the contact between roller and workpiece during the flow forming process. Material may flow beneath the roller in axial direction (L) or circumferential direction (S). If the length of circumferential contact is much longer than the axial contact length, then the axial plastic flow dominates the circumferential one. Axial flow must overcome the circumferential in order to avoid huge friction phenomena and avoid defects in the final product (waves on the external surface and thickness inhomogeneity). The authors develop simple formulas for S and L. In this way, it is possible to evaluate the S/L ratio for establishing dominant flow and defect insurgence. This methodology has been tested and validated for different conditions and materials by several papers, through experimental and numerical methods [Jackson and Allwood, 2009, Rajan and Narasimhan, 2001, Roy et al., 2010, Parsa et al., 2008, Jalali Aghchai et al., 2012, Podder et al., 2012].

Roy et al. [2010] extend this work in order to obtain a detailed analytical expression of contact zone. Division of contact in various sectors allows the authors to identify different contribution of process parameters in the contact surface area. Experimental results confirm validity of model and its relation with S/L. The mathematical model has a complex geometrical approach even if it does not correlate the material and superficial proprieties.

Park et al. [1997] develop an upper-bound method built in comparison with traditional tube ironing. Stream functions are developed in order to evaluate the changing speed in the material during for backward and forward flow forming processes with the same approach. Plastic stream stress and working forces are calculated taking into consideration three different types of velocity fields in the material (one trapezoidal and two spherical).

Nagarajan et al. [1981] adopt previous models for shear forming and spinning (such as Mohan and Misra [1970]) and report a systematic evaluation of them through experiments and empirical data (process efficiency) to establish the effectiveness of the models. Rotarescu [1995] applies a similar approach for flow forming of tubes using spherical tools (balls). The author develops a different contact zone model in order to evaluate the multi-balls deformation mechanism.

Xue et al. [2011] develop a multi-objective optimizing algorithm (using the Fortran language) in order to evaluate a staggered configuration of the rollers (three rollers in a row) in forward flow forming. This design of the flow forming machine permit what would traditionally be multi-pass processes to be implemented in only one step. Lee and Lu (Lee & Lu 2001) develop a simple formula for the calculation of the tension during a six rollers flow forming process through monitoring continuously the forces with power sensors. The total force of deformation and its frictional contributions (in plasticization zone and non- plasticization zone) are evaluated but without considering the energy consumption.

Numerical Finite Element Models (FEM) allow aspects of the flow forming process to be evaluated that are challenging to assess analytically (e.g. roller deformation). Numerical simulation avoids the expense of experiments and allows precise understandings of process trade-offs to be developed. However, the implicit necessity of 3-dimensional modeling and complexity of contact surfaces create difficulties in this kind of approach. Despite this, eleven papers have reported numerical models for flow forming.

Three papers use an implicit approach [Xu et al., 2001b, Kemin et al., 1997b,a, Yang and Lin, 1997], meanwhile six use an explicit approach [Wong et al., 2005, Lexian and Dariani, 2008, Parsa et al., 2008, Jalali Aghchai et al., 2012, Li et al., 1998, Mohebbi and Akbarzadeh, 2010]. Wong et al. [2004] compare both approaches. Only two paper [Xu et al., 2001b, Li et al., 1998] model numerically friction between roller and workpiece, (while other authors neglect friction contributions to displacement). Mainly commercial software (e.g. ABAQUS) are used and modified for developing solving codes.

[Wong et al., 2004] combine two different roller path and different rollers geometry (flat and with a nose) in order to evaluate their effect. Two different types of roller are identified: radial and axial. These are determined by the approach direction. Both radial and axial paths are possible depending on the approach direction taken towards the blank. In the radial approach the axis is perpendicular to the spindle axis, in the axial paths, it is parallel. The influence of these two methods on final proprieties and working force and defects are combined with influence of roller geometry.

Lexian and Dariani [2008] develop a non-linear model that simulates the contact surface between roller and workpiece, excluding the friction among the parts. Surfaces are modeled with 3D-shell elements. Kemin et al. [1997a] use 3D-brick elements in order to evaluate working forces in a three staggered roller deformation process. Differently from all other researchers, they use the ADINA FEA software. This attempt extends the authors previous work on 2-dimensional modeling of the flow forming process Kemin et al. [1997b] in order to evaluate the linearity/non-linearity of the contacts in a two roller flow forming system. The symmetry of the point of contact make it possible to model a surfaces that rotate with the contact points during the process.

Li et al. [1998] developed a rotational transformation matrix in order to morph the simple hinges model on the contact surface in polar coordinates. This coordinate transformation is applicable in both the flow forming variants, if 3D elements are applied, in order to easily define the constraints with mandrel and rollers.

Xu et al. [2001b] applied differential equations to the numerical model follow a particular methodology (Markov). The stress and strain states are evaluated and resemble different state of tension around the contact zone for reverse and frontal flow forming. Also if the model is complex, the results agree with Hayama's approach (giving further validity to this model). Explicit and implicit solutions for FEA are proposed by Wong et al. (2004) for the flow forming of lead. From the analysis results, the implicit method appears to give the best correlation with the experimental results. However, Parsa et al. (Parsa et al. 2008) report an explicit solution, justifying this choice with the possibility to maintain the interaction between nodes and the consequent transfer of forces with better coherency. Mohebbi and Akbarzadeh (Mohebbi & Akbarzadeh 2010) also use an implicit solver for simulating the flow forming process. In order to evaluate the local deformation, pins are mounted on the model experimental validation's workpiece. Jalali Aghchai et al. [2012] use DoE for evaluating the most influential factors for diametral growth. The S/L ratio is used to validate their models results. Some of the authors use a DoE methodology to structure the analysis produced by FEM investigations. In this way only statistical relevant parameters for the selected responses are evaluated during numerical modeling.

Implicit code is more related the to nature of the problem than the explicit one. The difficulty of converging solutions for the highly nonlinear process and the high computational cost of implicit approaches have pushed researchers to select explicit methods. Overall the explicit approach seems to be the best alternative because of its robustness, computational efficiency, and its ability to produce a largely quasi-static response. Explicit code is also conditionally stable although it is affected by challenges inherent in implementing sufficient time steps due to the long process cycle time. One proposal for overcoming this computational problem is to reduce the number of increments by increasing material density or loading speed, as expressed in Wo et al. [2000]. Although, this approach may increase computational speed effects, it will decrease solution accuracy (i.e. impacting on inertial effects).

D.1.3 Experimental Investigations

In flow forming, empirical studies have been used to seek correlations between inputs (e.g. the workpiece material's properties and process parameters such as the radial, tangential and axial forces on the rollers) and outputs (e.g. surface roughness, mechanical properties or dimensional accuracy).

A notable example of this approach is [Hayama and Kudo, 1979a] who report an experimental investigation into backward and forward tube-spinning (effectively flow forming with two rollers) through different reduction ratios and parameters setting (feed rate and rollers angle) on mild steel. First, they evaluate the impact of process variables on the product's dimensional accuracy. They explicitly distinguish between different material flow conditions using the concept of a plastic wave (created in the upper zone of contact between the roller and the workpiece) of material displaced along the workpiece. A coefficient that defines the size of the plastic wave is defined and used to evaluate the 'stability' of the process. Not surprisingly larger wave sizes are associated with an unstable process.

The experimental validation of an analytical model of flow forming is reported in Hayama and Kudo [1979b] that represents the volume of material that flows in axial direction, (which is a fraction of the volume of material involved in the deformation process). These parameters give a numerical explanation of the physical phenomena of deformation. The results confirm the influence of thickness reduction ratio, feed rate and roller geometry on process stability and accuracy.

Experimental work by Jahazi and Ebrahimi [2000] also demonstrates that the axial flow must overcome the circumferential flow in order to avoid friction phenomena and avoid defects in the final product (e.g. waves on the external surface and thickness inhomogeneity). Singhal et al. [1987] test these theories on hardest and low deformable materials by conducting experiments on various alloys such as pure Titanium, Titanium alloys (Incoloy 825), Ni-Cr steel (Inconel 600) and stainless steel (AISI-304). Different reduction ratios were tested to evaluate the final material proprieties and dimensional accuracy, as well as a microscopic investigation for evaluating the final product hardness.

Chang et al. [1998] also investigated the forming limits of Aluminum alloys for forward and backward flow forming, adopting different process parameters and roller configurations. The tested materials are two different alloys (2024 and 7075) and two different heat treatments (full-annealed and solution-treated), giving a total of four combinations. Micro-spinnability and macro-spinnability are evaluated for these four combinations of materials and heat treatments. The latter is evaluated by varying the thickness reduction until failure (destructive testing) or until reaching the desired reduction ratio (non-destructive methods). Micro-spinnability is evaluated with non-destructive methods such as microscopic techniques (Transmission Electron Microscopy - TEM , Scanning Electron Microscopy - SEM, Optical Microscopy - OM) and Vickers hardness measurement for detecting the presence of microcracks and microvoids on the surface.

Jahazi and Ebrahimi [2000] investigates the effect of flow forming on steel using Vickers and Rockwell hardness tests. By assessing yield strength and final true strain of the material, they are able to measure the fracture resilience of the material. The trials are conducted for different rollers geometry and reduction ratios. They also map the relationship between axial contact and circumferential contact, which are evaluated using the S/L methodology [Gur and Tirosh, 1982]).

Rajan and Narasimhan [2001] investigate the occurrence of defects in flow forming steel tubes production. The authors use a sequence of non-destructive/destructive investigations that consist of a proof pressure test followed by a burst pressure test, in order to evaluate the final product proprieties. Rajan et al. [2002b] perform different tests on flow formed pressure vessels in AISI 4130 steel in order to evaluate the effect of the heat treatments (annealing, normalizing, quenching and tempering). Rajan et al. [2002c] also investigate the production of flow formed pressure vessels, applying high pressure until material failure (Sevensonn model). The microstructure is investigated in order to detect the grade of grain elongation, in comparison with thickness reduction. The authors described a number of distinct phases of the forming process using a flowchart and apply analytical method to determine the preform dimensions and the expected ultimate strength.

Groche and Fritsche [2006] apply the flow forming to the production of a wheel with internal gear teeth. Their description of the development of three dedicated mandrels and roller configurations is a significant contribution. [Gupta et al., 2007] investigate flow formed crack propagation mechanism for Niobium alloys. Material proprieties are evaluated through SEM investigation and hardness tests with visual inspection to locate defects. Davidson et al. [2008] investigates the causes of roundness errors and variability in other measures of flow forming quality.

[Roy et al., 2009] test surface micro hardness (Berkovic) of a workpiece to map true stress and strain resulting from forward flow forming operation. Evolution of strain is characterized by roller/mandrel contact and thickness reduction ratio. The authors develop two expressions in order to evaluate the strain due to the mandrel effect and the rollers effect. The sum of these two strains gives the total deformation on the axial direction. A local frame is defined in the contact zone, where functions determine its angular limit and allow an analytical expression of the contact surface to be developed. Interaction zone extension is measured iteratively for the whole process.

Haghshenas et al. [2011] relate the indentation hardness (Berkovich) and the Von-Mises true strain for flow forming of splined steel wheels. In this way, equivalent stress can be deduced for the critical point of the workpiece. The measurements of hardness were performed at different points on the wheels, particularly around the ribs where the deformation is largest. The authors map the strain on the mandrel's external surface, for different reduction ratios. The same approach is used later in Haghshenas et al. [2012] for evaluating hardening in internal splined wheels.

[Podder et al., 2012] discuss the influence of preform heat treatment on the reduction ratio and its influence on final strength for backward flow forming. To do this they map the true stress and strain for different heat treatments condition (e.g. spheroidizing, hardening and tempering, annealing).

Notarigiacomo et al. [2009] investigate the influence of process parameters on fatigue behavior of flow formed wheels for automotive industry. The authors develop an experimental correlation between strength and surface proprieties of wheels. They develop and validate a FEM fatigue model which is able to predict increasing of fatigue life in connection with thickness variation.

Design of Experiments (DoE)

DoE is a methodology for designing programs of experiments to determine the relationship between factors affecting processes and their output. By identifying cause-and-effect relationships process inputs can be managed to optimize outputs.

Davidson et al. [2008] use Taguchi Orthogonal Arrays (OAs) in order to evaluate the critical factors and their influence on the mean value of reduction ratio for an aluminium alloy. The authors also use another statistical method, called analysis of variance (ANOVA), with the aim of quantifying the relative influence of each parameter. Using this, a general optimization based on the selected parameter levels is developed. In another investigation on aluminium alloys, Nahrekhalaji [2010] use classic DoE with fractional factorial design in order to characterize the flow formed diameter thorough a polynomial regression equation. Although the number of variables is probably too high (related to the number of trails) to give a robust statistical significance to the results (i.e. error degree of freedom in ANOVA analysis would be too low).

Srinivasulu et al. [2012a] develop a characterization of the process through the use of a particular classic DoE design (Box-Behnken), which is strictly related with RSM (Response Surface Methodology) evaluation of the results. Their ANOVA takes into consideration the importance of the degrees of freedom. The RSM is able to predict the internal diameter in the selected range of variables with good approximation (i.e. the error is less than 0.08%). Table D.1 summarizes characteristics of the reported application of DoE to investigation of flow forming process. Jalali Aghchai et al. [2012] use fractional factorial DoE and graphical method (i.e. RSM) in order to characterize the variables of their model for steel. They report that ANOVA determines the reduction ratio has more influence on the process than roller geometry and axial speed. The authors proposed an optimized set of the variables built by simulation trials for validation. Wang and Long [2013] use only an interaction plot and analysis of means without producing optimization of output.

D.1.4 Prediction Models

Prediction of product final geometry

Relating the final product geometry to specific process parameters is one of the main aims of researchers working flow forming. However the task is far from simple; for example although the final diameter is imposed by roller distance several effects, such as springback, material proprieties and tension state also influence the final shape of the flow formed product. Accuracy of product diameter and dimensional tolerance are related to both process parameters

	Davidson et al. (2007)	*Nahrekhalaji et al (2009)*	*Srinivasulu et al (2012)*	*Wang et al. (2013)*	*Jalali Aghchai et al. (2012)*
DoE methods	Taguchi OAs (L9)	Classic DoE (Fractional Factorial)	Classic DoE (Box-Benknen design)	Taguchi OAs (L4)	Classic DoE (Box-Benknen design)
Experiments' aim	Optimization	Characterization, Modeling	Characterization, Modeling, Optimization	Screening, Robustization	Optimization
Repetitions	-	-	-	2	-
Number of trials	9	3	17	4	17
Variables number	3	5	3	3	3
Selected variables	Depth of cut, Spindle speed, Feed rate	Thickness reduction ratio, Spindle speed, Feed rate, Initial thickness, solution time, aging time	Roller Radius, Spindle speed, Feed rate	Feed rate, Spindle speed, Material (mild steel, aluminium)	Thickness reduction ratio, Feed rate, Roller nose radius
Variables levels	3 (max, med, min)	2 (max, min)	2 (max, min)	2 (max, min)	3 (max, med, min)
Responses number	1	1	1	3	1
Selected responses	Thickness reduction ratio	Final external diameter	Final internal diameter	Final internal diameter, minimum wall thickness, final depth	Diametral growth
Evaluation method	ANOVA, Non standards plot	ANOVA, Polynomial Regression, Normal Plot	ANOVA, RSM, Polynomial Regression, Normal Plot	Interaction plot, ANOM	ANOVA, RSM

Table D.1: Summary of experimental DoE approaches to flow forming.

and machine configuration, so researchers have investigated how these interact to determine the final geometry. The diametral growth of formed parts is studied analytically and numerically, but experimental approaches are mainly used for springback and roundness/ovality evaluation:

Diametral growth affects mainly soft material like aluminum or copper alloys [Singhal et al., 1990, Hayama and Kudo, 1979b]. In this case, it increases with feed rate and thickness reduction. Only in case of highest thickness reduction and thickness reduction ratio, is it found to decrease. In case of low and medium carbon steel, problem of diametral growth appear with high thickness reduction and also in backward flow forming. In other words a large reduction of thickness (i.e. analogous to "depth of cut" in machining terminology) combined with lower feed rates can also produce diametral growth [Davidson et al., 2008]). Management of the contact ratio between circumferential and axial length (S/L) is the primary technique for minimizing this factor [Rajan and Narasimhan, 2001].

There is no theoretical model available to accurately predict *springback*. It generally depends on the amount of reduction, the strain hardening exponent of the material, the geometry of the roller and the feed rate [Rajan and Narasimhan, 2001].

Roundness error is influenced by thickness reduction and feed rate. Reduction increasing decreases workpiece roundness, due to most uniform deformation under the roller. On the other hand, this deformation causes other defects (e.g. waviness). So, Davidson et al. [2008] propose 2mm of thickness reduction as an optimal solution. Feed rate increasing is proportional to roundness; while defects are only slightly correlated with variations in mandrel speed. So feed rate, thickness reduction, material properties and roller geometry impact significantly on product geometrical proprieties.

However, *geometrical inaccuracies* evolve into defects when they overcome certain levels (e.g. out-of- roundness). Table D.2 summarizes main effect of process parameters on the appearance of defects.

In this area, it is clear that improved FEM models, including material characterization, and experimental models would have a great impact on the accuracy of geometrical prediction. Better connection needs to be established between analytical models, FEM and experimental validation. However for now, the S/L ratio remains a good measure of the impact of process parameters on flow forming process accuracy.

Prediction of surface properties

Although typical ranges of surface roughness values for different materials have been established the precise relationship between process parameters and surface roughness is an open question in flow forming research.

Singhal et al. [1987] suggest that surface finish is independent from reduction ratio and always less than 0.9 m (Ra values) for stainless steel and hard to deform alloy, such as Titanium or Inconel. Lubricant selection has an impact on surface finishing of flow formed materials. For steel, surfaces are between 0.5 and 0.8 m and although different lubricants and reduction ratios change these values, surface roughness never moves beyond the cited range [Prakash and Singhal, 1995]. Increasing feed rate impacts negatively on surface roughness, due to the associated increase in radial force. With a constant roller radius value, Rajan and Narasimhan [2001] notice an increase in roughness (from 0.8 μm to 1.6 μm) as the feed ratio increasing (from 50 mm/rev to 100 mm/rev). The same authors develop an empirical relationship (D.1) for calculating the height of the feed marks on the workpiece surface. The relationship shows that for decreasing feed rate and increasing roller radius, superior surface roughness tends to be achieved.

$$h = R - \frac{1}{2}\sqrt{4R^2 - f^2} \quad \text{(D.1)}$$

Where, h is the height of the mark on the workpiece [mm], f is the feed ratio [mm/rev] and R is the roller radius [mm].

Although researchers have shown that material microstructure, feed rate and roller dimensions are parameters with most impact on surface roughness there is still a need for further investigations into the influence of other process characteristics on final surfaces roughness. In the future, it is likely that FEM models would be able to use material grains as element and consequently predict surface roughness but such a capability still needs modeling refinement and experimental validation.

Prediction of mechanical proprieties

In addition to the process parameters (i.e. speeds and feeds) the material properties of the formed parts depend on the microstructure and heat treatment of the workpiece. The following investigations have attempted to quantify these interactions.

For example the, tensile strength of flow formed parts changes from longitudinal direction to radial due to the grain structure created by cold forming. Radial ultimate tensile stress is measured as 0.93 the hoop tensile strength in Rajan et al. [2002b]. Singhal et al. [1987] register an increasing tensile strength with reduction up to 0.75, for all tested materials (steel, Titanium and Inconel). For reductions beyond 0.8, however, the tensile strength was found to decrease. In Prakash and Singhal [1995] for a blank thickness of 4mm, the tensile strength of the stainless steel AISI-304 increased from 637 MPa to about 1421 MPa at about 0.8 reduction and the yield strength (0.2% proof stress) form 431 MPa to about 1324 MPa. The ductility decreased to below 0.1 and the mechanical proprieties exhibit negligible correlation with feed rate and mandrel speed [Notarigiacomo et al., 2009]. Similarly for Aluminum, Chang et al. [2001] determine that the ultimate tensile strength has a relationship with the amount of thickness reduction (Figure D.1).

In Podder et al. [2012], true stress-true strain curves for steel are seen to conform closely to Hollomon's relationship. Notarigiacomo et al. [2009] investigate the fatigue strength of flow formed components. Experimental investigations suggest a partial correlation between fatigue strength and surface roughness. A closer correlation is found between fatigue strength and microcracks on surfaces generated by flow forming processes. For a reduction of 0.4, a general improvement in fatigue life is estimated for all tested steels (from 20% to 40% of fatigue strength increasing).

The avoidance of further machining operations and heat treatments motivates researchers to continue to improve proprieties prediction. Indeed defining a product's final proprieties correctly ensures proper process design and so minimizes further operations for reaching product

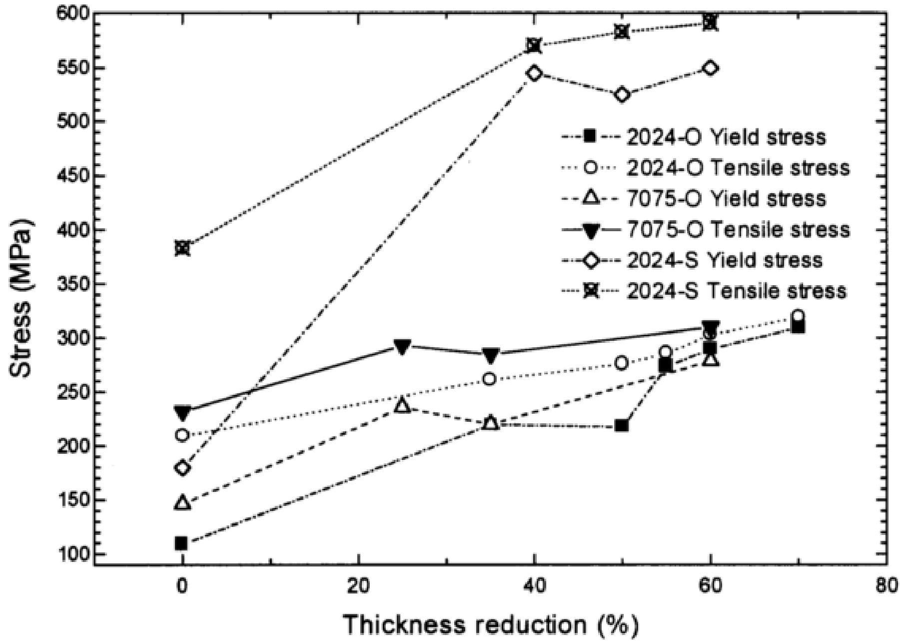


Figure D.1: Axial tensile properties of 7075-O, 2024-O and 2024 aluminium tubes for different reduction ratios [Chang et al., 1998].

quality.

