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A Review of Rolling System Design Optimisation

V. Oduguwa and R. Roy*

Enterprise Integration,

School of Industrial and Manufacturing Science,

Cranfield University, Cranfield, Bedford,

MK43 0AL, United Kingdom (UK).

T. +44 (0)1234 754073, F. +44 (0)1234 750852

voduguwa@hotmail.com and r.roy@cranfield.ac.uk

ABSTRACT

Rapid product development and efficient use of existing resources are key competitive drivers in the steel industry and it is imperative that solution strategies are capable of delivering high quality solutions at low cost. However, traditional search techniques for rolling system design (RSD) are ad hoc and users of them find it very difficult in satisfying the required commercial imperatives. This paper presents a comprehensive review of approaches for dealing with RSD problems over the years in terms of modelling and optimisation of both quantitative and qualitative aspects of the process. It critically analyses how such strategies contribute to developing timely low cost optimal solutions for the steel industry. The paper also explores the soft computing based technique as an emerging technology for a more structured RSD optimisation. The study has identified challenges posed by RSD for an algorithmic optimisation approach, especially for evolutionary computing based techniques.

* Corresponding Author

Keywords

Rolling system, Optimisation, Engineering design, Soft Computing

1. INTRODUCTION

Rolling is an important steel manufacturing process to provide a wide range of products used in the automotive, construction, and engineering industries. However, due to increasing competition in the steel industry, there is an ever-increasing demand on the steel manufacturers to become more flexible, more responsive and to be competitive with energy efficiency. The competition is fierce, complex products are being required at higher quality for the same cost and margins are continuously being squeezed. Optimal rolling system designs can play a significant role in dealing with these challenges. Motivated by the need to enhance new products and process development strategies to deliver a spectrum of high quality design solutions at low cost, the steel industry is increasingly adopting scientific approaches in favour of traditional approaches. Several algorithmic optimisation approaches are emerging as alternative solutions to deal with the complex search space properties of the real world process problems.

Rolling system design (RSD) is a complex problem due to the non-deterministic nature of the process and the large number of processing conditions involved. It is a core skill often conducted by experts using their experience and intuition. These procedures are largely based on trial and error and can be expensive and time consuming. It can significantly influence the ability to deliver new products to the markets. The overall aim of this paper is to provide a comprehensive review of process optimisation approaches for solving the rolling system design problem. The paper provides a description of the features of a rolling system design and critically analyse the approaches to a rolling system design. The study looks at Quantitative (Q^T) and Qualitative (Q^L) information involved in the design. The review is classified into the following areas: approximate Q^T models, approximate Q^L models, manual search methods, Q^L and Q^T optimisation, soft computing approaches in RSD, and multi-pass RSD. For each classification, the review explores how the reported techniques search for good RSD solutions in terms of efficiency and cost. The paper then critically analyses how such strategies contribute to developing timely low cost solutions that are optimal for the steel industry. The paper also explores soft computing based techniques as an emerging technology for a more structured optimisation of an RSD.

This paper is organised as follows. Section 2 introduces RSD by identifying and classifying the features of RSD while section 3 presents a comprehensive review of the RSD approaches over the years. Section 4 discusses the challenges of RSD as an optimisation problem and evaluates RSD in relation to new product development strategies. Finally, section 5 presents a summary of the reviewed approaches and concludes with an outline of the future research directions.

2. ROLLING SYSTEM DESIGN

Rolling system design is the preparation of a series of roll pockets and draughting sequences for roll passes that are necessary to obtain a group of roll profiles. The purpose of RSD is to ensure the correct production of roll profiles within the constraints of the mill with acceptable qualities, minimum cost [1] and maximum output. This problem can also be referred to as a multi-pass search problem for multiple passes.

Effective RSD aims to achieve the optimum number of passes with the desired geometry avoiding roll defects whilst maximising the reduction in the cross section area per pass. This is normally achieved by considering the geometrical, mechanical, thermal, thermo-mechanical and metallurgical behaviours of the