Prediction of microstructure and its effects

The ability of the flow forming process to modify and influence microstructure is an extremely important part of the process. Material behaviour plays a fundamental role in severe cold plastic forming processes, so a preform's microstructure and heat treatments can be significant factors in the results. Evolution of microstructure for different process configuration has been investigated by several authors.

The anisotropy of the final flow formed structured is investigated in Rajan et al. [2002a]. The grains are stretched along the flow forming axis and, as consequence, the catastrophic cracks created by burst tests happen in the hoop direction instead of the axial. As exposed in Haghshenas et al. [2011] for steel, elongation of the worked material grains along the feed axes is noticed as well as the stretch of ferrite grains in zone of high plastic deformation.

These zones are usually located in the mandrel contact zone.

Generally, increasing carbon content and increasing amount of alloying elements decrease spinnability as well as inclusion and precipitates. The literature suggests that generally, alloy steel with more than 4% of carbon should not be used [Rajan et al., 2002b]. For hard to deform material (Titanium, Incoloy and Inconel), Singhal et al. [1987] notice no significant changes in micro-hardness for various reduction ratios. At the beginning of the operation, there is increase in hardness, although at about 0.6 reduction it becomes almost constant. Microscopic examination of a 0.85 reduction sample was carried out and it was found that the tube had developed microcracks. In Gupta et al. [2007], a niobium alloy is worked successfully with a good reduction rate (0.2-0.25). This kind of alloy exhibits significant hardening with only one pass, which can compromise the structure integrity in sequent forming steps. Consequently the authors recommend annealing treatment between the passes. Chang et al. [1998] also note that aluminum alloys may reach a spinnability of 0.7, which is limited only for solution-treated alloys. Figure D.1 shows alloys' microstructures for different thickness reductions. The micro-hardness investigation shows a clear inhomogeneity of hardness due to the anisotropy of the final structure, due to the elongated grains in axial direction. This behavior increases exponentially with the magnitude of thickness reduction. Indeed surface hardness demonstrates the same type of relationship with thickness reduction [Chang et al., 1998, Nagarajan et al., 1981, Molladavoudi and Djavanroodi, 2010]. Different heat treatments (e.g. quenching, tempering, annealing) are evaluated in Jahazi and Ebrahimi [2000] to establish the influence of the parameter on the final microstructure of the flow formed parts. Annealing does not give resilience to crack propagation, less strength and hardness. But tempering and quenching have the opposite effect although impurities and inclusions limit their usage. The authors propose an optimum heat treatment cycle, based on an ideal combination of resulting strength and toughness. Rajan et al. [2002b] agree with the previous statement, including normalizing in the tested heat treatments for steels. The

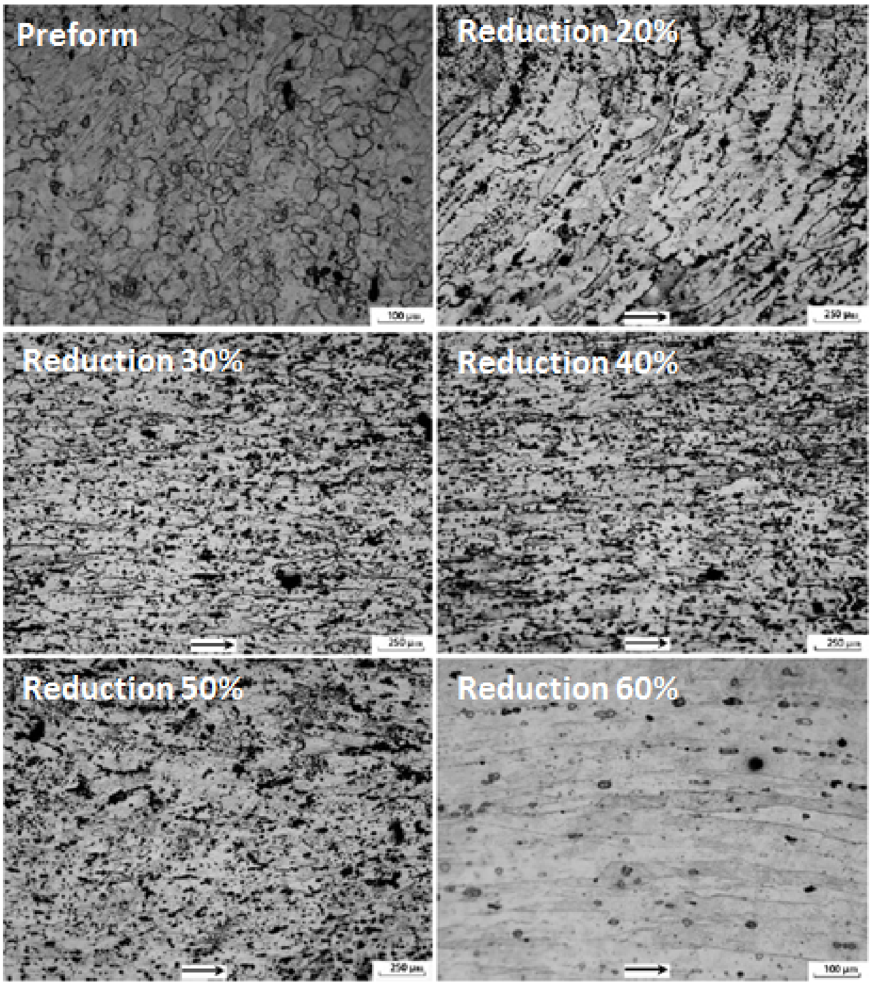


Figure D.2: Microstructure of full annealed 7075 aluminium alloy, 0.2 thickness reduction, 0.3 thickness reduction, 0.4 thickness reduction, 0.5 thickness reduction, 0.6 thickness reduction [Molladavoudi and Djavanroodi, 2010].

annealing improves steel formability and decrease working stresses and forces but do not provide enough tensile strength to make the final part, distinctive from the other hardening treatments. Numerical modeling is still not able to reliably predict grain dimension after forming process. Heat treatments are tested by several authors but not for the complete range of available materials and process parameters, consequently even empirical models are unavailable.

Prediction of power and tool forces

One of the early objectives of academic research was the analytical prediction of forces in flow forming process. A total of twenty papers have reported different approaches to force prediction in flow forming and conventional spinning (fourteen analytical, four numerical and two experimental). The forming force is composed by three mutually orthogonal components: radial, axial and tangential (or circumferential, if a polar reference system is adopted). In the literature the reference system always indicated axial axes as the mandrel one.
For soft materials, Hayama and Kudo [1979a] develop a connection between the reduction rate of thickness and process instability by an evaluation of the wave of material thorough consideration about the variation of the measured radial forces. Usually, the radial force is constant with the stroke of the roller. Indeed if it begins to increase, the process is considered unstable. With these criteria, it is possible to evaluate the critical reduction ratio (called the limit degree of thinning) and feed ratio in order to obtain a steady plastic flow. The authors assert that forward spinning has a bigger set of stable conditions than backward. A linear relationship is also denoted between the reduction ratio and the inverse of the feed rate. Hayama and Kudo [1979b]also present an analytical evaluation of the working forces and how they change as a function of the reduction ratio. The effect of the increasing of roller's attack angle is investigated in Singhal et al. [1990] for hard materials.
Radial force in tubes spinning is bigger than axial force, that in turn is bigger than the tangential component for every configuration and process parameters [Hayama and Kudo, 1979b, Park et al., 1997, Prakash and Singhal, 1995, Wong et al., 2004, Parsa et al., 2008, Roy et al., 2009, Xu et al., 2001b]. All three components of forming force increase with the reduction ratio and feed rate [Hayama and Kudo, 1979b, Singhal et al., 1990]. Increasing the roller diameter increases both with radial and axial components [Singhal et al., 1987, Jolly and Bedi, 2010], with only negligible effect on tangential component [Singhal et al., 1990]. Axial force recorded is higher with reducing feed rate because of the higher real reduction achieved. Fric-

Process parameters	*Force components*			*Total forming Power*
	Axial	*Tangential*	*Radial*	
Increasing feed ratio	+	+	+	+
Increasing mandrel speed	negligible	Negligible	negligible	negligible
Increasing working depth	not available	not available	not available	not available
Increasing thickness reduction ratio	+	+	+	+
Increasing preform diameter	+	Negligible	+	+
Increasing roller attack angle	+	+	-	optimum exists
Increasing roller nose radius	not available	not available	not available	not available
increasing roller diameter	+	Negligible	+	+
increasing friction factor	+	+	not clear	optimum exists
Increasing preform hardness	+	not clear	not clear	not clear
Increasing preform yield strength	+	+	+	+
Increasing preform ductility	not clear	not clear	not clear	not clear

Table D.2: Effect of process parameters on forming forces (components) and forming power.

tion factor impacts on radial, axial and tangential forces but it does not have a significant effect on power consumption [Park et al., 1997]. Table D.2 summarizes the effect of process parameters, roller geometry and preform. Exactly how material microstructure, hardness and ductility impacts on tool forces are still not clear and severely case dependent. Prediction of instantaneous stress and accumulated strain is a necessary step in the process of forces prediction. The same approach allows damage evolution to be assessed in the workpiece during forming operation. Interestingly none of the authors surveyed are concerned about residual stress insurgence and their impact on stress/strain behaviour and proprieties of worked product. Material microstructure evolution is also not studied in comparison with strain behaviour during process.

Roy et al. [2009] determine the maximum equivalent plastic strain from experimental measures of surface hardness. A map of true strain is developed for all contact regions. Functions, which correlate experimental values and maximum equivalent strain, are developed for different thickness reduction (while keeping constant other parameters). The authors [Roy et al., 2009] also get a maximum admissible strain which allows them to map available thickness reductions for AISI 1020 steel. Haghshenas et al. [2011] use a similar procedure for mapping equivalent strain of two aluminum alloys (6061 and 5052-O). The alloy with greatest point-to-point difference in equivalent plastic strain on a formed workpiece has the highest final yield stress propriety. The authors associate strain behaviour only with high variability in alloy grains, and yield stress increasing to hardening behavior.

Front tension increases with the deformation ratio but also decreases with frictional forces increase (between workpiece and mandrel, as described by Lee and Lu [2001]) though sensor measurement during flow forming of tubes.

Xu et al. [2001b] identify complex tensional and strain states in the contact zone. They divide contact into three zones: metal before and behind axial direction of roller (zone A), tangential regions (zone B) and contact zone (zone C), called radial. The first one has a tri-axial compressive tensional state, which produces compression in axial direction and tension in tangential and radial directions. When compression in zone B overcomes the tension in contact zone C, it results in compression in the axial direction producing tube reduction meanwhile tension in radial direction leads to material piling. Figure D.3 shows schematic diagram stress and strain in the various regions of the workpiece (top) and deformation distribution in axial, radial and tangential directions (bottom). The numerical model results in agreement with Hayama and Kudo [1979b].

Prediction of failure

Prediction of instant stresses, accumulated strains and damage evolution should lead to an understanding of failure mechanisms and the prediction of failure [Music et al., 2010]. Interestingly experimental, numerical and analytical studies all have slight different definitions of "failure". Due to absence of general connection between strain/stresses and modes of failure, latter researchers have been identified as the manifestations of fracture and defects. For

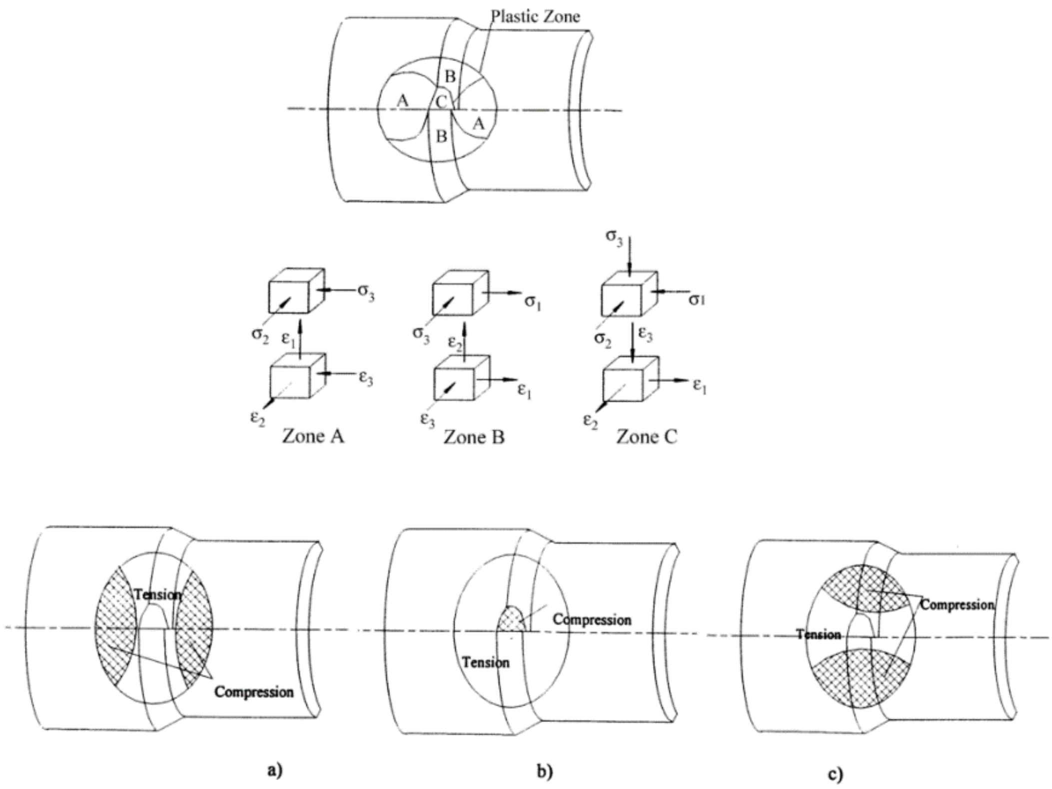


Figure D.3: Schematic diagram of stress and strain in various regions (top). Distribution of deformation in various direction: (a) axial direction; (b) radial direction; (c) tangential direction [Xu et al., 2001b].

example some of the authors in this section identify fracture as a phenomenon caused by tension in forward flow forming and buckling in backward.

Chang et al. [1998] identified the critical reduction ratios for *microcracks* propagation. Exceeding these values, the fractures become visible with a microscope. The main reason for generating this phenomenon is the nucleation of microvoids (due to inclusions and incoherent particles). This propagation is registered both on surface and within the material matrix. Also if the material appears to have good macro-spinnability proprieties, microcracks eventually extend to form cracks both in axial and circumferential direction. These defects generated on the surface will degrade the surface finish and eventually reduce the feasible thickness reduction, even if the visual quality of the part remains unchanged. Although these deformation have little effect on the ultimate tensile strength, they affect fatigue life and result in extended *macrocracks* for higher reduction ratio. Microcracks and macrocracks are strictly connected with flow stability [Rajan et al., 2002b]

Excessive diametral growth (thickness variation), ovality (out-of-roundness), fish scaling (or bulging or waviness), wrinkling and springback are the main forms of defects, which may occur during flow forming process.

Ovality (out-of-roundness) is influenced by feed rate and roller radius, but the defect can be minimized through correct selection of these two parameters, as demonstrated in Srinivasulu et al. [2012a]. Decreasing feed rate produces deformation in the radial direction, which in turn causes an increase of ovality. Highest values of feed rate combined with low reduction rate produce largest ovality. Podder et al. [2012] also assert influence of heat treatments and microstructure on ovality.

Wrinkling is caused by lack of a proper mandrel support and excessive feed rate, as investigate in Gupta et al. [2007] for Niobium alloys. High and complex tensional states are the main causes of these defects. As results at tip of the wrinkles, microcrackings are generated due to combined bending and buckling.

Fish scaling (bulging or waviness) is mainly due to none uniform grain size, particle inclusion and residual stresses. Low roller attack angles and feed rates may develop defects that lead to cracking [Rajan and Narasimhan, 2001]. Essentially a high fee rate produce wave-like surfaces, even more if in combination with elevate depth of cut [Davidson et al., 2008]. Large attack angle in combination with high feed rate are responsible for these defects in backward and forward tube spinning [Hayama and Kudo, 1979a].

As mentioned, the relationship between defects and the ratio of circumferential and axial contact length is used by several authors. S/L ratio expresses plastic flow quality for given of process parameters; therefore it represents a simple and effective instrument for obtaining indications about defects insurgence. If the axial contact length (L) is greater than the circumferential length (S), circumferential plastic flow dominates (S/L<1). Consequently geometrical inaccuracies and defects emerge in this case. Increasing the S/L ratio causes interfacial friction to enhance the axial flow. In this case (S/L>1) and most of the material flows in axial direction and defects tend to disappear. Although, if the contact ratio becomes too large (S/L>>1), the friction coefficient becomes close to unity and the material flows under the roller along a direction angle, which is smaller than the attack angle. In this case, wave-like surfaces and thickness variation in workpiece occur.

D.2 Centrifugal Casting - Case Study II

D.2.1 Analytical Investigations

Some analytical models of the centrifugal casting process have been reported in the literature [Gao and Wang, 2000, Biesheuvel and Verweij, 2000] focus on the investigation of the centrifugal casting of Functional Grade Materials (FGM).

Biesheuvel and Verweij [2000] developed a model to describe the cast profile that develops during centrifugal casting of a bimodal particle ensemble, with particles of different size and density; the model can be used to describe the development of non-homogeneous cast profiles. Gao and Wang [2000] developed a predictive model based on a multiphase modelling framework has been developed for creating FGM by centrifugal casting. The authors use water as the matrix and glass beads as the particle phase, and perform unidirectional solidification experiments in a rectangular test cell to validate their multiphase mode.

D.2.2 Numerical Investigations

Numerical articles [Chang et al., 2001, Fu et al., 2008, Keerthiprasad et al., 2011, Ping et al., 2006, Song et al., 2012, Zagorski and Sleziona, 2007, Long and Zebin, 2016] focus on predicting microstructure mechanics (in macroscale and microscale), fluid dynamic behaviour (turbulences and fluid states), temperature and velocity fields, and mould filing conditions for different process parameters and mould geometries.

For Aluminium alloys, Chang et al. [2001] develop a stochastic model for predicting both the solidification of grain in vertical centrifugal casting. The model is developed in two parts: a cellular automaton (CA), which can simulate the evolution of the macrostructure during the solidification process (i.e. two-dimensional right angle coordinates for the structure simulation), and a finite volume method, which calculates the transferred heat (i.e. one-dimensional polar coordinate for the temperature field). Using a modified CA, the evolution of the dendritic structure could also be studied. The authors studied the effects of process parameters on the solidified structure. The computational efficiency was found in agreement with experimental results (Figure D.4). Moderate mould rotation speed, low melt superheat, low mould preheat temperature and a slight higher solute concentration are the best combination of process parameters for obtaining the fine equi-axed grain structure in vertical centrifugal casting. Similarly, Ping et al. [2006] develop a multi-scale model for vertical centrifugal casting of a Ti-Al alloy, combining 3D finite difference method (i.e. macroscale) with a 2D cellular automaton (i.e. micro-scale) simulation. The macro-model simulated fluid flow, heat transfer and mass transfer, while the micromodel modelled the nucleation and microstructural growth during centrifugal casting conditions. In this way the model was able to predict the influences of mould rotation speed, superheat, and mould material on microstructure formation. After testing their model, the authors conclude that the role of rotation speed is much greater than that of superheat and mould material, which have even lower impact in the case of high rotational speeds (Figure D.5)).

Zagorski and Sleziona [2007] use a Computational Fluid Dynamic (CFD) program to simulate the molten metal pouring and the velocity distribution of the particles at the initial stages of moulding rotation. The velocity field definition is useful for identifying the position of reinforcing particles (SiC) in a metal matrix and so controlling its final structure. Both the pro-

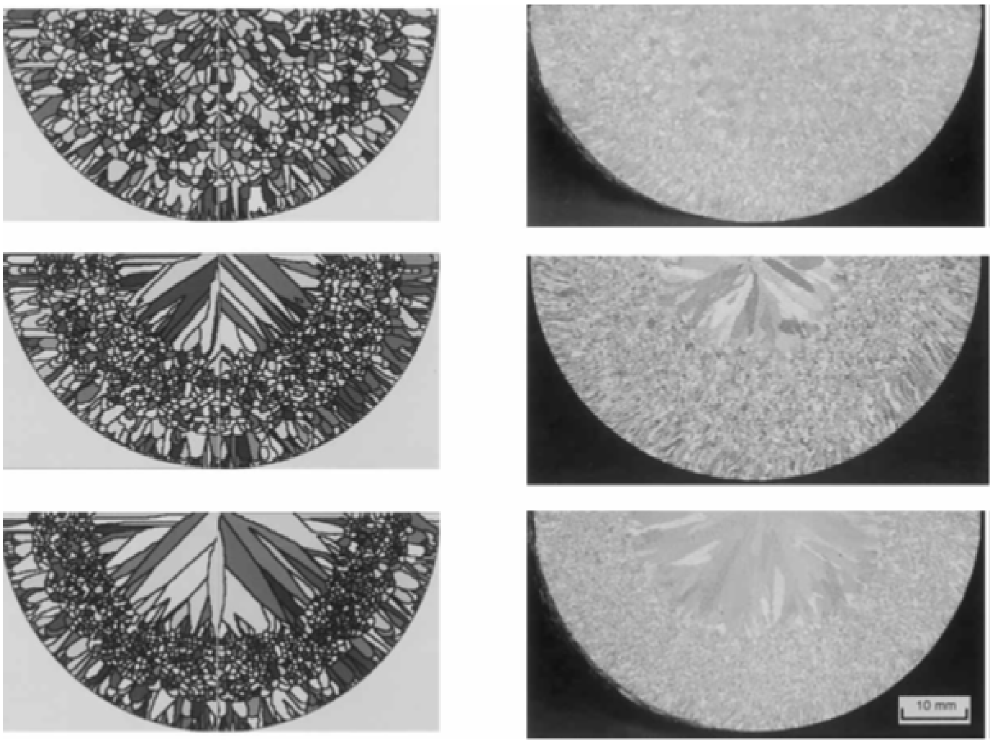


Figure D.4: Comparison of the simulated and experimental macrostructures of an AlSi alloy for various mould preheat temperatures: a) 10°C, b) 70°C, and c) 150°C[Chang et al., 2001]

cess parameters and the presence of reinforcement particles affect the initial segregation and variability of the final structure.

Fu et al. [2008] apply simulation to the fabrication of TiAl exhaust valves. Using the Navier-Stokes equations for a Newtonian fluid (using Carreau-Yasuda viscosity), the model provides a prediction of variations in the mould filling process for different parameter values. The authors test different runners and gating configurations for producing components, nested in an optimized tree-type arrangement (i.e. concurrently optimizing process parameters). The mould filling process is divided into two main phases (forward and backward filling), which affect the final component quality (i.e. level of porosity and voids). The optimal design enlarged the gate, which enabled sequential solidification and avoided the formation of defects. Test and X-rays tests validated the relationship between these parameters.

Keerthiprasad et al. [2011] study the dependence of the flow field from the process param-

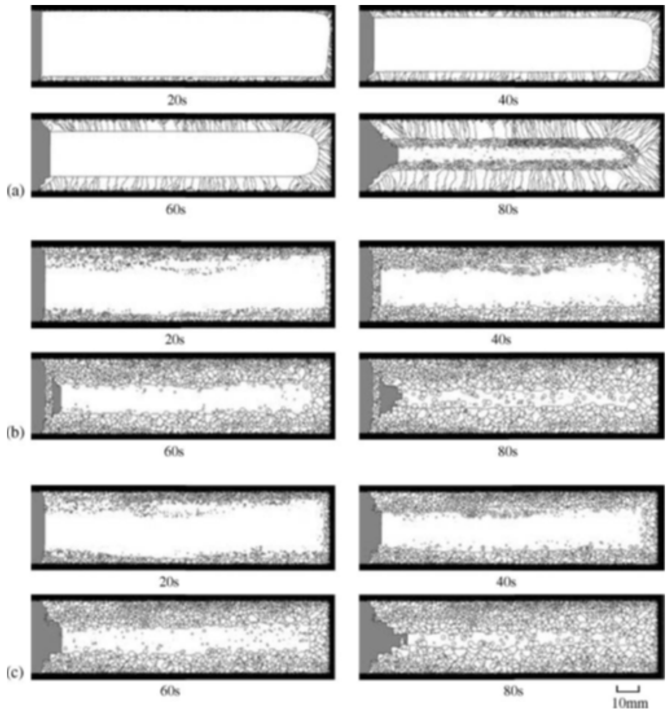


Figure D.5: Simulated microstructures of Ti-6Al-4V alloy at different solidification and mould rotation speeds in centrifugal casting: (a) 0 rpm, (b) 160 rpm, (c) 260 rpm [Ping et al., 2006]

eters and the dimension of the casted component. The authors correlate the simulation of the flow field (CFD) with experiments on a physical analogue (using water/oil and a transparent mould), to investigate the influence of rotational speed. This process was effective at modelling the formation of hollow cylinders and turbulence modes (i.e. for horizontal casting) in the fluid, which allow the identification of critical values of fluid's angular velocity and the different type of flow in the mould zones. For example, at low speeds, secondary vortices at the end of the mould appear (Ekmann flow), which are negligible at high rotation; as the rotations increase, the flow becomes laminar (Couette flow) and another turbulent flow, which form contra- rotating vortices (i.e. wave patterns), appears at very high rotational rate (Taylor flow). Viscosity, thickness of fluid cylinder and aspect ratio (ratio of length and internal/external diameter) influence the flow regimes and their influences on the flow field. The results are applied to the simulation and actual casting of an Al-Si alloy. The flow field‘s impact on the casting process was shown to be in agreement with simulation and cold experiments.

Song et al. [2012] develop a model for simulating the segregation of eutectic MC carbides during the solidification, using cylindrical coordinates. The resulting temperature field has a “sandwich” shape, because the segregation of MC adjacent to the die wall is minimal due to the quick solidification of this layer. The experimental validation showed how the eutectic carbides segregation has a high influence on the carbides distribution and the performance of the final product.

Similarly to Fu et al. [2008], Long and Zebin [2016] simulate the mould filling and solidification process of horizontal centrifugal casting, focusing on the prediction of shrinkage cavities and porosities. The influence of parameters on the casting effects can also be analysed by systematically varying the casting parameters, in controlled trials the results provide the numerical reference for production optimization of engine cylinders.

D.2.3 Experimental Investigations

Experimental articles [Chirita et al., 2008, Huang et al., 2011, Jain et al., 2016, Karun et al., 2015, Lee and Hyun, 2012, Liu et al., 2005, Luan et al., 2010, Sui et al., 2016, Watanabe et al., 2003] focus mainly on the impact of process parameters and materials interaction (i.e. moulds and workpiece) on the final product microstructure and mechanical properties.

Watanabe et al. [2003] test the behaviour of centrifugal casting when filling complex patterns (cavities) using ANOVA and X-ray inspections. Two different Titanium (Ti-Al and Ti-Cu) alloys have been compared, resulting in similar capabilities (i.e. high viscosity prevent the complete filling of the cavities).

Using vacuum casting equipment (i.e. an induction melting furnace), Liu et al. [2005] investigated centrifugal casting conditions, including superheating, rotation speed at a fixed mould temperature for producing Ti-Al automotive valves. The vacuum conditions can increase maximum superheat giving a better filling of the mould (i.e. improved fluidity). Integrity, porosity, and the microstructure have been evaluated as sufficient for the required application (car valves) and the cast quality results improved (i.e. less oxygen content and porosities). SEM analysis showed a fully lamellar microstructure (i.e. Tabb particles distributed uniformly in lamellar $\alpha_2 + \gamma$ matrix).

For Aluminium alloys, Chirita et al. [2008] report an increase in mechanical tensile strength increasing respectively on the external 35% and internal 28% side of the casting; they also reported a 160% increase and fatigue proprieties (300% increase on fatigue life and 50% fatigue limit decreases on the external side) due to centrifugal casting application (compare with gravity casting process) in the while casting (i.e. not just in the external part of the component). The results suggests that centrifugal casting processes are suitable for alloys with similar phase or metal densities. Regarding the production of piston engines (i.e. generally structural elements), centrifugal casting results are ideal when specifications (particular in tensile strength and hardness) are increasing with the distance from the rotational axis. The authors hypothesis that three process features are mainly responsible for these effects: centrifugal pressure, vibration and fluid dynamics (due to centrifugal pressure and gravity): the process can be explained as a combination of at least two of these variables (e.g. centrifugal pressure and vibration or centrifugal pressure and fluid dynamics). Figure D.6 shows the properties variation with different variable combinations and mechanical property differences for gravity and centrifugal castings (in different zones of the component). Luan et al. [2010] conduct studies on the morphology and distribution of the eutectic carbides during the manufacturing of high speed steel (HSS) rolls by centrifugal casting (i.e. comparing the results against the usage of iron and sand moulds). Analysing the microstructure by OM and SEM, as well as by X-ray diffraction (XRD) and X-ray energy dispersive spectrum (EDS), the authors identify the growth of chrysanthemum-like and branch-like MC carbides, as well as MC_2 carbides (Figure D.7). The authors test different solidification rates (i.e. different process parameters settings), deduct that a higher solidification rate gives finer carbides and

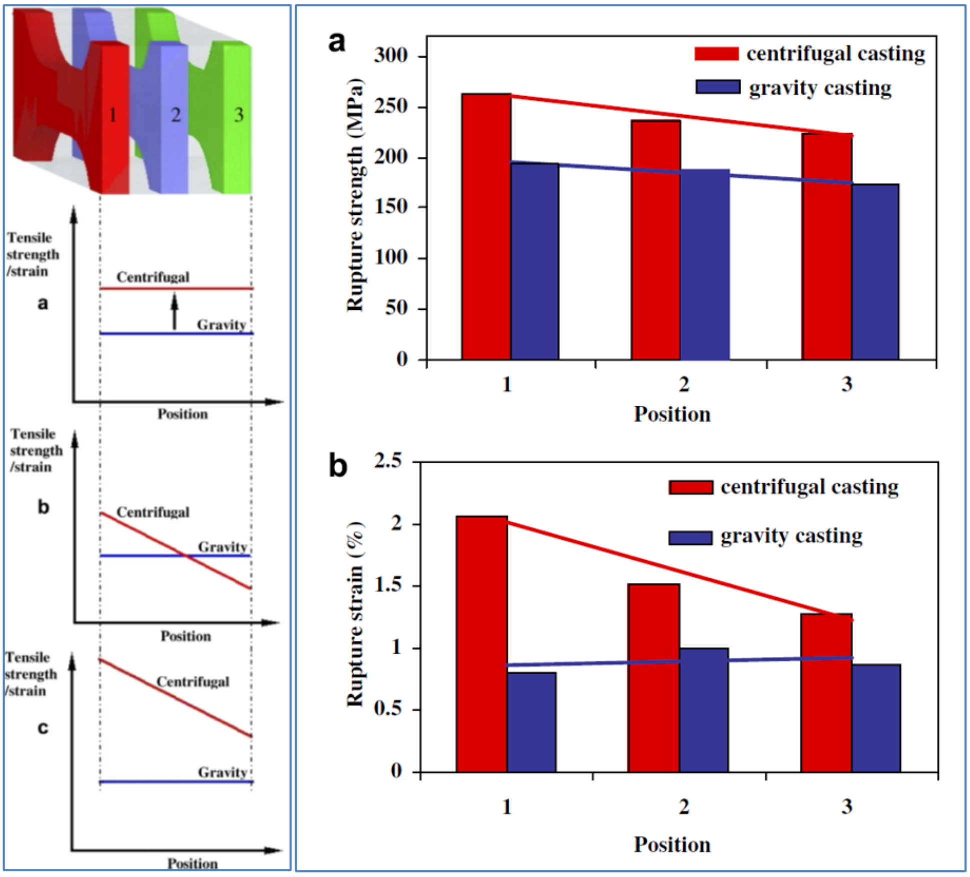


Figure D.6: Left - (a) Ultimate strength and (b) rupture strain results for bothcentrifugal and gravity castings in different positions of the casting- Right - Scheme of the mechanical properties variation with the following variables: (a) vibration or fluid dynamics; (b) centrifugal pressure; (c) combined effect of (a) and (b). Adadapted from Chirita et al. [2008].

a more homogeneous microstructure. The tests identify that iron moulds and low temperature as optimal, because they provide a faster rate of solidification.

Huang et al. [2011] optimize the production of aluminium alloys pistons, reinforced by SiC particles. The process parameters (i.e. alloy slurry temperature, mould temperature and mould rotational speed) modifications are able to reinforce the final component locally and modifying its final proprieties (i.e. hardness, wear resistance and thermal expansion coefficient). Application of centrifugal casting benchmark against gravity casting resulting in more than a 60% decreasing of mass loss by wearing in every zone of the component (reaching a maximum of 70.3%) and an increasing of hardness of $\simeq$ 20 HRB.

Lee and Hyun [2012] evaluate the manufacturing lotus-type porous copper by centrifugal casting at various rotational velocities under a hydrogen gas pressure of 0.1 MPa (more economic, in this case, than a simple centrifugal casting). Application of different centrifugal casting rotational speed were found to control the resultant material porosity and pore sizes. Similarly, Karun et al. [2015] produce a functionally graded material (FGM) by reinforcing Aluminium with SiC particles. Again the authors state that an increase in rotational speed increases the wear resistance of the component.

Jain et al. [2016] report on the design of a special purpose machine (SPM) for producing turbine bearing. The rotor was be composed of two faceplates because of the product's dimensions.

Sui et al. [2016] investigate the effect of the pouring temperature on centrifugal casting of TiAl alloy. Through SEM investigation, the authors could study the micro-hardness and the different microstructural phases along the component, created by the interaction between materials at the interface between mould and molten material. The aim was to minimize the layer of interaction and improving the micro-hardness. The researchers found that decreasing the pouring temperature decrease the interaction, reducing the heat and mass transfer, and generating a variety of new solid solutions and phases such as TiO_2, $Al_2\ O_3$, and Ti_3Al at the interface. As a consequence, the hardness generally declines along the interface to the inner substrate.

D.3 Closed-Die Forging - Case Study II

Some of the authors use expert systems framework interfaced with CAD and FEM, in order to deliver a correct forging process sequence and parameters, optimizing the forging costs [Duggirala et al., 1994, Caporalli et al., 1998, Esche et al., 2001]. Other authors use an inverse approach for optimizing the component final shape or preform by minimizing the forg-

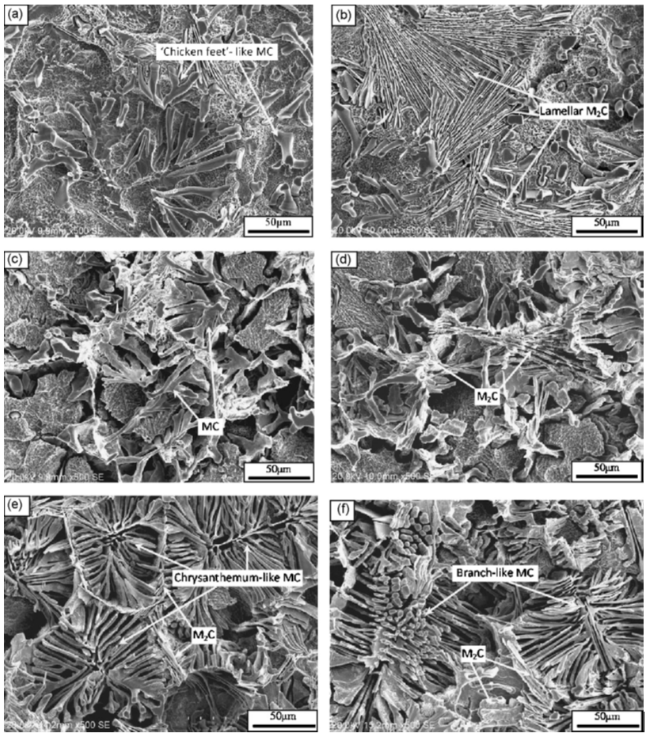


Figure D.7: SEM micrographs of the morphology of deep etched eutectic carbides [Luan et al., 2010]

ing forces and costs, by the usage of numerical predictions [Santos et al., 2002, Zhao et al., 2004]. Some authors focus on particular numerical investigations, for optimizing the die and preform shape design [Han et al., 1993, Bonte et al., 2010, Altan and Vazquez, 1996]. Gao and Wang [2000], Jo et al. [2001]s on modelling numerically the effect of the die design on final material properties and optimizing them by algorithms. Similarly, Zhao et al. [1997] use the difference between the final and the desired shape as the optimization target. Other authors investigate with numerical models for some particular die design and their optimization, for example the cold forging of gears [Groenbaek and Birker, 2000], flashless forging of rods and complex parts [Vazquez and Altan, 2000] or radial forging [Ghaei and Movahhedy, 2007]. Regarding the DoE approaches, Wei and Lin [2011] use Taguchi for optimizing both forging force and die-filling for helical gears production by FEM simulation. Applying Taguchi to FEM, [Zhang et al., 2014] optimize the microstructure and die-filling of rib-web precision forging. Sanjari et al. [2008] combine the usage of Taguchi and GA for optimizing the radial forging process though FEM. Similarly to the previous authors, Equbal et al. [2014] use Taguchi orthogonal array (a grey-based Taguchi method) for optimizing the hot forging parameters and die design parameters, evaluating their statistical (using ANOVA) impact on billet temperature and forging load. Kermanpur et al. [2010] evaluate the die design and process parameters influence on the ingots forging defects and performances, in both FEM and experimental conditions. Chen and Jung [2008] use Taguchi and orthogonal array and ANOVA for controlling the hot forging product variation in properties. The author use the DoE routine implemented in DEFORM. Walters et al. [2003] use the same approach, explaining also how the statistical approach to FEM modelling can impact the forging simulation [Walters et al., 2015a,b].

Several authors focus on die wear modelling and die life prediction. Archard [1953] has been able to develop a simple analytical formulation of the wear, able to predict the material loss by the contact force and materials hardness. This equation has been extensively used in many fields for predicting contact and wear of hard materials. Thompson and Thompson [2002] develop a code for implementing the Archard equation in ANSYS, using it to modify the elastic strain in an element in an explicit manner. Also Lee and Jou [2003] apply the Archard model to FEM investigation, validating their results by wear, high temperature hardness and non-isothermal ring compression tests to warm forging of automotive transmission outer-race. Kim et al. [2005a] develop a prediction model for predicting the die life, based on both abrasive wear (i.e. using Archard model) and plastic deformation, using FEM. Behrens [2008] modify the Archard model by adapting it to the hot forging process, the author has been able to link the FEM introducing new optimization constants to the formulation. Similarly to the previous authors, Abachi et al. [2010] quantify the wear of forging dies by applying FEM to the Archard model.A first review of the holistic approaches for predicting and measuring the die life has been made by Lange et al. [1992]. Regarding this approach, Brucelle and Bernhart [1999] developed framework for assessing the die life comparing the in-process data with FEM numerical investigation.

Appendix E

Case Study IA and IB: Flow Forming Models and Results

E.1 Geometrical Modelling for Flow Forming Process

E.1.1 Volume Constancy

Reduction ratio t is defined as in (E.1)

$$t = \left(\frac{D_1}{D_0}\right) \tag{E.1}$$

Referring to Figure E.1: D_0, initial external diameter D_1, final external diameter; D_i, internal diameter; L_1, final length. Using volume constancy (E.2), we can obtain (E.3)

$$V_0 = V_1 \tag{E.2}$$

$$L_0 \left({D_0}^2 - {D_i}^2\right) = L_1({D_1}^2 - {D_i}^2) \tag{E.3}$$

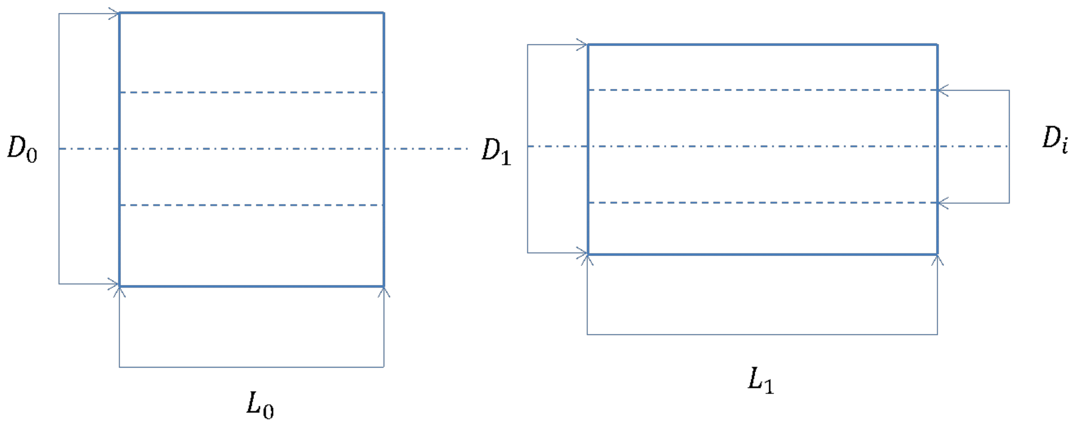


Figure E.1: Volume constancy for a simple pipe.

From (E.3), it is possible to obtain the final lengthL_1 (E.4).

$$L_0 = \ L_1 \left(\frac{{D_0}^2 - {D_i}^2}{{D_1}^2 - {D_i}^2} \right) \tag{E.4}$$

From (E.4), the initial diameter D_1 (E.5) is derivable.

$$D_0 = \sqrt{\frac{L_1 \left({D_1}^2 - {D_i}^2\right) + {D_i}^2}{L_0}} \tag{E.5}$$

E.1.2 Volume Constancy Modification

Volume constancy (E.3) need to be modified for equalizing a tubular blank volume with a flanged component. Referring to figure B1, the new features of flanged pipe are the flanges' lengths (L_{f1},L_{f2}), flanges' diameters (D_{f1},D_{f2}), chamfers' length (L_{c1}, L_{c2}) and chamfers' angles ($\alpha_1,\ \alpha_2$). So, (E.3) could rewrite as (E.6).

$$V_1 \quad = V_{f1} + V_{f2} + V_{i2} \ + V_{c1} \ + V_{c2} \tag{E.6}$$

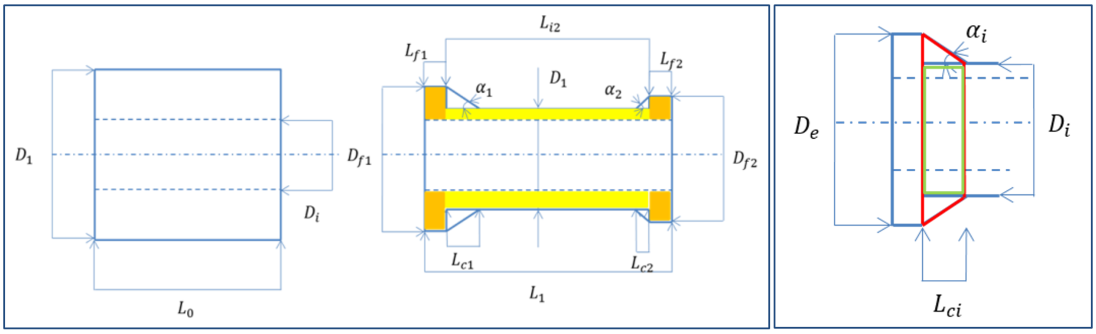


Figure E.2: Volume constancy modification for a flanged pipe.

Referring to Figure E.2 (left), V_f1 and V_{f2} correspond to flanges volume (orange), V_{c1} and V_{c2} to chamfer volume (white) and V_{i2} to internal volume (yellow). Flanges volume and internal volume could be calculated as cylindrical pipe. Chamfer volumes could be considered as hollow cone frustums. Referring to Figure E.1, chamfer volume was calculate as in (E.7)

$$V_{ci} = \frac{1}{3}\pi L_{ci}\left(\frac{D_e^2 + D_e D_i + D_i^2}{4}\right) - \pi L_{ci}\frac{D_i^2}{4} \qquad \text{(E.7)}$$

First factor of the equation represents the red zone in Figure E.2 (right), and second factor the green one. Defining the chamfer length $L_{ci} = cot\left(\alpha_c\right)\frac{D_e - D_i}{2}$ and applying to (E.7), it can be written

$$V_{ci} = \frac{1}{24}\pi cot\left(\alpha_c\right)\left(D_e^3 + 2D_i^3 - 3D_e D_i\right) \qquad \text{(E.8)}$$

Applying (E.8) to (E.6), modified volume constancy (E.9)could be written as follows.

$$\begin{aligned} L_1\left(D_1^2 - D_i^2\right) = L_{f1}\left(D_{f1}^2 - D_i^2\right) + L_{f2}\left(D_{f2}^2 - D_i^2\right) + L_2\left(D_{i2}^2 - D_i^2\right) + \\ + \frac{1}{6}cot\left(\alpha_1\right)\ \left(D_{f1}^3 + 2D_2^3 - 3D_{f1}D_2^2\right) + \\ + \frac{1}{6}cot\left(\alpha_2\right)\ \left(D_{f2}^3 + 2D_2^3 - 3D_{f1}D_2^2\right) \end{aligned} \qquad \text{(E.9)}$$

Hypothesizing that: $\alpha_1 = \alpha_2 = \alpha$; $D_{f1} = D_{f2} = D_f$. Blank length equation (E.9) becomes (E.10)

$$L_1 = \frac{D_f^2 - D_i^2}{D_1^2 - D_i^2}(L_{f1} + L_{f2}) + \left(\frac{D_2^2 - D_i^2}{D_1^2 - D_i^2}\right) L_{i2} + \frac{1}{3}cot\,(\alpha)\left(\frac{D_f^3 + 2D_2^3 - 3D_f D_2^2}{D_1^2 - D_i^2}\right) \tag{E.10}$$

As in the inverse equation (E.5), D_1 could be derived as in (E.11).

$$D_1 = \left(\frac{(L_{f1} + L_{f2})\left(D_{f2}^2 - D_i^2\right) + L_2\left(D_{i2}^2 - D_i^2\right) + \frac{1}{6}cot\,(\alpha)\ \left(D_{f1}^3 + 2D_2^3 - 3D_{f1}D_2^2\right)}{L_1} + D_i^2\right)^{\frac{1}{2}} \tag{E.11}$$

If two (or more) consecutive flanged pipes needed to be realized, second term of (E.9) multiplied for two (or more).

E.2 Flow Forming Force Modelling: Energy Based Flow Model

Total flow forming energy (U_e) is described in (E.12) [Hayama and Kudo, 1979a,b]

$$U_e = U_f + U_b = (U_{if} + U_a + U_{ff} + U_r) + (U_{ib} + U_{fb}) \tag{E.12}$$

Referring to figure E.3: and equation (E.12), every energy contribute can be described as follows:

1. U_f, energy consumed in ranges of z>0.

2. U_b, energy consumed in ranges of z>0.

3. U_{if}, plastic deformation energy under roller for z>0.

4. U_{ib}, plastic deformation energy under roller for z<0.

5. U_a, plastic flow velocity discontinuity energy on roller entrance (HE')

6. U_{ff}, frictional energy consumed on contact surface between roller/blank and blank mandrel for z>0.

7. U_{fb}, frictional energy consumed on contact surface between roller/blank and blank mandrel for z>0.

8. U_r, plastic flow velocity discontinuity energy on roller exit (EL)

Referring to figure E.3, some of the parameters can be rewritten as follows.

- $t_y = \frac{1}{2}DR + t - \sqrt{\frac{1}{4}DR^2 - x^2}$
- $t_z = t_y + z\ tan(\alpha)$
- $t_n = t_y + z_n tan\,(\beta)\ = t_y + z_n\ tan(\alpha)$
- $x_a = x_b = DR\sqrt{t_0 - t}$
- $t'_y = \frac{dt_y}{dx} = \frac{x}{\sqrt{\frac{1}{4}DR^2 - x^2}}$
- $z_1 = (t_0 - t_1)\,cot(\alpha)$

Angle β is the release angle of roller. According to Hayama and Kudo [1979b] and several other authors, β should be equal to attack angle α, in order to stabilize flow forming process. As consequence, the length of peripheral contact on x axes (x_a, x_b) can be considered as equal. Given this, Singhal et al. [1990] rewrote the energy equations as follows

$$U_{if} = \frac{2}{\sqrt{3}}\sigma_y \int_0^{x_a} Kt_y cot\,(\alpha)\ log\left(\frac{t_0}{t_y}\right)dx \tag{E.13}$$

$$U_{ib} = \frac{2}{\sqrt{3}}\sigma_y \int_0^{x_b} Kt_y cot\,(\alpha)\ log\left(\frac{t_n}{t_y}\right)dx \tag{E.14}$$

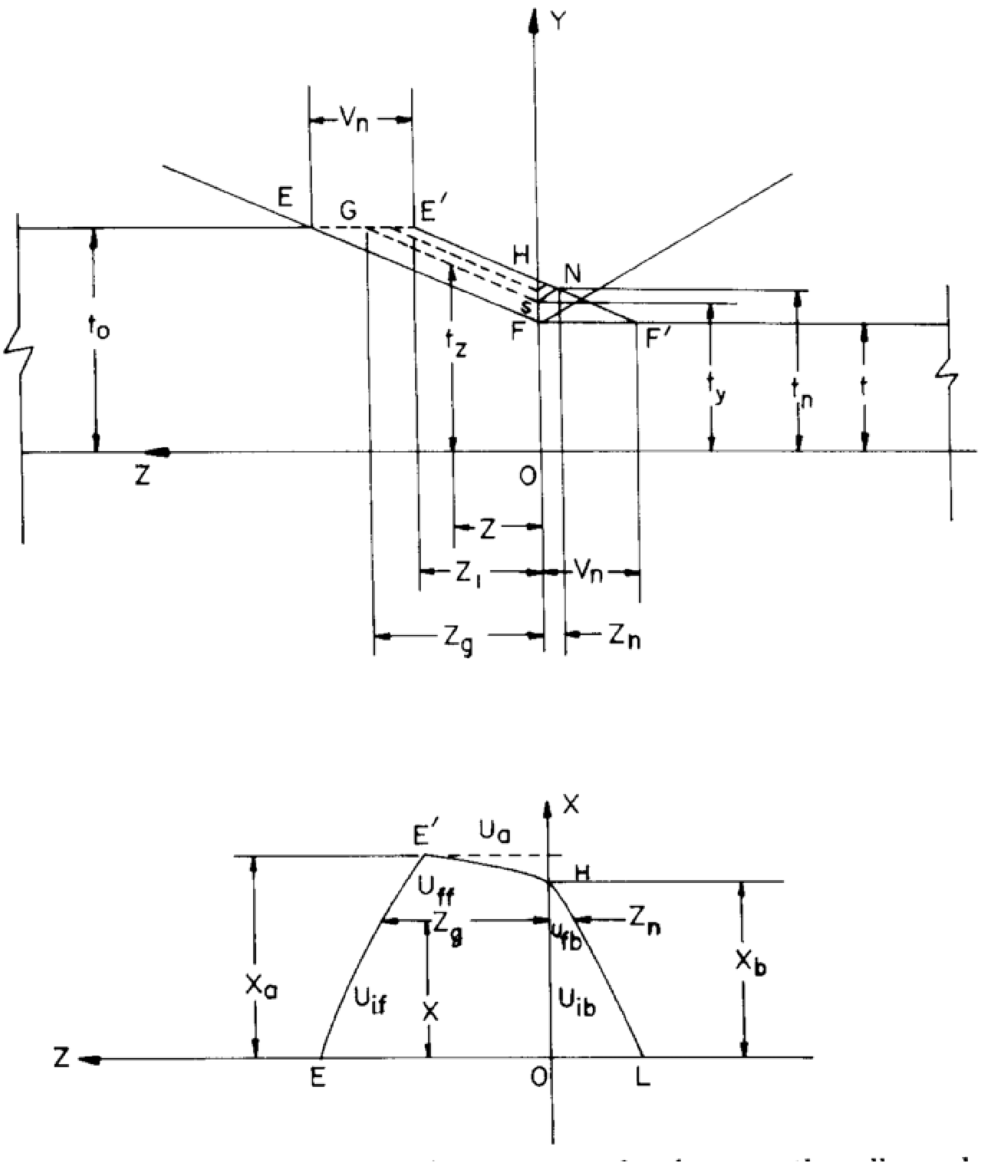


Figure E.3: Energy method, contact zone model for flow forming [Hayama and Kudo, 1979b]

$$U_a = \frac{1}{2\sqrt{3}}\sigma_y V_0 \frac{x_a}{\sqrt{\frac{1}{4}DR^2 - x_a^2}} \int_0^{z_1} (t_1 + z\ tan\,(\alpha)) \sqrt{(t_1 + z\ tan\,(\alpha))^2 + z^2}$$
$$+z^2 logz^2 log(t_1 + z\ tan(\alpha) + z\sqrt{(t_1 + z\ tan(\alpha))^2 + z^2})dz \tag{E.15}$$

$$U_{ff} = \frac{1}{\sqrt{3}}\sigma_y V_0 m \int_0^{x_a} \frac{x}{\sqrt{\frac{1}{4}DR^2 - x^2}}$$
$$[(z_g\ cot(\alpha)\log(\frac{t_0}{t_y})) - cot(\alpha)^2(t_0 log(t_0) - t_0 + t_y + t_y log(t_y))] \tag{E.16}$$

$$U_{fb} = \frac{1}{\sqrt{3}}\sigma_y V_0 m \int_0^{x_b} \frac{x}{\sqrt{\frac{1}{4}DR^2 - x^2}}$$
$$[(z_n\ cot(\alpha)\log(\frac{t_0}{t_y})) - cot(\alpha)^2(t_0 log(t_0) - t_0 + t_y + t_y log(t_y))] \tag{E.17}$$

$$U_r = \frac{1}{\sqrt{3}}\sigma_y V_0 (t_{0^2 - t^2}) cot(\frac{1}{2}\alpha) \tag{E.18}$$

With,

- $K = t'_y V_o$
- V_o, peripheral speed of rotation
- σ_y,yield stress
- m, friction coefficient

These expressions were numerically using Maple, for evaluating all energy contributions. Forces were calculated using integration of velocity displacement in on y-axis over contact area (f for $z > 0$, b for $z < 0$). Velocity displacements were calculated as follows Singhal et al. [1987].

- $Y_f = \int_0^{x_a} Kt_y cot\,(\alpha)\ log\left(\frac{t_0}{t_y}\right)dx = \frac{U_{ia}}{\frac{2}{\sqrt{3}}\sigma_y}$

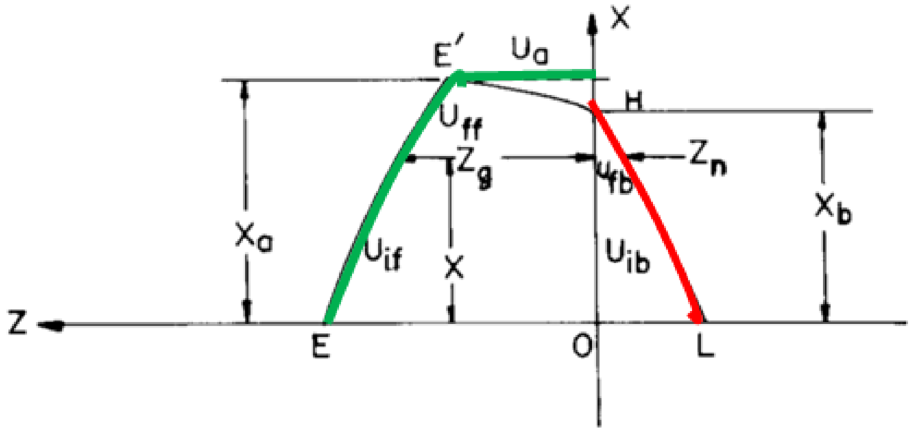


Figure E.4: Definition of the contact zone for the case-study: $z_g(z > 0)$ in red and $z_n(z < 0)$ in green.

- $Y_b = \int_0^{x_a} Kt_y cot\,(\alpha)\; log\left(\frac{t_n}{t_y}\right) dx = \frac{U_{ib}}{\frac{2}{\sqrt{3}}\sigma_y}$

Contact surface area were calculated trough definition of z_g(z>0) and z_n(z<0). Referring to Figure E.4, the first was defined as a parabola passing for vertex $E = (0, z_E)$ and point $E' = (x_a, z_{E'})$. The second was similarly defined but passing for vertex $E = (0, z_E)$ and point$E' = (x_a, z_E)$. Consequently,

$$z_g = \frac{z_E' - z_E}{x_a^2}x^2 + z_E \tag{E.19}$$

$$z_n = \frac{z_L}{x_b^2}x^2 + z_L x \tag{E.20}$$

Using (E.19) and (E.20), the contact surface were calculated as in (E.21) and (E.22).

$$S_f = \int_0^{x_a} z_g dx = \frac{z_E \;\; - z_E}{3}x_a + z_E x_a \tag{E.21}$$

$$S_b = \int_0^{x_b} z_n dx = \frac{4}{3}z_L \; x_a \tag{E.22}$$

Thus, radial force P_r contributes in z>0 and z<0 can be expressed as in (E.23) and (E.24) .

$$P_{rf} = \frac{U_f}{Y_f} S_f \tag{E.23}$$

$$P_{rb} = \frac{U_b}{Y_b} S_b \tag{E.24}$$

Consequently, the total radial forces (y-axis) and the the axial force (z-axis) can be written as in (E.25) and (E.26) respectively.

$$P_r = P_{rf} + P_{rb} \tag{E.25}$$

$$P_z = P_r \tan(\alpha) \tag{E.26}$$

E.3 Time and Cost Models

E.3.1 Time model (Flow-Turning model)

Referring to Figure A3.1, forming lengths (green) and transverse lengths (red) can be identified for every flow forming pass $(i - th)$. For i-th flow forming pass: $L_{forming,pass-i}$(E.27), total formed length i-th pass; $L_{transverse,pass-i}$ (E.28), total transverse length; L_{Ok}, k-th formed length; L_{Tk}, k-th transverse length for i-th pass, N_o, number of forming length sections, N_T, number of transverse length sections.

$$L_{forming,pass-i} = \sum_{K=1}^{N_o} L_{Ok} \tag{E.27}$$

$$L_{transverse,pass-i} = \sum_{K=1}^{N_T} L_{Tk} \tag{E.28}$$

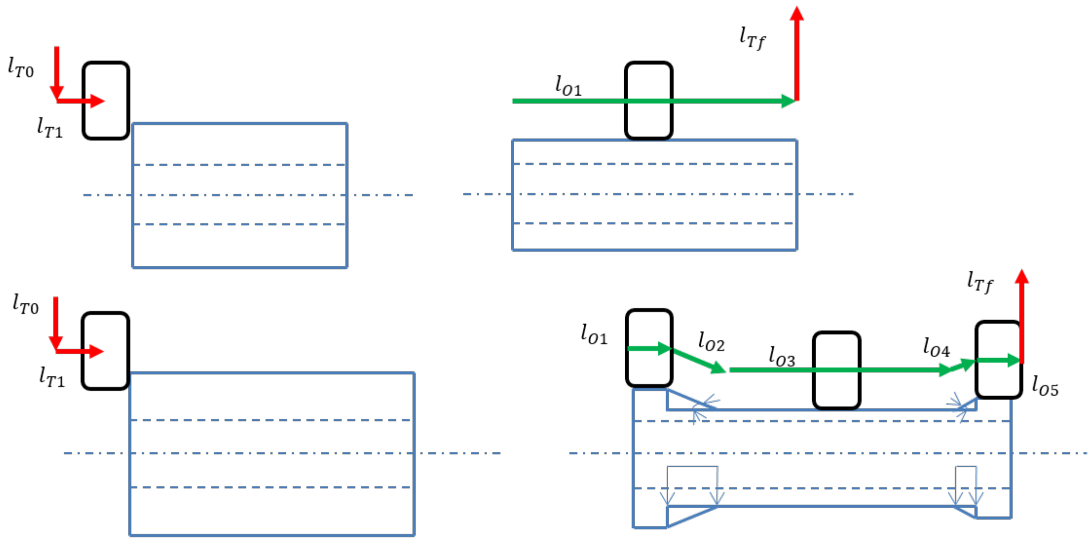


Figure E.5: Precess-time modelling for simple pie (up) and flanged pipe (down). Schematic of flow forming tool-path: transverse motion (red) and forming motion (green)

For $i{-}th$ flow forming pass, $t_{forming,pass\ i}$ (E.29), total forming time, $t_{transverse,pass\ i}$ (E.30), total transverse time, F_{pass-i}, feed rate in mm/min, v_{pass-i}, transverse speed in mm/min. Total operative time in $t_{operative,pass\ i}$ is expressed as in (A3.5).

$$t_{transverse,pass\ i} = \frac{v_{pass-i}}{L_{transverse,pass\ i}} \tag{E.29}$$

$$t_{transverse,pass\ i} = \frac{v_{pass-i}}{L_{transverse,pass\ i}} \tag{E.30}$$

$$t_{operative,pass\ i} = t_{forming,pass\ i} + t_{transverse,pass\ i} \tag{E.31}$$

E.3.2 Hybrid Cost Model

Cost model was created in order to calculate manufacturing cost, derived from Kalpakjian and Schimd [2009], Allen and Swift [1990], Swift and Booker [2013]. Only direct costs were involved in calculation. (i.e. costs directly imputable to process). Total cost expression (E.32) includes labour cost (E.36), material cost (E.34), tool cost (E.38), working operative cost (E.37) as variable costs (E.33). Machine depreciation (E.40) and maintenance cost (E.41) has been considered as constant. The indirect costs were not considered in this investigation.

As shown in Equation (E.31), the process time can be calculated referring to the selected process parameters. The total process cost can be calculated as in (E.32). A hybrid cost model has been used for calculating the total process costs (E.33).

$$C_{Total/piece} = C_{Direct-Variable} + C_{Direct-Fixed} + C_{Indirect} \tag{E.32}$$

$$C_{Direct,Variable} = C_{Material} + C_{Labour} + C_{Tool} + C_{Working} \tag{E.33}$$

$$C_{Material} = V_{preform}\ \rho\ c_{material} \tag{E.34}$$

With, $C_{Material}$, total material cost, $V_{preform}$, preform volume (mm^3) ρ, material density (kg/mm^3), $c_{material}$, material cost ($£/kg$).

Flow forming process can be dived in five main phases and correspondent times: t_{set-up}, set-up time, machine programming in order to absolve the task (machine stopped, idle machine time); t_{load}, part loading time, workpiece clamping on the machine (machine stopped, idle machine time); t_{FFi}, forming time, divided in preliminary operations ($t_{(pre,ops)i}$)ending operation ($t_{(end-ops)i}$) and working time ($t_{(operative)i}$) (machine working, idle worker time); part unloading, released worked part from the machine (machine stopped, idle machine time); t_{Qcheck}, quality check time, assigned only to a fixed sample of pieces (not idle time, in parallel with other operations). During the flow forming operation, the workpiece do not usually change clamping references, so the forming passes can be done consecutively with no idle time.

Total flow forming operation time for a single piece (including quality check) can be written as in (E.35).

$$t_{total/piece} = t_{set-up} + \sum_{i=1}^{n-passes} (t_{(load)i} + t_{(unload)i} + t_{(pre,ops)i} + t_{(operative)i} + t_{(end-ops)i}) + t_{Qcheck} \tag{E.35}$$

Therefore, the correspondent labour cost could be defined as (E.36).

$$C_{Labour} = C_{skilled\ worker} + C_{unskilled\ worker}(t_{set-up} + t_{load} + t_{unload} + t_{FFI} + t_{Qcheck}) \tag{E.36}$$

With, C_{Labour}, total labour cost (£);c_{labour}, labour cost per min ($£/min$); t_{set-up}, set-up time (min); t_{FFI}, forming time (min); t_{unload}, unloading time(min); t_{load},loading time(min); t_{Qcheck}, quality check time(min). Forming powers (i.e. analytically calculated by the energy base analytical method) have been used for calculating energy expenditures during the flow forming process. Therefore, the forming operation cost can be formulated as in (E.37).

$$C_{Working} = \sum_{i=1}^{n-passes} (W_{forming-i} + W_{transverse-i}) c_{energy}\ t_{FFi} \tag{E.37}$$

With, $C_{Working}$, total working cost (£); $W_{forming-i}$, forming power calculated through the energy based model (Appendix D); $W_{transverse-i}$ machine transverse energy, considered as ($W_{transverse} = 0.01 W_{forming}$); c_{energy}, energy cost ($£/W$).

Tools cost could be written as follows, giving a rough estimation of tool life (E.38).

$$C_{Tool} = C_{\ single\ tool} \frac{T_{tool\ life}}{t_{op\ I} + \ldots)} \tag{E.38}$$

C_{Tool}, tool cost imputable to flow forming operation (£); $C_{\ single\ tool}$, single tool set cost (£); $T_{tool\ life}$, medium tool life (min); $\frac{T_{tool\ life}}{t_{op\ I}+\ldots}$, portion of tool life used by process (%).

Fixed costs were assigned to all the process, because they are specifically not assigned to a single operation (E.39)

$$C_{Direct,\ Fixed} = C_{Machine\ Depreciation} + C_{Maintenance} + \dots \tag{E.39}$$

Machine deprecation is defined as in (E.40) as in Kalpakjian and Schimd [2009]

$$C_{Machine\ Depreciation} = C_{Machine}\ \frac{t_{total/piece}}{y_{depreciation} d_{working} h_{working} 60} \tag{E.40}$$

With,$C_{Machine\ Depreciation}$, depreciation cost (£); $C_{Machine}$, total machine cost (£); $t_{total/piece}$, lead-time (min); $y_{depreciation}$, machine fixed depreciation years ($years$); $d_{working}$, machine working days per year ($days/years$); $h_{working}$, machine working hours per day ($min/days$). Maintenance cost (E.41) can be expressed as a part of the machine depreciation (E.40).

$$C_{Machine\ Depreciation} = C_{Machine}\ \frac{t_{total/piece}}{y_{depreciation} d_{working} h_{working} 60} \tag{E.41}$$

E.4 Flow Forming Cost and Time Calculations

Seat Valve - Flow Forming Cost

Pass	Process Phase	Time [min]	Cost [£/min]: Variable Direct cost: Labour cost	Variable Direct cost: Tool Cost	Variable Direct cost: Machining Cost	Fixed Direct cost: Machine: Depreciation	Fixed Direct cost: Machine: Maintenance	Fixed Direct cost: Machine: Others	Indirect Costs: Others	Cost per Part [£/part]	Cost per Batch [£]
	Set-up time	180	0.16025641			1.318	0.092	0		283	11304043.78
	Loading part	1.00	0.10			1.318	0.092	0		1.51	60556.65
I pass	Preliminary ops	0.20	0.10	0.50		1.318	0.092	0		0.40	16111.33
I pass	Run time	0.18		0.50	5.44	1.318	0.092	0		5.78	231075.63
I pass	Ending ops	0.20	0.10	0.50		1.318	0.092	0		0.40	16111.33
II pass	Preliminary ops	0.20	0.10	0.50		1.318	0.092	0		0.40	16111.33
II pass	Run time	0.43		0.50	5.14	1.318	0.092	0		5.96	238377.79
II pass	Ending ops	0.20	0.10	0.50		1.318	0.092	0		0.40	16111.33
III pass	Preliminary ops	0.20	0.10	0.50		1.318	0.092	0		0.40	16111.33
III pass	Run time	0.76		0.50	6.04	1.318	0.092	0		7.49	299494.24
III pass	Ending ops	0.20	0.10	0.50		1.318	0.092	0		0.40	16111.33
	Unloading part	2.00	0.10			1.318	0.092	0		3.03	121113.31
	Quality inspection	4.00	0.20			1.318	0.092	0		6.44	257611.23
	Lead Time per part	5.57								26.19	12608940.62
	Lead Time per batch	0.00		Cost not assigned in this operation						Tot. [£/part]	Tot. [£]
	(quality inspection excluded)						**Raw Material cost**			374.92 [£/par	######## [£]
	Parts number (Batch Volume)	40000.00								**Total Cost per Part [£/part]**	**Total Cost [£]**
										401.11	27605731.4
							Cost per valve (6 valves)			66.85	

Raw Material			
Raw Part Volume [mm^3]	17821074.70	Material cost [£/kg]	2.68
Material Density [kg/mm^3]	0.00	Raw piece cost [£]	374.92
Raw Part Weight [kg]	139.90	Total Raw pieces cost [£]	14996790.79

Tool Cost					
Tool Life Expextancy [min]	10000.00	Total Working time [min]	0.76	Needed Tools number	0.00008
Tool Cost [£]	5000.00				
SingleTool cost per minute [£/min]	0.50	Total tools cost [£/min]			0.50

Machine cost	Total cost	Year cost	Hour cost	Minute cost
Machine cost	800000.00	160000.00	79.05	1.32
Machine's depreciation years	5.00			
Maintenance cost (7%)	56000.00	11200.00	5.53	0.09
Other machine costs (lubricant, ...)	0.00	0.00	0.00	0.00

Workers cost	Annual Cost	Hour cost	Minute cost
Unskilled Worker	13000.00	6.25	0.10
Skilled Worker	20000.00	9.62	0.16
Senior Worker	25000.00	12.02	0.20

Indirect cost -Other costs

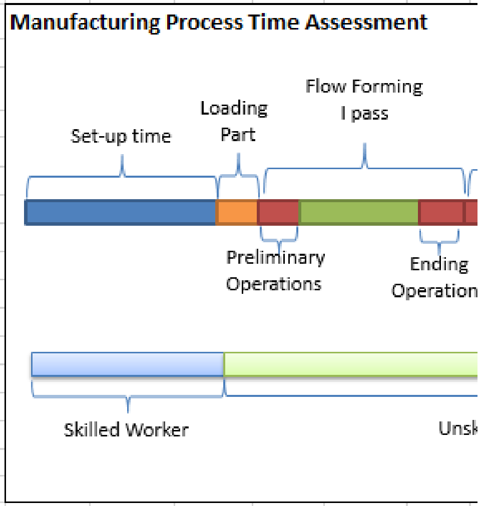


Table E.1: Process cost calculations for Case study IA.

	Geometrical Parameters				Operative parameters					
	Reduction Ratio	Final Diameter [mm]	Initial Length [mm]	Final Length [mm]	Formed Length [mm]	Trasverse Length [mm]	Feed Rate [mm/min]	Rapid Trasverse rate [mm/min]	Spindle Speed [rpm]	Feed Rate [mm/rev]
Pass I	0.139	155	111.28	165.69	111.2783706	1025	625	6250	500	1.25
Pass II	0.129	135	165.69	250.54	165.6948306	1020	625	6250	500	1.25
Pass III	0.121	118.69	250.54	390.14	372.869158	1020	625	6250	500	1.25

	Approach Length T0	Trasverse Length T1	Forming Length 01					Final Trasverse Tf
Pass I	25	500	111.2783706					500
	Approach Length T0	Trasverse Length T1	Forming Length 01					Final Trasverse Tf
Pass II	20	500	165.6948306					500
	Approach Length T0	Trasverse Length T1	Forming Length 01	Forming Length 02	Forming Length 03	Forming Length 04	Forming Length 05	Final Trasverse Tf
Pass III	20	500	189.432	41.70515795	94.488	47.244		500

	Run time			Required Power		Energy Cost	Run Cost
	Working Time [min]	*Movimentation time [min]*	Total Run Time [min]	Forming Power [W]	Movimentation power [W]		
Pass I	0.178045393	0.164	0.342045393	60631.97	3031.598477	0.0854	5.436868709
Pass II	0.265111729	0.1632	0.428311729	57337.76	2866.887799	0.0854	5.141476579
Pass III	0.596590653	0.1632	0.759790653	67317.34	3365.867127	0.0854	6.036346105

Energy Cost	8.54 pence/ kW
	0.0854 £/ kW

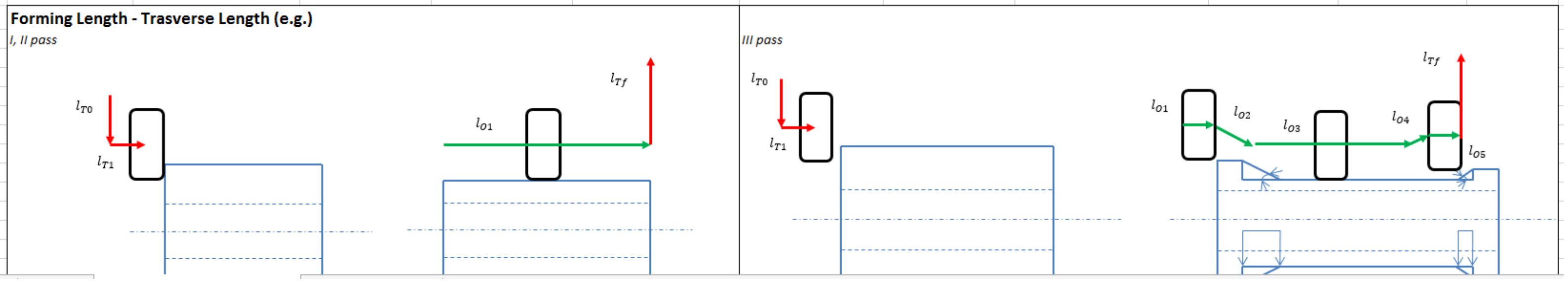


Table E.2: Process time calculations for Case study IA.

Riser Pipe, - Flow Forming Cost

Pass	Process Phase	Time [min]	Cost [£/min] – Variable Direct cost – Labour cost	Variable Direct cost – Tool Cost	Variable Direct cost – Machining Cost	Fixed Direct cost – Machine – Depreciation	Fixed Direct cost – Machine – Maintenance	Fixed Direct cost – Others	Indirect Costs – Others	Cost per Part [£/part]	Cost per Batch [£]
	Set-up time	160	0.16025641			1.318	0.092	0		251	25120.10
	Loading part	3.00	0.10			1.318	0.092	0		4.54	454.17
I pass	Preliminary ops	0.20	0.10	1.20		1.318	0.092	0		0.54	54.28
I pass	Run time	0.18		1.20	5.44	1.318	0.092	0		5.90	590.15
I pass	Ending ops	0.20	0.10	1.20		1.318	0.092	0		0.54	54.28
II pass	Preliminary ops	0.20	0.10	1.20		1.318	0.092	0		0.54	54.28
II pass	Run time	0.43		1.20	5.14	1.318	0.092	0		6.26	625.93
II pass	Ending ops	0.20	0.10	1.20		1.318	0.092	0		0.54	54.28
III pass	Preliminary ops	0.20	0.10	1.20		1.318	0.092	0		0.54	54.28
III pass	Run time	0.76		1.20	6.04	1.318	0.092	0		8.02	801.92
III pass	Ending ops	0.20	0.10	1.20		1.318	0.092	0		0.54	54.28
	Unloading part	5.00	0.10			1.318	0.092	0		7.57	756.96
	Quality inspection	4.00	0.20			1.318	0.092	0		6.44	644.03
	Lead Time per part	**12.17**								38.06	29318.93
	Lead Time per batch	0.00		Cost not assigned in this operation						Tot. [£/part]	Tot. [£]
	(quality inspection excluded)						**Raw Material cost**			4527.1 [£/par	4.53E+05 [£]
	Parts number (Batch Volume)	**100.00**								**Total Cost per Part [£/part]**	**Total Cost [£]**
										4565.21	**482033.2**

Raw Material			
Raw Part Volume [mm^3]	274621940.2	Material cost [£/kg]	2.10
Material Density [kg/mm^3]	0.00000785	Raw piece cost [£]	4527.14
Raw Part Weight [kg]	2155.78	Total Raw pieces cost [£]	452714.27

Tool Cost					
Tool Life Expectancy [min]	10000.00	Total Working time [min]	0.76	Needed Tools number	0.00008
Tool Cost [£]	12000.00				
SingleTool cost per minute [£/min]	1.20	Total tools cost [£/min]			1.20

Machine cost	Total cost	Year cost	Hour cost	Minute cost
Machine cost	800000.00	160000.00	79.05	1.32
Machine's depreciation years	5.00			
Maintenance cost (7%)	56000.00	11200.00	5.53	0.09
Other machine costs (lubricant, ...)	0.00	0.00	0.00	0.00

Workers cost	Annual Cost	Hour cost	Minute cost
Unskilled Worker	13000.00	6.25	0.10
Skilled Worker	20000.00	9.62	0.16
Senior Worker	25000.00	12.02	0.20

Indirect cost -Other costs

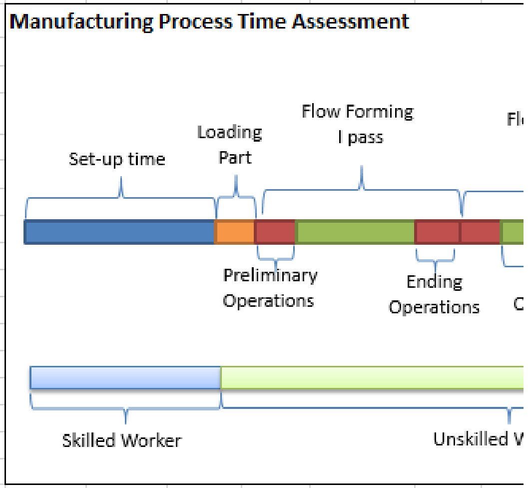


Table E.3: Process cost calculations for Case study IB.

Riser Pipe - Forming cost and time

	Geometrical Parameters				Operative parameters					
	Reduction Ratio	Final Diameter [mm]	Initial Length [mm]	Final Length [mm]	Formed Length [mm]	Trasverse Length [mm]	Feed Rate [mm/min]	Rapid Trasverse rate [mm/min]	Spindle Speed [rpm]	Feed Rate [mm/rev]
Pass I	0.137	561	548.39	165.69	548.39	1089	540	5400	300	1.8
Pass II	0.135	485	1097.10	250.54	1005.47	1083	540	5400	300	1.8
Pass III	0.120	427	2970.00	390.14	189.43	1058	540	5400	300	1.8

	Approach Length T0	Trasverse Length T1	Forming Length 01					Final Trasverse Tf
Pass I	89	500	548.39					500
	Approach Length T0	Trasverse Length T1	Forming Length 01	Forming Length 02	Forming Length 03	Forming Length 04	Forming Length 05	Final Trasverse Tf
Pass II	83	500	36	38.00	893.47	38.00	36	500
	Approach Length T0	Trasverse Length T1	Forming Length 01					Final Trasverse Tf
Pass III	58	500	189.432					500

	Run time			Required Power		Energy Cost	Run Cost
	Working Time [min]	*Movimentation time [min]*	Total Run Time [min]	Forming Power [W]	Movimentation power [W]		
Pass I	1.016	0.202	1.22	2897551.30	144877.56	0.09	259.82
Pass II	1.862	0.201	2.06	3690033.28	184501.66	0.09	330.89
Pass III	0.351	0.196	0.55	1175734.80	58786.74	0.09	105.43

Energy Cost	8.54 pence/ kW
	0.0854 £/ kW

Forming Length - Trasverse Length (e.g.)

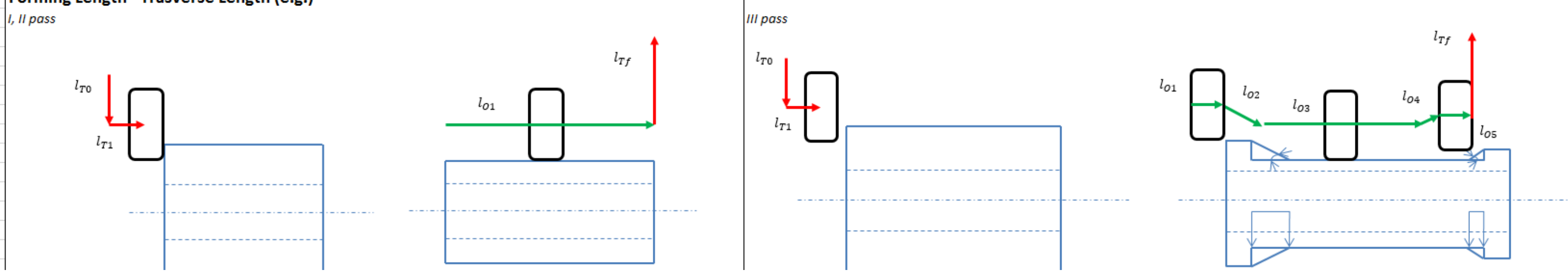


Table E.4: Process time calculations for Case study IB.

Appendix F

Case Study II: Centrifugal Casting Models, Optimization Models and Results

F.1 Differential Analysis: Cost Models

As the direct machining cost per hour is the same, the turning cost can be written as the sum of the operative and the idle turning time (Equation (F.1)). The solid blank cost can be deduct from the billet volume, material density and material cost (given by the solid blank supplier). When large diameters are required for the solid blank, the steel supplier cannot match properly the required dimension, so an estimation of the final diameter is given in (Equation (F.4)). The required solid blank's outer diameter and length also need to take into account the machining allowances (Equation (F.5)).

$$C_{Tu} = T_{Tu}c_M = (T_{Op} + T_{Id})c_M \tag{F.1}$$

Cost Models Nomenclature

C_{TM}, total cost of machining from a solid blank (£)
$C_{T_{CC}}$, total cost of machining from a centrifugal casting blank(£)
C_{SB}, cost of solid blank (£)
C_{CCB}, cost of centrifugal casting blank (£)
C_M, machining cost (£)
C_I, indirect costs (£)
C_{Tu}, turning costs (£)
T_{Tu}, turning total time (£)
V_f, final volume of the part (mm^3)
V_{SB}, volume of the solid blank (mm^3)
V_{CCB}, volume of the centrifugal casting blank (mm^3)
R_{Tu}, machining removal rate (mm^3/min)
c_M, machining cost
T_{Op},turning machine working time (min)
T_{Id}, turning idle time (set-up, tool change ...) (min)
C_{SB}, cost of the solid blank (£)
V_{SB}, volume of the solid blank (mm^3)
ρ_{Mat}, material density (kg/mm^3)
c_{Mat}, material cost (£/kg)
OD_{SB}, external diameter of the solid blank (mm)
L_{SB}, length of the solid blank (mm)
t_{SB}, thickness of the solid blank (mm)
OD_F, maximum outer diameter of the final semi-finished component (mm)
OD_{F_b}, minimum outer diameter of the final semi-finished component (mm)
ID_F, inner diameter of the final semi-finished component (mm)
L_F, total length of the final semi-finished component (mm)
l_f, length of the final semi-finished component in contact with fluid (mm)
OD_{CCB}, outer diameter of the centrifugal casting part (blank) (mm)
ID_{CCB}, inner diameter of the centrifugal casting part (blank) (mm)
t_{CCB}, thickness of the centrifugal casting part (blank) (mm)

Centrifugal Casting Model Nomenclature

OD_m, outer diameter of the centrifugal casting mould (mm)
ID_m, inner diameter of the component after centrifugal casting (mm)
L_m, length of the centrifugal casting mould (standard case) (mm)
L_m^*, length of the centrifugal casting mould (special case) (mm)
$ID_{\min}$, minimum internal diameter (standard case) (mm)
$ID_{\min}^*$, minimum internal diameter (special case) (mm)
C_{CC}, total cost of a centrifugal casting component
C_{Mel}, melting cost
C_{Aux}, auxiliary cost (excluding mould cost) (£)
C_{En}, energy cost (£)
C_{CCO}, centrifugal casting operation cost (including labour and direct costs) (£)
C_{PrM}, proof machining cost (£)
m_c, mass of the molten material (kg)
m_v, mass of the centrifugal casting part after proof machining (kg)
c_{MaM}, material melting cost coefficient (£/kg)
c_{ChM}, machining chips re-melting cost coefficient (£/kg)
c_{Aux}, auxiliary cost coefficient (£/kg)
c_{En}, energy cost coefficient (£/kg)
c_{CCO}, centrifugal casting operation cost coefficient (£/kg)
c_{PrM}, proof machining cost coefficient (£/kg)
ρ_m, material density before the centrifugal casting operation (kg/mm^3)

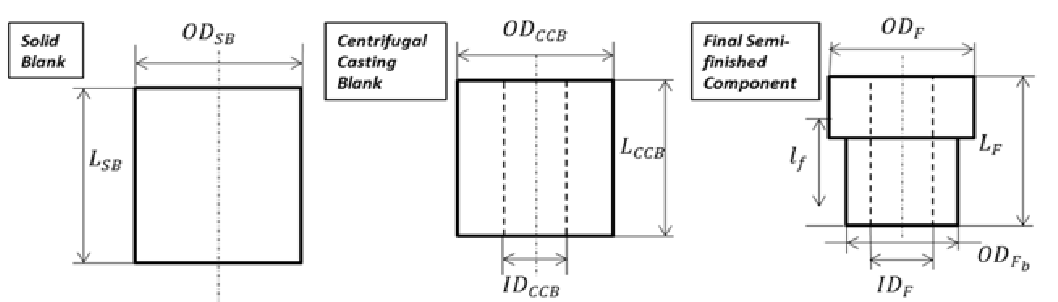


Table F.1: Centrifugal casting models' nomenclature.

$$C_{SB} = V_{SB}\rho_{Mat}c_{Mat} \tag{F.2}$$

$$V_{SB} = \frac{\pi}{4}\left(OD_{SB}^2\right)L_{SB} \tag{F.3}$$

$$OD_F + 20mm = \begin{cases} > 350\ mm = Non\ Standard\ order \rightarrow OD_{SB} = OD_F + 40mm \\ > 350\ mm = Non\ Standard\ order \rightarrow OD_{SB} = OD_F + 40mm \end{cases} \tag{F.4}$$

$$L_{SB} = L_F + 5mm \tag{F.5}$$

The centrifugal casting blank cost is defined by the Centrifugal Casting cost model (Equation (F.18)), which will be presented in details in the next sub-section and Appendix F.2. As discussed previously, the centrifugal casting blank needed machining allowances even though proof machined. Therefore, the final required centrifugal casting blank dimensions are as in Equation (F.6). The length does not require machining allowances, as it is already cut to shape and proof machined.

As the material is the same for both the processes and the dimensions are similar to each other, the machining parameters can be considered as constants. Therefore, an estimation of the machining time can be done based on the removal rate. The removal rate expression Equation (F.3) can be used for calculating the solid blank turning time (Equation (F.8)) and centrifugal casting blank turning time (Equation (F.9)) specifically. The expression for the centrifugal casting blank volume (Equation (F.10)), solid blank volume (Equation (F.3)) and final (pre-finishing operations) volume (Equation (F.11)) can be used for calculating the required machining time.

$$\begin{cases} OD_{CCB} = OD_f + 20mm \\ ID_{CCB} = ID_f - 20mm \end{cases} \tag{F.6}$$

$$R_{Tu} = \frac{V_F - V_{SB}}{T_{Tu}(solid\ blank)} = \frac{V_f - V_{CCB}}{T_{Tu}\ (centrifugal\ casting\ blank)} \tag{F.7}$$

$$T_{Op}(solid\ blank) = \frac{V_F - V_{SB}}{R_{Tu}} \tag{F.8}$$

$$T_{Op}(centrifugal\ casting\ blank) = \frac{V_F - V_{CCB}}{R_{Tu}} \tag{F.9}$$

$$V_{CCB} = \frac{\pi}{4}\left(OD_{CCB}^2 - ID_{CCB}^2\right) L_{CCB} \tag{F.10}$$

$$V_F = \frac{\pi}{4}\left(OD_F^2 - ID_F^2\right)(L_F - l_f) + \frac{\pi}{4}\left(OD_{F_b}^2 - ID_F^2\right) l_f \tag{F.11}$$

F.2 Centrifugal Casting Cost Model

- Input
  - Final Dimensions (OD_f, ID_f, L_f)
  - Centrifugal casting cost coefficients (c_{MaM}, c_{ChM}, c_{Aux}, c_{En}, c_{CCO}, c_{PrM})
- Output:
  - Mould Dimensions aka Casting blank dimensions (OD_m, ID_m, L_m)
  - Centrifugal casting cost (C_{CC})

F.2.1 Phase 1: Mould Selection

Firstly, a standard or custom mould case needs to be selected, depending on the final dimensions of the component (Equation (F.12)). The screening parameter is the ratio between outer diameter itself and the inner one because the component size and its thickness influence the pouring of the melting metal and its proper solidification during the mould spinning. Using the centrifugal casting supplier data (i.e. AMPO), two cases can be distinguished, when the outer diameter (larger than 800 mm) or the ratio (bigger than 3) are too high, so that the mould needs to be shorter than the standard case (usually more than 2000 mm), to allow the molten material to spin and solidify properly. Special moulds are more expensive because they produce fewer components in comparison with a longer mould (i.e. stacked production). For this reason, the formula Equation (F.13) distinguishes between a "Standard Case" and "Special Case", utilising this distinction in all the mould selection phase. The second step is to select the mould dimensions. They can be estimated from external diameter of the final part. The relationships (F.13)(F.14) and (F.15) have been derived using general linear models from a centrifugal casting supplier.

$$Selecting\ case: \begin{cases} if\ OD_f < 800mmAND\ \frac{OD_f}{ID_f} < 3 \rightarrow Standard\ Case \\ if\ OD_f > 800mm\ OR\ \frac{OD_f}{ID_f} > 3 \rightarrow Special\ Case\ (*) \end{cases} \tag{F.12}$$

Initially the mould's outer diameter is selected. This selection depends on the supplier availability and also the customer's demand (i.e. final target diameter). A step graph (Figure F.1) has been developed from the supplier's mould dimensions (including both the standard and special cases). Selecting the required outer diameter (x-axis) as input, the step graph defines an outer diameter for the mould (y-axis).

Selecting Mould dimensions: The mould length is selected through Equation (F.13), again a distinction is made between standard and special cases. Two expressions were ob-

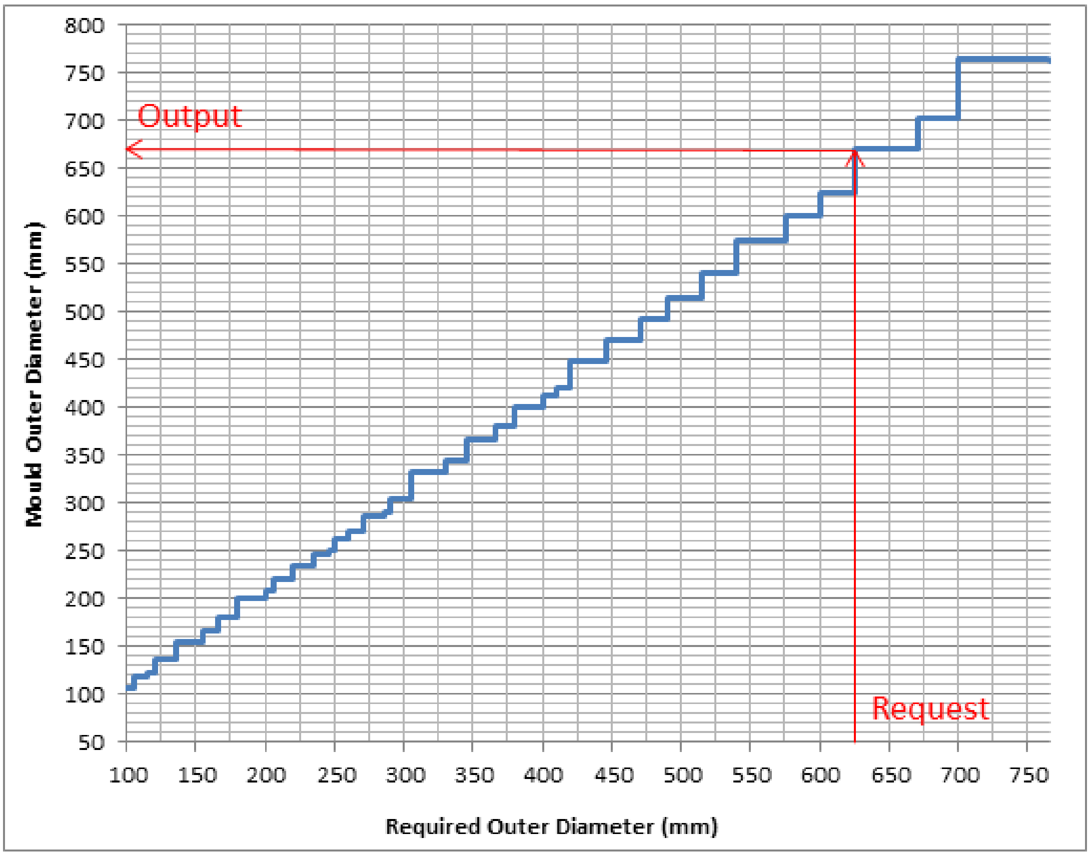


Figure F.1: Step diagram for selecting the centrifugal casting mould outer diameter from the required outer diameter.

tained from a general linear model from the supplier data. The input to the equation is the previously obtained mould outer diameter of the mould. The standard case length equation has an absolute average error of 6.68 % and the special case formula 8.12 % (calculated from the casting suppliers data [AMPO, 2016b]).

1. Selecting ODm: Figure F.1 show the relationship between the external diameters of the mould and the required outer diameters of the component. The selection of the external diameter depends on the available moulds and the specification of the customers. These dimensions reflect to the centrifugal casting supplier available range of moulds.

2. Selecting L_m: in the two different cases the mould length can be estimated as in equation (F.13)

$$\begin{cases} if\ Standard\ Case \rightarrow L_m = 3186 - 1815OD_m \\ if\ Special\ Case \rightarrow L_m^* = 253.5 + 0.357OD_m \end{cases} \tag{F.13}$$

The produced inner diameter (i.e. component after centrifugal casting process) is dependent on the volume of molten material that is poured in the spinning mould. As stated above, the mould's internal diameter is selected through the minimum internal diameter allowed. The internal diameter formulas (Equations (F.14) and (F.15)) have been derived through a general linear model from the supplier data. Having as input the mould outer diameter and length (previously selected), the calculation of the minimum diameter are able to verify if the required inner diameter if feasible. In the standard case (Equation (F.14)), if the required inner diameter is bigger than the minimum calculated inner diameter, the first can be selected, although an allowance of 10 mm (i.e. to machine away) should be included. This needs to be taken into account because of the debris and smaller particles gathered on the internal part of the component (due to less centrifugal force). If the requested diameter is smaller than the standard minimum inner diameter, the special case one is considered. If the required diameter is even less than the special case minimum inner diameter, the mould needs to be totally filled with the metal (so the internal diameter is 0) and machined to the size. In the special case (Equation (F.15)), only special minimum inner diameter is compared with the required one. The standard case minimum inner diameter equation has an absolute average error of 8.56 %, meanwhile has the special case formula has 2% (calculated from the casting suppliers data [AMPO, 2016b]). **Selecting ID_m**: equations (F.14) refers to the standard case, equations (F.15) refers to the special case.

$$\begin{cases} ID_{min} \quad = -255 - \ 0.655OD_m + 0.287L_m + 0.001387OD_m^2 \\ \qquad\qquad\qquad\qquad - 0.00006L_m^2 + 0.00014OD_mL_m \\ if\ ID_f > ID_{min} \quad \rightarrow ID_m = ID_f - 20 \\ if\ ID_f < ID_{min} \wedge ID_f > \ ID^*_{min} \rightarrow ID_m = ID_f - 30\ mm \\ if\ ID_f < ID^*_{min} \rightarrow ID_m = 0 \end{cases} \tag{F.14}$$

$$\begin{cases} ID_{min} \quad = -255 - \ 0.655OD_m + 0.287L_m + 0.001387OD_m^2 \\ \qquad\qquad\qquad\qquad - 0.00006L_m^2 + 0.00014OD_mL_m \\ if\ ID_f > ID_{min} \quad \rightarrow ID_m = ID_f - 20 \\ if\ ID_f < ID_{min} \wedge ID_f > \ ID^*_{min} \rightarrow ID_m = ID_f - 30\ mm \\ if\ ID_f < ID^*_{min} \rightarrow ID_m = 0 \end{cases} \tag{F.15}$$

F.2.2 Phase 2: Centrifugal Casting operation model

The output of the previous phase permits estimation of the mass of the casted component (Equation (F.16)), meanwhile the definition of the required dimensions permits estimation of the final mass, including the proof machining operation (Equation (F.17)).

The total centrifugal casting operation cost (i.e. which will be used as the centrifugal casting blank cost) is estimated as in Equation (F.18).

$$m_c = \pi \left(\frac{OD_m^2}{4} - \frac{ID_m^2}{4} \right) L_m \rho_m \tag{F.16}$$

$$m_v = \pi \left(\frac{OD_f^2}{4} - \frac{ID_f^2}{4} \right) L_f \rho_f \tag{F.17}$$

$$C_{CC} = C_{Mel} + C_{Aux} + C_{En} + C_{CCO} + C_{PrM} \tag{F.18}$$

The identified cost determinants are as follows: melting cost (Equation (F.19)) (i.e. including both the melting cost of the raw material and the re-melting of the proof machining chips); auxiliary cost (Equation (F.20)) (i.e. excluding the moulding cost); energy Cost (Equation (F.21)); casting operation cost (Equation (F.22)) (i.e. gross cost of the operation, including labour, set-up, depreciation and moulding); proof machining cost (Equation (F.23)). All the costs are related to the casting and final masses through coefficients. The material melting cost coefficient used is usually the alloy surcharge meanwhile the melting chips coefficient is a measure of the saving produced by material saving.

$$C_{Mel} = (m_c c_{MaM}) - ((m_c - m_v)\, c_{ChM}) \tag{F.19}$$

$$C_{Aux} = (m_c c_{Aux}) \tag{F.20}$$

$$C_{En} = (m_c c_{En}) \tag{F.21}$$

$$C_{CCO} = (m_c c_{CCO}) \tag{F.22}$$

$$C_{PrM} = ((m_c - m_v)\, c_{PrM}) \tag{F.23}$$

Usually the final length in excess can be amortized by other centrifugal casting productions (i.e. other customers' request) or re-melted, so the final length (L_m) and requested length (L_f) can be considered coincident ($L_m = L_f$).

The considered model input values are:

- Cost of machining per hour per hour: 86 £/h
- Centrifugal casting coefficients (used by the centrifugal casting for 420 STST): material melting cost coefficient (c_{MaM}): 1.8 £/kg; machining chips re-melting cost coefficient (c_{ChM}): 1.17 £/kg; auxiliary cost coefficient (c_{Aux}): 0.31 £/kg; energy cost coefficient (c_{En}): 0.62 £/kg; centrifugal casting operation cost coefficient (c_{CCO}): 2 £/kg; proof machining cost coefficient (c_{PrM}): 2 £/kg.
- Material data (solid blank, 420 STST): density, 7200 kg/m^3; cost 2.3 £/kg .

F.3 Helix-Turning Formulation

In Figures F.2 and F.3, the turning helix has been displayed. In point O, the global frame of the component is composed by the axis x, y , z and the unit vectors ($\underline{i}, \underline{j}, \underline{k}$). T is the point of contact of the tool. The local frame is composed of three unit vectors:$\underline{c}$, tangent to the circumference, to which corresponds the cutting speed vector v_c; $\underline{t}$, tangent to the helix trajectory, to which corresponds the helix speed vector v_H; $\underline{a}$, parallel to the workpiece axis and coincident to the tool motion axis (liner trajectory), to which corresponds the feed speed vector v_H. The helix equation parametric equation can be expressed as in (F.24)

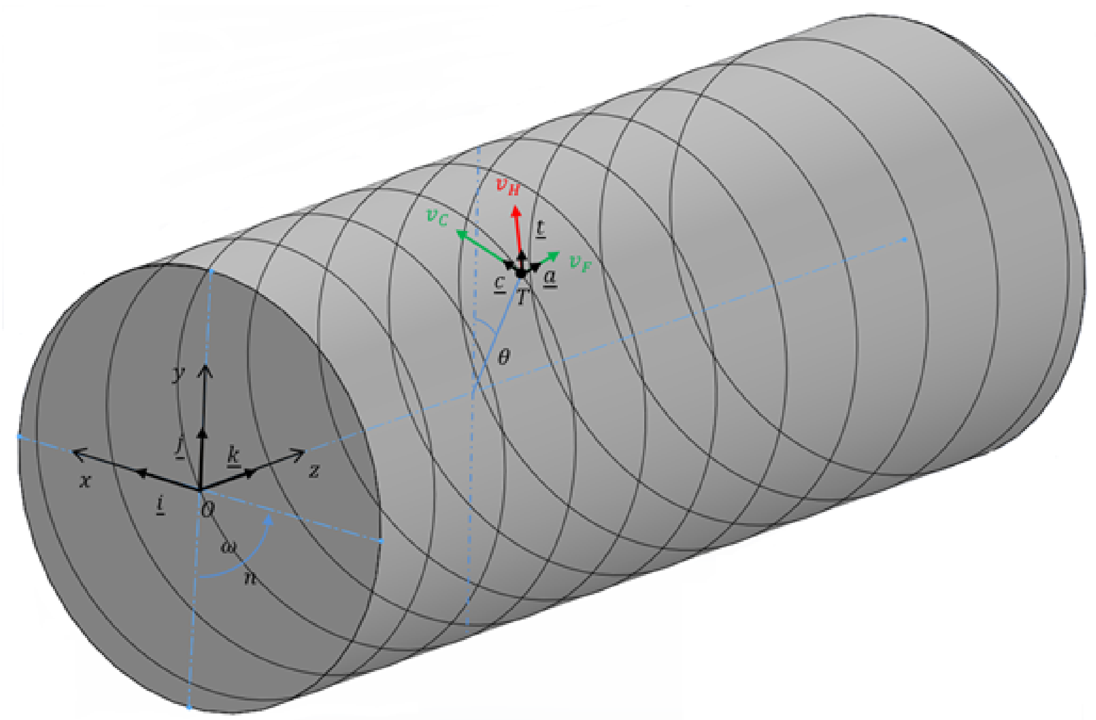


Table F.2: Turning helix model (isometric view).

$$\begin{cases} x = rcos\,(\theta) \\ y = rsin(t(\theta) \\ z = c\theta \end{cases} \tag{F.24}$$

With,

- $\theta \in [0, k\pi[$
- $x, y \in [0, r]$
- $z \in [0, L]$

The main features of the helix are as follows.

- $c = \frac{p}{2\pi}$
- Helix pitch, p

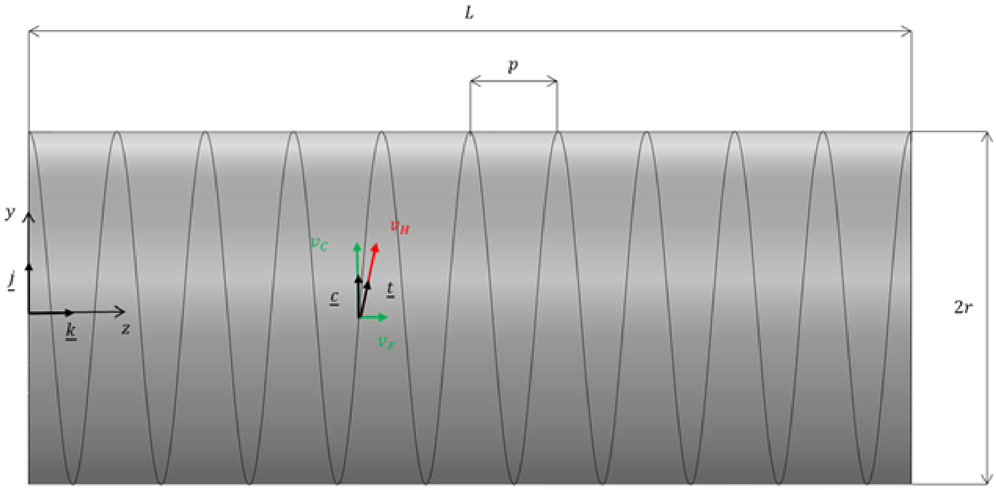


Table F.3: Turning helix model (lateral view).

- Slope, $\frac{c}{p}$
- Number of turns, $\frac{\theta_T}{2\pi}$
- Torsion, $\tau = \frac{c}{r^2+c^2}$
- Curvature, $k = \frac{r}{r^2+c^2}$

The velocity of a point on the helix can be written as (F.25)

$$\underline{v} = v_x\underline{i} + v_y\underline{j} + v_z\underline{k} = \frac{dx}{dt}\underline{i} + \frac{dy}{dt}\underline{j} + \frac{dz}{dt}\underline{k} = (-r\frac{d\theta}{dt}sin\,(\theta))\underline{i} + r\frac{d\theta}{dt}cos(\theta)\underline{j} + c\frac{d\theta}{dt}\underline{k} \tag{F.25}$$

Velocity vector can be written as in (F.26)

$$\begin{aligned}\underline{v} = \|\,v\|\;\underline{t} = \sqrt{v_x^2 + v_y^2 + v_z^2}\underline{t} = \sqrt{\frac{d^2\theta}{dt^2}(r^{\;\;2}\;(sin^2\,(\theta) + cos^2\,(\theta)\;\,) + c^2)}\underline{t} = \\ = \sqrt{(r^2 + c^2)}\frac{d\theta}{dt}\underline{t}\end{aligned} \tag{F.26}$$

If the motion is uniform, it is possible to write (F.27)

$$fracd^2\theta dt^2 = 0,\;\frac{d\theta}{dt} = \omega \tag{F.27}$$

Arc Length: the total helix arc length can be derived integrating the velocity (F.26) as in (F.28) and (F.29)

$$ds = vdt, \int_0^l ds = \int_{t_0}^t |v|\, dt \tag{F.28}$$

$$l_H = \int_{t_0}^t \sqrt{(r^2 + c^2)} \frac{d\theta}{dt} dt = \sqrt{(r^2 + c^2)} \theta_{t_0}^t \tag{F.29}$$

Classic Turning Formulation The classic formulation use the following inputs

- F, feed rate (mm/lap)
- n, spindle speed (lap/min)
- a, depth of cut (mm)
- l, working engagement (mm)

The feed velocity (F.30), cutting speed (F.31) and cutting time (F.32) classic formulations can be written as follows

$$v_f = Fn \tag{F.30}$$

$$v_c = \pi D_c n \tag{F.31}$$

$$t_c = \frac{l}{Fn} \tag{F.32}$$

Helix equivalence For the helix the speed can be written as (F.33)

$$v_H = l_H / t_c \tag{F.33}$$

Having the total number of turns θ_T, the length (F.29) can be rewritten as (F.34)

$$l_H = \sqrt{(r^2 + c^2)}\theta_T \tag{F.34}$$

Given, $z = c\theta$, with $z = L$, it is possible to write (F.35)

$$\theta_T = \frac{L}{c} = \frac{L}{p/2\pi} \tag{F.35}$$

The cutting time t_c must be the same for both the formulations. Having $L = l$ and $t_c = \frac{l}{Fn}$, the cutting time can be also written as (F.36)

$$t_c = \frac{\sqrt{(r^2 + c^2)}\frac{2\pi L}{p}}{\sqrt{(r^2 + c^2)}\omega} = \frac{2\pi L}{p\omega} \tag{F.36}$$

The hypothesis $t_c(helix) = t_c(classic)$ can be dimensionally checked as in (F.37)

$$\frac{2\pi L}{p\omega} = \frac{L}{Fn} \rightarrow \left[\frac{2\pi L}{p\omega}\right] = \frac{mm}{\frac{mm}{rad}\frac{rad}{s}} = \frac{mm}{\frac{mm}{lap}\frac{lap}{s}} = \left[\frac{L}{Fn}\right] \tag{F.37}$$

Therefore, the helix pitch can be written as (F.38)

$$p = \frac{2\pi Fn}{\omega} = 60F \tag{F.38}$$

Velocity Hypothesis The helix speed and the cutting and feed rate speed must be complementary, so (F.39) can be formulated.

$$v_H = \sqrt{v_c^2 + v_f^2} \tag{F.39}$$

Hybrid Formulation In (F.40) the helix and classic formulation are combined by substituting the v_H (F.39) in cutting time equation (F.36), as in the (F.33)

$$t_c = \frac{\sqrt{({r_i}^2 + c_i^2)}\frac{2\pi L_i}{p_i}}{\sqrt{v_{c_i}^2 + v_{f_i}^2}} \tag{F.40}$$

With $c = \frac{p}{2\pi}$, it is possible to write (F.41) and finally derive (F.42)

$$t_c = \frac{\sqrt{(r)^2 + \left(\frac{Fn}{\omega}\right)^2}\frac{\omega L}{Fn}}{\sqrt{v_c^2 + v_f^2}} = \left(\frac{\frac{L^2\omega^2}{F^2n^2}(r^2 + \frac{F^2n^2}{\omega^2})}{F^2n^2 + 4\pi^2r^2n^2}\right)^{\frac{1}{2}} = \left(\frac{L^2(\frac{\omega^2}{F^2n^2}r^2 + 1)}{(n^2(F)^2 + 4\pi^2r^2)}\right)^{\frac{1}{2}} \tag{F.41}$$

$$t_c = \frac{L}{n}\left(\frac{\frac{\omega^2}{F^2n^2}r^2 + 1}{F^2 + 4\pi^2r^2}\right)^{\frac{1}{2}} \tag{F.42}$$

A dimensional check (F.43) shows the validity of the formula (F.42)

$$t_c = \left[\frac{L}{n}\left(\frac{\frac{\omega^2}{F^2n^2}r^2 + 1}{(F)^2 + \pi^2r^2}\right)^{\frac{1}{2}}\right] = \frac{mm}{\frac{1}{s}}\left(\frac{\frac{\left(\frac{1}{s}\right)^2 mm^2}{\frac{mm}{1}^2\frac{1}{s^2}} + 1}{(\frac{mm}{1})^2 + mm^2}\right)^{\frac{1}{2}} = \frac{mm}{\frac{1}{s}}\left(\frac{1}{mm^2}\right)^{\frac{1}{2}} = \frac{mm}{mm/s} = s \tag{F.43}$$

In conclusion, with $\omega = \frac{2\pi n}{60}$ and $D = 2r$ (so $D^2 = 4r^2$) the cutting time become (F.43)

$$t_c = 60\frac{L}{n}\left(\frac{\left(\frac{\pi D}{60\ F}\right)^2 + 1}{F^2 + \pi^2 D^2}\right)^{\frac{1}{2}} \tag{F.44}$$

F.4 Turning Model Formulation

Referring to figure B4.1 it is possible to define: *Finishing Diameters (10 mm hypothesis)*

$$OD_F = OD + 10 \tag{F.45}$$

Turning Model Nomenclature

OD, external final diameter after finishing (mm)
OD_F, external machined diameter before finishing (mm)
OD_{CCB}, external centrifugal casting blank diameter after proof machining (mm)
OD_M, external centrifugal casting blank diameter (mm)
ID, internal final diameter after finishing (mm)
ID_F, intern machined diameter before finishing (mm)
ID_{CCB}, internal centrifugal casting blank diameter after proof machining (mm)
ID_M, internal centrifugal casting blank diameter (mm)
OD_b, external final diameter of the bottom section after finishing (mm)
OD_{b_F}, external final diameter of the bottom section before finishing (mm)
OD_{CCB}, external centrifugal casting blank diameter after proof machining (mm)
OD_M, external centrifugal casting blank diameter (mm)
N_{E_T}, theoretical number of turning process passes for the external zone
N_{I_T}, theoretical number of turning process passes for the internal zone
N_{Eb_T}, theoretical number of turning process passes for the external bottom section zone
N_E, rounded number of turning process passes for the external zone
N_I, rounded number of turning process passes for the internal zone
N_{E_b}, rounded number of turning process passes for the external bottom section zone
L, component (turning) length (mm)
l, bottom section (turning) length (mm)
a, depth of cut (mm)
F, feed rate (mm)
n, rotational speed (1/min)
T_{Tu}, total turning time (min)
t_{IN_T}, total internal turning time (min)
t_{EX_T}, total external turning time (min)
$T_{EX_{bT}}$, total external bottom section turning time (min)

External and Internal Turning Derivation Nomenclature

a_i, depth of cut for the i_{th} turning operation (mm)
F_i, feed rate for the i_{th} turning operation (mm)
n_i, rotational speed (1/min)
N, total number of turning passes for the whole machining operation
N_e, rounded external number of turning passes
N_i, rounded internal number of turning passes
L_i, turning length for the i_{th} turning operation (mm)
L_T, generic total turning length (mm)
D_i, total turning diameter for the i_{th} turning operation (mm)
OD_i, external turning diameter for the i_{th} turning operation (mm)
OD_0, external turning diameter for the i_{th} turning operation (mm)
OD_T, external turning diameter for the i_{th} turning operation (mm)
OD_T, external turning diameter for the i_{th} turning operation (mm)
OD_0, initial outer turning diameter (mm)
OD_f, final outer turning diameter (mm)
ID_i, generic internal turning diameter for the i_{th} turning operation (mm)
ID_0, initial inner turning diameter (mm)
ID_f, final inner turning diameter (mm)

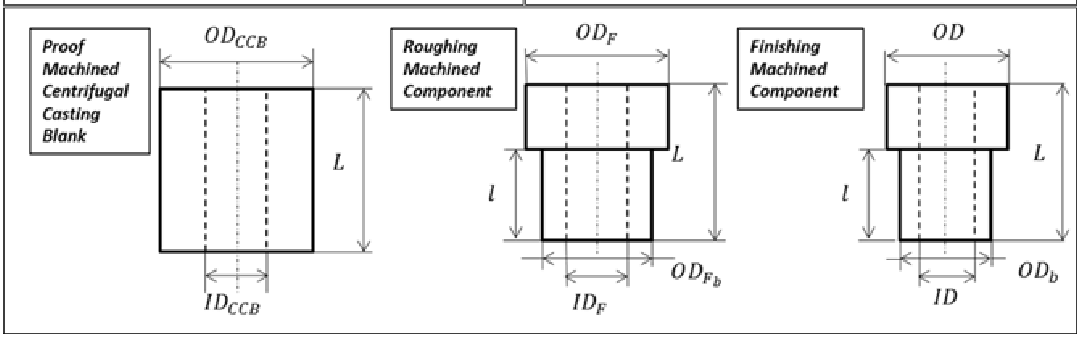


Table F.4: Turning model nomenclature.

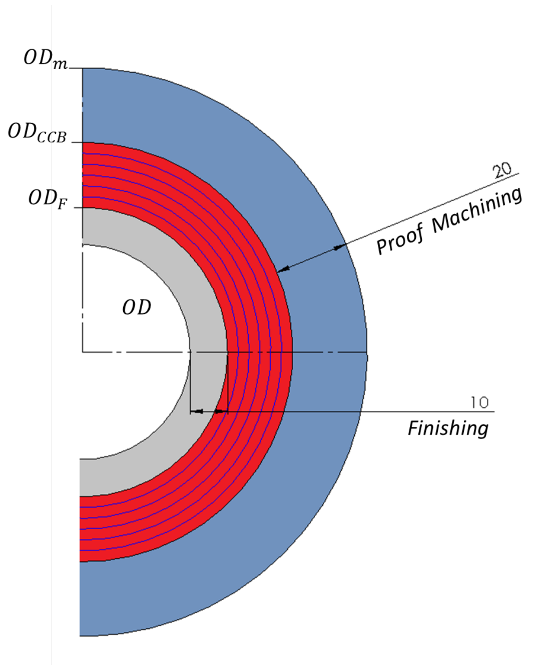


Table F.5: External turning process scheme and nomenclature scheme (blue: proof machining zone; red: roughing zone; grey: finishing zone)

$$OD_{F_b} = OD_b + 10 \tag{F.46}$$

$$ID_F = ID - 10 \tag{F.47}$$

Roughing Machining Theoretical number of turns

$$N_{E_T} = \frac{OD_{CCB} - OD_F}{a} = \frac{OD_m - OD - 30}{a} \tag{F.48}$$

$$N_{I_T} = \frac{ID_F - ID_{CCB}}{a} = \frac{ID - ID_m - 30}{a} \tag{F.49}$$

$$N_{Eb_T} = \frac{OD_F - OD_{F_b}}{a} = \frac{OD - OD_b}{a} \tag{F.50}$$

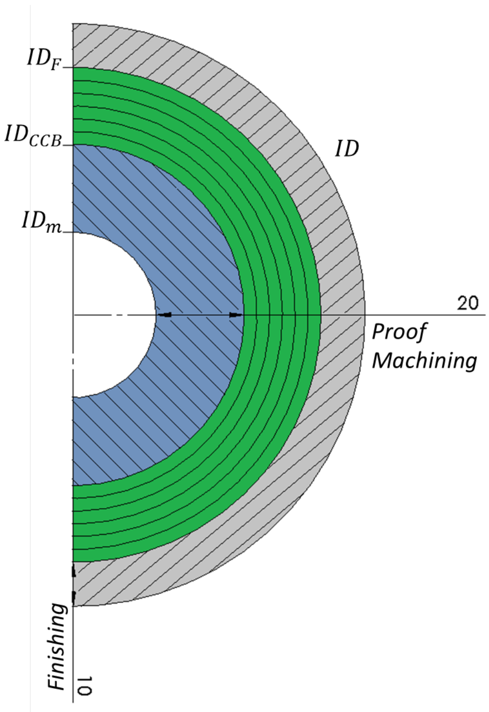


Table F.6: External turning process scheme and nomenclature scheme (grey: finishing zone; green: roughing zone; blue: proof machining zone).

Rounded number of turns (natural number)

$$N_E = roundup\left(\frac{OD_m - OD - 30}{a}\right) \tag{F.51}$$

$$N_{E_b} = roundup\left(\frac{ID - ID_m - 30}{a}\right) \tag{F.52}$$

$$N_I = roundup\left(\frac{OD - OD_b}{a}\right) \tag{F.53}$$

Proof Machined Diameters (20 mm allowances from CC blank)

$$OD_{CCB} = OD + 10 + N_e a = OD_m - 20 \tag{F.54}$$

$$ID_{CCB} = ID + 10 + N_e a = ID_m - 20 \tag{F.55}$$

For a single turning operation, the machining parameters can be considered as constant, so the following hypotheses result generally valid for the turning process parameters.

- $a_i = costant = a$
- $n_i = costant = n$
- $F_i = constant = F$

In addition, in all three cases, the turning length can be considered constant ($L_i = cost = L$) for a single turning operation. Therefore (F.56) can be written

$$\sum_{i=1}^{N} L_i = NL_T \tag{F.56}$$

Therefore, using the turning helix formula, the total turning time can be written as (F.57)

$$\begin{aligned} t_T = \sum_{i=1}^{N} t_i = t_1 + t_2 + \cdots + t_N = \frac{60L}{n}\sqrt{\frac{1+\pi^2 D_1^2}{F^2+\pi^2 D_1^2}} + \frac{60L}{n_1}\sqrt{\frac{1+\pi^2 D_2^2}{F^2+\pi^2 D_2^2}} + \dots \\ \cdots + \frac{60L}{n}\sqrt{\frac{1+\pi^2 D_N^2}{F^2+\pi^2 D_N^2}} = \frac{60NL}{n}\sqrt{\frac{1+\pi^2\sum_{i=1}^{N} D_i}{F^2+\pi^2\sum_{i=1}^{N} D_i}} \end{aligned} \tag{F.57}$$

Distinction needs to be made for the external and internal turning.

In *external turning case* ($D_i = OD_i$)

$$OD_i = OD_0 - (a_1 + a_2 + \cdots + a_i) \tag{F.58}$$

Although with $a = constant$ it becomes

$$OD_i = OD_0 - (a + 2a + 3a + \cdots + N_i a) = OD_0 - \sum_{i=1}^{N_{i_E}} i(a) \tag{F.59}$$

The last sum can be written as

$$\sum_{i=1}^{N_e} i(a) = \frac{N_e\left(N_e+1\right)a}{2} \tag{F.60}$$

Therefore

$$OD_i = OD_0 - \frac{N_e\left(N_e+1\right)a}{2} \tag{F.61}$$

Therefore

$$\sum_{i=1}^{N_e} OD_i = N_e OD_0 - \frac{N_e\left(N_{i_e}+1\right)a}{2} \tag{F.62}$$

Similar conclusions can be drafted for the *internal turning case* $(D_i = (ID_i))$ The general inner diameter after *i-passes* can be written as

$$ID_i = ID_0 + (a_1 + a_2 + \cdots + a_i) \tag{F.63}$$

Therefore, dually to the outer diameter case

$$ID_i = ID_0 + \frac{N_i\left(N_i+1\right)a}{2} \tag{F.64}$$

Therefore the total external turning time formula become

$$t_{E_T} = \frac{60 N_e L_T}{n}\sqrt{\frac{1+\pi^2\left(N_e OD_0 - \frac{N_e(N_e+1)a}{2}\right)^2}{F^2+\pi^2\left(N_e OD_0 - \frac{N_e(N_e+1)a}{2}\right)^2}} \tag{F.65}$$

With $N_e = round\left(\frac{OD_0 - OD_f}{a}\right)$

Similarly the total internal turning time

$$t_{I_T} = \frac{60 N_i L}{n}\sqrt{\frac{1+\pi^2\left(N_i ID_0 + \frac{N_i(N_i+1)a}{2}\right)^2}{F^2+\pi^2\left(N_I ID + \frac{N_i(N_i+1)a}{2}\right)^2}} \tag{F.66}$$

In the examined case, the total turning time can be written as

$$
\begin{aligned}
T_{Tu} = t_{IN_T} + t_{EX_T} + t_{EX_{bT}} = \\
\frac{60N_E L}{n}\sqrt{\frac{1+\pi^2\left(N_E\left((OD-10)-\frac{N_E\left(N_{i_E}+1\right)a}{2}\right)\right)^2}{F^2+\pi^2\left(N_E\left((OD-10)-\frac{N_{i_E}\left(N_{i_E}+1\right)a}{2}\right)\right)^2}}+ \\
+\frac{60N_I L}{n}\sqrt{\frac{1+\pi^2\left(N_I\left((ID+10)+\frac{N_I(N_I+1)a}{2}\right)\right)^2}{F^2+\pi^2\left(N_I\left((ID+10)+\frac{N_I(N_I+1)a}{2}\right)\right)^2}}+ \\
+\frac{60N_{E_b} l}{n_i}\sqrt{\frac{1+\pi^2\left(N_{E_b}\left((OD_b-10)-\frac{N_{E_b}\left(N_{E_b}+1\right)a}{2}\right)\right)^2}{{F_i}^2+\pi^2\left(N_{E_b}\left((OD_b-10)-\frac{N_{E_b}\left(N_{E_b}+1\right)a}{2}\right)\right)^2}}
\end{aligned}
\tag{F.67}
$$

F.5 GA Results

GA results	Population	Generations	FF1 - Total Cost [£]	FF2 - Cutting Force [N]	Power [kW]	MRR [mm^3/min]	Roughness [Ra]	Machining Time [min]	Machining Cost [£]	Casting blank Cost [£]
No Constrains	100	500	2133.59	4364.13	41.58	1.19E+06	23.75	53.97	77.17	1302.15
	200	500	2140.82	4070.99	38.66	1.10E+06	20.91	60.19	86.08	1302.13
	500	500	2130.13	4313.27	41.38	1.18E+06	24.37	51.59	73.78	1302.14
3 Constrains	50	50	2162.31	2225.57	16.64	4.75E+05	3.25	80.76	115.48	1303.37
	50	100	2153.81	2345.85	17.60	5.03E+05	3.46	76.93	110.00	1302.20
	50	200	2153.18	2225.56	17.54	5.01E+05	3.60	76.61	109.55	1302.21
	50	500	2149.36	2226.14	18.12	5.18E+05	3.49	74.00	105.82	1302.13
	100	50	2149.52	2186.69	18.43	5.27E+05	2.45	76.36	109.19	1302.42
	100	100	2149.30	2059.50	17.72	5.06E+05	2.65	74.34	106.30	1302.16
	100	200	2152.54	2195.10	19.03	5.44E+05	3.08	68.97	98.62	1302.16
	100	500	2157.92	1919.30	16.43	4.70E+05	2.28	80.03	114.45	1302.15
	200	50	2147.10	2118.42	18.45	5.27E+05	3.32	72.55	103.75	1302.29
	200	100	2143.75	2229.81	19.39	5.54E+05	3.46	69.98	100.07	1302.24
	200	200	2144.27	2190.83	19.00	5.43E+05	3.30	71.01	101.54	1302.14
	200	500	2144.86	2181.59	18.96	5.42E+05	3.37	70.10	100.24	1302.13
	500	50	2148.39	2093.58	18.05	5.16E+05	3.06	74.57	106.63	1302.28
	500	100	2143.69	2190.37	18.86	5.39E+05	3.14	71.42	102.13	1302.15
	500	200	2140.81	2261.62	19.39	5.54E+05	3.07	69.74	99.73	1302.14
	500	500	2143.91	2189.16	18.87	5.39E+05	3.19	71.55	102.32	1302.13

Table F.7: GA runs summary table (settings, average fitness functions and constraints function values).

Individual Number	OD [mm]	ID [mm]	a [mm]	n [RPM]	F [mm/lap]	OD_b[mm]	l_f[mm]	L_f[mm]	ID_m [mm]	FF1 - Total Cost [£]	FF2 -Cutting Force [N]	Power [kW]	MRR [mm^3/min]	Roughness [Ra]	Machining Time [min]	Machining Cost [£]	casting blank Cost [£]
1	495.5	410.5	7.3	254.0	0.25	477.7	65.7	415.0	370.0	2124.3	2949.7	25.10728	7.17E+05	3.86	56.08	80.20	1302.16
2	495.5	410.5	7.3	254.0	0.25	477.8	65.7	415.0	370.0	2124.4	2929.5	24.95216	7.13E+05	3.86	56.08	80.19	1302.17
3	499.2	410.6	6.2	254.0	0.25	477.8	65.7	415.0	370.0	2140.4	2289.9	19.90094	5.69E+05	3.36	66.03	94.42	1302.15
4	499.3	410.5	6.2	254.0	0.25	477.8	65.7	415.0	370.0	2163.4	1772.4	15.05742	4.30E+05	1.93	87.16	124.64	1302.16
5	499.2	410.6	6.2	254.0	0.25	477.8	65.7	415.0	370.0	2142.3	2244.3	19.464	5.56E+05	3.19	67.73	96.85	1302.16
6	499.2	410.5	6.2	253.9	0.25	477.7	65.7	415.0	370.0	2179.6	1537.5	12.88429	3.68E+05	1.41	101.99	145.84	1302.16
7	499.4	410.5	5.6	254.0	0.25	477.8	65.7	415.0	370.0	2204.6	1448.5	12.31522	3.52E+05	1.55	97.05	138.79	1302.17
8	495.5	410.9	7.1	254.0	0.25	477.7	65.5	415.0	370.0	2127	2796.7	23.80929	6.80E+05	3.65	57.64	82.43	1302.16
9	499.2	410.7	6.2	254.0	0.25	477.7	65.7	415.0	370.0	2151.5	2031.2	17.44786	4.99E+05	2.55	75.73	108.29	1302.16
10	495.5	410.5	7.1	254.0	0.25	477.7	65.7	415.0	370.0	2124.7	2879.2	24.56145	7.02E+05	3.86	56.08	80.19	1302.16
11	499.3	410.5	6.2	254.0	0.25	477.8	65.7	415.0	370.0	2147.2	2106.8	18.17838	5.19E+05	2.81	72.20	103.25	1302.23
12	499.2	410.5	6.2	254.0	0.25	477.7	65.7	415.0	370.0	2167.2	1713.1	14.50028	4.14E+05	1.78	90.62	129.59	1302.15
13	499.2	410.5	6.2	254.0	0.25	477.7	65.7	415.0	370.0	2169.5	1676.8	14.16546	4.05E+05	1.70	92.76	132.65	1302.16
14	499.2	410.5	6.2	253.9	0.25	477.7	65.7	415.0	370.0	2179.6	1537.5	12.88429	3.68E+05	1.41	101.99	145.84	1302.16
15	499.2	410.5	6.2	254.0	0.25	477.7	65.7	415.0	370.0	2160	1836.9	15.65069	4.47E+05	2.08	83.96	120.06	1302.16
16	495.5	410.5	7.3	254.0	0.25	477.8	65.7	415.0	370.0	2157.5	1931.5	15.84104	4.53E+05	1.55	88.33	126.32	1302.16
17	495.5	410.5	7.3	254.0	0.25	477.8	65.7	415.0	370.0	2155	1983.6	16.30311	4.66E+05	1.65	85.83	122.74	1302.16

Table F.8: Last generation of individuals for GA application (100 individuals population and 100 generations): variables optimal sets (Pareto individuals), fitness functions and constrain function values Part I

Individual Number	OD [mm]	ID [mm]	a [mm]	n [RPM]	F [mm/lap]	OD_b[mm]	l_f[mm]	L_f[mm]	ID_m [mm]	FF1 - Total Cost [£]	FF2 -Cutting Force [N]	Power [kW]	MRR [mm^3/min]	Roughness [Ra]	Machining Time [min]	Machining Cost [£]	casting blank Cost [£]
18	499.4	410.5	6.2	254.0	0.25	477.9	65.5	415.0	370.0	2137.1	2375.8	20.73168	5.92E+05	3.65	63.34	90.57	1302.16
19	499.3	410.6	6.2	254.0	0.25	477.8	65.7	415.0	370.0	2172	1649.4	13.91767	3.98E+05	1.65	94.31	134.86	1302.18
20	495.5	410.6	7.1	254.0	0.25	477.8	65.7	415.0	370.0	2130.5	2640	22.34661	6.38E+05	3.19	61.64	88.14	1302.15
21	499.3	410.5	6.2	254.0	0.25	477.8	65.7	415.0	370.0	2149.4	2059.5	17.72304	5.06E+05	2.65	74.34	106.30	1302.16
22	499.2	410.5	6.2	253.9	0.25	477.8	65.7	415.0	370.0	2139.4	2325.1	20.22371	5.78E+05	3.45	65.20	93.23	1302.16
23	495.5	410.6	7.1	254.0	0.25	477.8	65.7	415.0	370.0	2128.5	2711.9	23.01632	6.58E+05	3.40	59.69	85.35	1302.16
24	495.5	410.5	7.1	253.9	0.25	477.7	65.7	415.0	370.0	2133.8	2516.5	21.21463	6.06E+05	2.90	64.68	92.50	1302.16
25	495.5	410.5	7.1	254.0	0.25	477.7	65.7	415.0	370.0	2144.6	2189.2	18.23334	5.21E+05	2.14	75.26	107.62	1302.16
26	499.3	410.5	6.2	254.0	0.25	477.8	65.7	415.0	370.0	2174.1	1612.9	13.57418	3.88E+05	1.55	97.06	138.79	1302.16
27	495.5	410.5	5.6	254.0	0.25	477.7	65.5	415.0	370.0	2190.5	1470.5	12.3909	3.54E+05	1.59	106.09	151.71	1302.23
28	499.3	410.5	6.2	254.0	0.25	477.8	65.7	415.0	370.0	2163.3	1779.8	15.11517	4.32E+05	1.93	87.16	124.64	1302.16
29	499.3	410.7	6.2	254.0	0.25	477.8	65.7	415.0	370.0	2135.9	2438.2	21.31854	6.09E+05	3.86	61.62	88.12	1302.22
30	495.5	410.6	7.1	254.0	0.25	477.8	65.7	415.0	370.0	2132	2586.1	21.84233	6.24E+05	3.05	63.06	90.18	1302.16
31	499.3	410.5	6.2	253.9	0.25	477.8	65.7	415.0	370.0	2158.2	1873.9	15.98633	4.57E+05	2.15	82.48	117.94	1302.16
32	495.5	410.5	7.1	254.0	0.25	477.8	65.7	415.0	370.0	2134.9	2479.9	20.88176	5.97E+05	2.81	65.71	93.97	1302.16
33	495.5	410.5	5.6	253.9	0.25	477.8	65.7	415.0	370.0	2187.4	1494.7	12.60576	3.60E+05	1.65	104.27	149.11	1302.23
34	495.5	410.9	7.1	254.0	0.25	477.9	65.5	415.0	370.0	2130	2690.1	22.81704	6.52E+05	3.35	60.19	86.06	1302.30
35	499.3	410.5	6.2	254.0	0.25	477.8	65.7	415.0	370.0	2145.8	2142.4	18.5128	5.29E+05	2.91	70.90	101.38	1302.23
									Average	*2149.30*	*2168.66*	*18.47*	*5.28E+05*	*2.66*	*75.39*	*107.80*	*1302.18*

Table F.9: Last generation of individuals for GA application (100 individuals population and 100 generations): variables optimal sets (Pareto individuals), fitness functions and constrain function values Part II

Appendix G

Systematic Literature Review of Manufacturing Optimization: Case Study II

G.1 Review of Numerical Approaches to Turning Process Optimization

Metal cutting is still essential for manufacturing units. For responding to the competitiveness and increasing demand for quality, optimization methods in metal cutting are vital for achieving continuous improvement of process output quality in products and processes include modelling of input-output and in-process parameter relationship and the determination of optimal cutting conditions [Mukherjee and Ray, 2006]

Firstly, Khan et al. [1997]) benchmark evolutionary algorithms' models for evaluating optimal machining conditions. The models analysed were Genetic Algorithm (GA), Simulated Annealing (SA) and a modification of the latter, called Continuous Simulated Annealing (CSA).

The authors compared the models among each other and also with gradient methods (i.e. Sequential Unconstrained Minimization Technique (SUMT), Box's Complex Search, Hill Algorithm (Sequential search technique), GRG (Generalized Reduced Gradient)). Five optimization problems has been presented in order to evaluate and compare them. From the convergence analysis and the comparison between the models (GA, SA, CSA) and the gradient solving methods, all the three benchmarked models show high reliability and converged to global minima in all the examined cases (i.e. without requiring any gradient information, so making them suitable for discontinuous functions). All the models' solutions are not influenced by the dimensions of the input vectors (i.e. variables number), although they increase the convergence time. Regarding the differences between the specific models, SA gives high precision and the code can be run longer to get higher precision. For GA, the precision is proportional and limited by the precision used for representing each variable (i.e. number of bits). CSA reached the highest precision due to its adaptive capability. GA, SA and CSA advantages over gradient methods include the higher total number of function and constraint evaluations. Although, the higher functions evaluations per run (i.e. giving a high convergence time) is a disadvantage that make them not highly reliable for real-time optimization.

Aggarwal and Singh [2005] review traditional (Lagrange's method, geometric programming, goal programming, dynamic programming) and more recent techniques (Fuzzy logic, genetic algorithm, scatter search, Taguchi technique and Response Surface Methodology (RSM)) for machining parameters optimization. For the first, the DoE based approaches (i.e. Taguchi and RSM) are more robust and are capable of making the process and products insensitive to non-controllable factors (e.g. environmental noise). Regarding the off-line optimization methods, optimizing the process (i.e. process parameters) and product design at early design stages, making the process insensitive to variation in noise variables and reducing the quality loss are very important to both research and practitioners.

Mukherjee and Ray [2006] describe the machining process parameters optimization techniques, taxonomizing them under different criteria. The authors describe the input-output and in-process parameter relationship modelling based on statistical, artificial neural network and fuzzy set theory as an endless list. Even though methods can give satisfactory results in many applications, the constraints, assumptions and shortcomings, that need to be made for their usage, limit their application. Furthermore, optimization problems complexity have increased because of the increasing resolution of both cutting process dynamic and mechanics. This increase have been made by introducing discrete and continuous parameter spaces as well as multi-modal differentiable as well as non-differentiable objective function(s). Therefore, "determination of optimal or acceptable near-optimal solution(s) by a suitable optimization technique based on input-output and in-process parameter relationship or objective function formulated from model(s) with or without constraint(s), is a critical and difficult task for researchers and practitioners"[Mukherjee and Ray, 2006]. Meanwhile conventional techniques provide a local optimal solution, non-conventional techniques, which are based on extrinsic models or objective functions, is only an approximation, and attempt to provide near-optimal cutting condition(s). Conventional techniques can be classified in two categories: experimental and iterative mathematical search techniques. The first includes statistical DoE (e.g. Taguchi method) and response surface design methodology (RSM). On the other hand, iterative mathematical search techniques include linear programming (LP), non-linear programming (NLP), and dynamic programming (DP) algorithms. Non-conventional techniques include the meta-heuristic search based algorithms. Three main types of metaheuristic search based algorithm are applied in machining process parameters optimization: genetic algorithm (GA), simulated annealing (SA), and tabu search (TS).

Heuristics can be generally defined as search techniques that are able to provide, among several alternatives, the most effective solution for achieving a certain goal. The search based algorithm provides a rule, or set of rules, for identifying an acceptable solution, or solutions, at a certain (or acceptable) computational cost. Heuristic-based search techniques find proper application cases whenever conventional techniques fail to achieve results or their computational cost is too high (e.g. an high dimensional search space with several local optima). They have been widely used for combinatorial process optimization, providing near-optimal solution, or solutions. In these cases, both researchers and practitioners prefer alternative cost effective near-optimal (or approximate) solution(s) than exact optimal, as it may be extremely difficult to find exact optimal point in higher dimensions, and multimodal search spaces [Mukherjee and Ray, 2006]. The metaheuristic searches, particularly the evolutionary algorithms, have been developed as "problem specific" solvers, guiding, or modifying heuristics to produce local optimal solutions. Regarding the evolutionary algorithms, [Mukherjee and Ray, 2006] provide the general applications advantages and disadvantages of their usage. GAs are generally preferred for single and multi-objective optimization of large (i.e. high number of variables) and complex problems. Even though they are the most frequently used, they present some disadvantages: convergence is not assured; selection of algorithm parameters (i.e. population, number of generations, mutation and crossover probability) has no general guidelines; high execution time and low convergence speed; using the same variable and settings, repeatability is not assured.

TS is most flexible and easiest to implement into optimization problems, having also a good computational speed. However, a great issue is the uncertainty of convergence of the algorithm in a finite number of steps (i.e. multi-modal objective functions), which instead is assured for the other metaheuristics.

SA's simplicity and effectiveness is offset by the strong effect of its parameters (i.e. cooling schedule). The parameters setting has no generally acceptable level of control for every cutting process. As in the GA case, the repeatability of the same results is not guaranteed.

G.2 Genetic Algorithm: a Brief Introduction

Figure G.1 shows the main features and framework of a GA. The population of GA is composed by single individuals (chromosomes or strings) that are evaluated for each generation using a fitness function (s) (or objective function(s)), which is the target function to minimize. Evaluation of strings corresponds to the act of finding a solution of the function(s): the space, where the solution is searched, depends by the fitness function itself and to the variables ranges, linear and non-linear constrains. All the individuals are composed by subunits (genes), resembling the DNA configuration. The chromosome representation generates a string of binary (binary coding) or real (real coding) numbers, representing the optimization problem variables, and so an acceptable fitness function solution, as a single individual. The required variables precisions and domains dimensions (variables ranges, linear and on-linear constrains) affect the length of the strings (particularly in the binary coding case), which influence the overall efficiency of the algorithm (i.e. for this reason, real coding is generally preferred with non-linear functions).

Selection stage reduces the population and chooses the individuals of the population for breeding (crossover or recombination), by screening out the individuals with relatively low fitness. The offspring will be the next generation, and selection drives the GA to improve the population fitness over the successive generations, using a degree if favouritism for selecting the better individuals (i.e. selection pressure). The selection methods can be ranked in two groups: fitness proportionate selection and ordinal-based selection. The first chooses the individuals basing on their relative values of fitness function (roulette-wheel selection method), the second picks up the individuals upon their ranking (ordering) within the population (tournament selection method).

Crossover is a stochastic operator that allows information exchanges between chromosomes (parents), generating new individuals (children) (Figure G.1). The main operators are simple

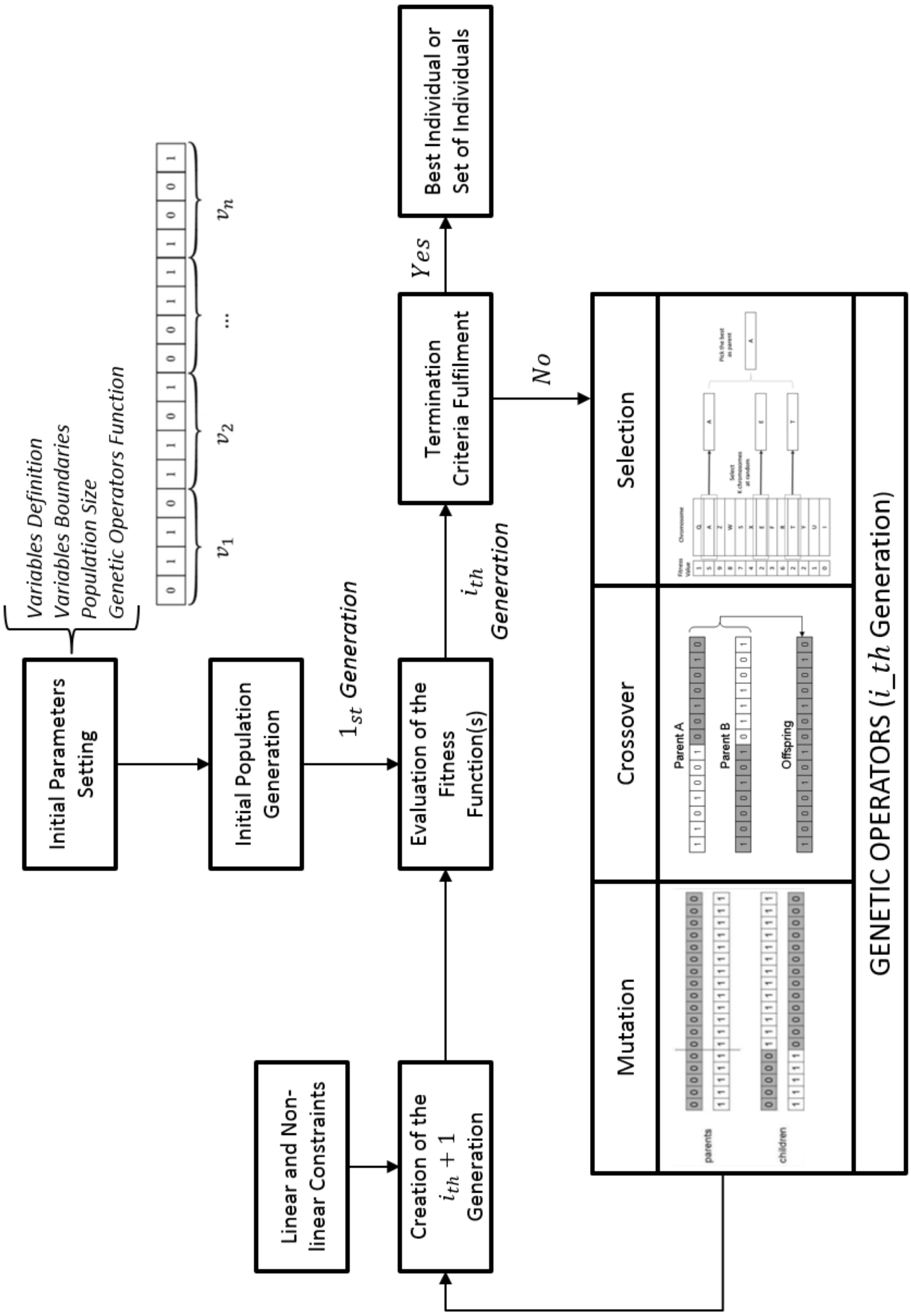


Figure G.1: A generic Genetic Algorithm framework, adapted from Goldberg [1989].

crossover (i.e. selecting two random cutting points and exchange the individuals' substrings), two or three points crossover, scattered, heuristic and arithmetical crossover (i.e. real number representation). The number of crossover in a generation is function of the crossover rate. Mutation operator produces spontaneous random changes into the strings, in order to introduce extra variability (i.e. avoiding the local minima). In a string for example, the mutation operator (e.g. binary uniform mutation) selects one or more bits and exchange their values inside the chromosome itself (Figure G.1). The main mutation operators are Gaussian, uniform and adaptive feasible functions. Countless other operators and algorithm modification or integration (i.e. with other methods) have been introduced during the years, although, for brevity, they are not going to be discussed in this work.

Algorithm termination is defined by the termination (or convergence) criteria. Usually, the exceeding of the defined generations number or number of evaluations (i.e. individuals having similar fit between every passes) are the selected criteria. However, both of them do not take into account the calculation accuracy (i.e. fitness function) but only the computing time. For considering this, a tolerance of variance of the population's best fitness function value (i.e. for a selected number of generations) is usually introduced. Therefore, if the change in the fitness function is not enough (more than the tolerance), the iteration is stopped.

The population size is usually between 50 units and 500 individuals (i.e. if too small, the algorithm may converge to a local minimum or non-Pareto set, if too big, computational time increases considerably). The crossover rate is a number between 0 and 1 that defines the probability ratio of the chromosomes mating in a single generation (i.e. if close to 0, the algorithm may converge to a local minimum or non-Pareto set, if close to 1, the crossover number lead to an increase in computational time). Similarly, the crossover rate is a number between 0 and 1, and measures the likeness that random elements of a chromosome will be flipped into something else (i.e. if close to 0, fruitful chromosomes modification could never be explored, if close to 1, the algorithm can have too many perturbation and lose its ability to use its own history to improve).

G.3 Review of Turning Process Optimization through Genetic Algorithms

G.3.1 Single-pass Turning Models

Cus and Balic [2003] use a GA search base algorithm for optimizing the turning process of steel. The authors propose a methodology using a parametric exponential function as the fitness function. The function includes three functions as exponents, describing respectively tool life, process cost and final surface roughness. As a termination criteria, the authors use acceptable boundaries for the mentioned functions.

Saravanan et al. [2003] use a lower number of variables (i.e. feed rate and cutting speed) for testing turning process optimization through GA and SA. The objective function is the unit production cost, which includes the tool cost (including tool life prediction). The authors conclude the SA gives marginally better results compared with GA.

Amiolemhen and Ibhadode [2004] produce several models for optimizing several CNC lathe turning operations (i.e. facing, turning, centring, drilling, boring, chamfering, parting), differentiating between roughing and finishing operations. The authors introduce a different unit production cost fitness function and use different constrains (Table 6.4) for every analysed operation. The resulting models and their constraints set define completely the turning processes, quantifying also a relation between finishing and roughing operations (although empirical).

Sardinas et al. [2006] use a micro GA for optimizing a turning process by two objective functions: turning time and tool life. The algorithm uses two different populations: one static and one dynamic. The first is processed with the classic GA operators, creating the second.

This new individuals are added to the static ones in the next iteration, meanwhile the other population remains unchanged, even if they violate the constraints, measuring the violation grade by an unfeasibility index. At the same time, fitness functions values are compared with an ideal Pareto front. Ranking the individuals by their unfeasibility index and their fitness function, an elitist population (Paretian solutions) can be retained after a defined number of iterations (called epoch). The elite population are added to the static one, repeating the cycle (called period). After a certain number of periods (i.e. 100), the algorithm is stopped. The authors use experimental derived fitness functions (i.e. tool life formulation) and constrain (i.e. tool force estimation).

Yildiz and Ozturk [2006] propose an integration of Taguchi robust design optimization (i.e. using S/N ratio and ANOVA) and GA. The authors test the computational power of single and multi-criteria optimization through this hybrid algorithm, comparing it with previous hybrid GAs in the literature.

Yang and Natarajan [2010] compare a multi-objective differential evolution (MODE) algorithm and non-dominated sorting genetic algorithm (NSGA-II) for the turning optimization of a particular tool (steel and tungsten carbide). The differential evolution (DE) algorithm acts on the GA by narrowing its search space during each step. The authors developed three regression models for deriving surface roughness, cutting zone temperature and tool wear relations. Using the same fitness functions and non-linear constrains for both, the authors conclude that, implementing a DE strategy, the GA has a sensible decrease in computational effort, although the solution space is considerably reduced.

D'Addona and Teti [2013] use the MATLAB GA optimization toolbox for optimizing the turning process of a cast steel blank with an HSS tool. The authors use the previous approaches and compare two crossover operators (single point and two-points) and mutation application. The authors compare the GA runs where only the crossovers or the mutation operators were acting. The authors deduce, as plausible, that only a combination of the two operators explore thoroughly the variables space.

G.3.2 Multi-pass Turning Models

Schrader [2003] develop an algorithm for simultaneously optimizing both roughing and finishing process time and tool life, taking also into account the part geometrical constrains. A preliminary procedure assigns feasible numbers for the depths of cut, and after randomizing the feed rate and cutting speed (i.e. remaining variables).

Yildiz [2013] use a similar approach to his previous paper (i.e. applying Taguchi robust design optimization) to multi-pass turning cost.

Alberti and Perrone [1999] combine the GA with a fuzzy logic (probabilistic) approach. In this way, the uncertainty, that affects both the constraints definition and the parameters, can be taken into consideration and linked to the process economics. The fuzzy approach provide a feasible and narrow domain to the GA application.

Wang et al. [2002] derive the input parameters and constrains from interpolation of machining databases and experimental measure. In place of excluding unfeasible individuals (i.e. out if constraints), they applied penalty functions for having a broader and complete process parameters mapping as output, for every different turning pass (i.e. optimizing two or three pass turning).

Onwubolu and Kumalo [2001] propose a local search GA-based technique in multi-pass turning operations with a high number of constrains (i.e. 20). GA optimizes not only roughing and finishing process parameters, but also the number of passes definition.

Appendix H

Case Study III: Closed Die Forging Models and Application

H.1 Hot Forging Models

In the hypothesis of excluding the indirect costs, the preform fabrication cost and the workpiece heating cost, the total operation cost (C_{F_T}) can be written as in (H.1). The elements of cost can be divided into three voices.

- Material Cost C_{Mt}
- Forging Operation Cost C_F
- Machining Cost C_{Mc}

$$C_{F_T} = C_{Mt} + C_F + C_{Mc} \tag{H.1}$$

The material cost can be expressed as in (H.2).

$$C_{Mt} = V_p \rho_m C_M \tag{H.2}$$

Where, V_p is the preform volume (mm^3), ρ_m is the material density ($\frac{kg}{mm^3}$), C_M is the material specific cost ($\frac{£}{kg}$)
The preform volume can be calculated by the die volume and flash volumes (H.3), which are deducted from the final volume (usually using a set of rules or by an iterative process).

$$C_{Mt} = V_p \rho_m C_M \tag{H.3}$$

Formulas for predicting the material cost (e.g. Knight [1992] or Boothroyd [1994]) from dies geometry would be not used (i.e. they are used for predicting the total costs before die design). Their criterion would be used instead for designing the die. The die volume contains material losses due to the required forging allowances.
The considered forging cost can be written as in (H.4).

$$C_F = C_{F_{op}} + C_{Die} + C_{Eq} + C_{La} \tag{H.4}$$

The cost contributions can be identified as follows

- Equipment cost (C_{Eq})
- Labour cost (C_{La})
- Forging operation cost ($C_{F_{op}}$)
- Die Cost (C_{Die})

The equipment cost (C_{Eq}) is the depreciation of the forging machine, so it depends on its selection, in turn depending on the required process parameters.
The labour cost (C_{La}) can be written as in (H.5)

$$C_{La} = c_L T \tag{H.5}$$

Where, T_F is the total process time (including set-up time), which is proportional to the production volume and forging speed (min);$c_L$is the forging cost per minute.

The forging operation cost (H.6) can be evaluated by the required power to be generated by the forging process (W_F, KW), the forging operational time (T_F, min) and the energy cost (E_c, KW/h).

$$C_{F_{op}} = \frac{W_F T_F E_c}{60,000} \tag{H.6}$$

The forging force can be evaluated as in (H.7).

$$W_F = \frac{dL}{dT} = \frac{Fds}{dt} = F_F v_F \tag{H.7}$$

Where, F_F is the total forging force (N) and v_F the ram speed (m/s).

The die cost (C_{Die}) is the fraction of die total cost related to the single operation (C_{Die_T}). For defining this, the die life (T_{die}) ratio expense on the forging time (T_F) need to be calculated, as in (H.8).

$$C_{Die} = \frac{C_{Die_T} T_{die}}{T_F} \tag{H.8}$$

The total cost of the die (C_{Die_T}) has been estimated by authors as Boothroyd [1994] and Thomas et al. [2016] as the die fabrication (C_{Die_F}) and die material (C_{Die_M}) costs (H.9). The author gave some empirical rules in order to estimate the die cost from the main geometrical features.

$$C_{Die_T} = C_{Die_F} + C_{Die_M} \tag{H.9}$$

The die life (T_{die}) is only an estimated of the die service time. Several empirical models have been detected about. Although, the wear (responsible also of stress corrosion cracking, fatigue ...) can be considered the main responsible of die failure. Some of the authors have been able to predict the die wear analytically. Archard's wear equation[Archard, 1953] is one of the main tools for predicting wear (H.10).

$$Q = \frac{KFL}{H} \tag{H.10}$$

Where, Q is the total volume of wear debris produced (mm^3), K is a dimensionless constant, F is the total normal load (N), L is the sliding distance (mm), H is the hardness of the softest contacting surfaces (MPa). Although Archard [1953] approach has been proved valid for many case studies, Behrens [2008]'s wear model (H.11) is dedicated to the hot forging process

$$w_n = \sum_{j=1}^{n} K \int \left(\frac{P}{H_{hot(d_j, M_j, T)}} \right)^a V dt \tag{H.11}$$

w_n is the wear depth after the nth forging cycle, K is the abrasive wear coefficient, P is the normal pressure (MPa) on the contact surface, H_{hot} is hot hardness (Vickers hardness, MPa), V is the sliding velocity (mm/sec) at the contact surface, a is an experimental constant, M_j is the tempering parameter, d_j is distance from surface (mm) at the j-th forging cycle, and T is the temperature (°C). In order to estimate the die life, it would be possible to introduce a limit volume of loss, proportional to the forging allowances (H.12). From the FEM analysis data, it would be possible to estimate the material loss and make a proportion to amount of cycles that the die can sustain before failing. This rough estimation did not taken into consideration important phenomenon as fatigue or thermal distortion.

$$w_n = w_{critical} \rightarrow T = T_{die} \tag{H.12}$$

The machining time can be estimated using the formula approached for every case study: using the machining removal rate. The machining cost (C_{Mc}) can be estimated through the removal rate constancy equation as (H.13)

$$C_{Machining} = \frac{c_M \Delta V}{MRR} \tag{H.13}$$

Where, MRR is the removal rate (mm^3/min), ΔV is the volume difference between forged part and final component (mm^3) and c_M is machining cost per hour (£$/min.$).

H.2 DoE Configurations for Hot Forging Optimization of a Valve Body

Different DoE resolutions have been selected for the Case Study III. The resolution of single DoE is defined as the ability to separate main effects and low-order interactions from one another.

- Response surface methodology (Box-Benken): not useful with multiple responses
- Full Factorial (3 levels)
  - 7 variables x 3 levels: 2187 runs (364 h)
  - 3 variables x 3 levels, 4 variables x 2 levels: 432 runs (72 h)
  - Preliminary screening of process parameters full factorial (3 variables x 3 levels), including the most significant in the final full factorial.
    - 5 variables x 3 levels: 243 runs (40 h)
    - 4 variables x 2 levels, 1 variables x 3 levels: 48 runs (8 h)
- Taguchi (3 levels)
  - 7 variables x 3 levels: L27, 27 runs (4.5 h)
  - 3 variables x 3 levels, 4 variables x 2 levels: L36, 36 runs (6 h)

- Full Factorial (2 levels)
  - 7 variables x 2 levels: 128 runs (21 h)
- Fractional Factorial (2 levels)
  - 7 variables x 2 levels
    * Resolution IV : estimate main effects not confounded by two-factor interactions, estimate two-factor interaction effects, but these may be confounded with other two-factor interactions: 16,32 runs (max 5h)
    * Resolution VII: estimate main effects not confounded by five-factor (or less) interactions, estimate two-factor interaction effects not confounded by four-factor (or less) interactions, estimate three-factor interaction effects not confounded by three-factor (or less) interactions estimate four-factor interaction effects, but these may be confounded with other four-factor interactions: 64 runs (10 h)
- Taguchi (2 levels)
  - 7 variables x 2 levels: L8, L12, L16, L32, max 32 runs (5 h)
- Packlett-Burman design (2 variables): Resolution III, too low (estimate main effects, but these may be confounded with two-factors interactions)
  - 7 variables x 2 levels, 3 replicates: 144 runs (24 h)

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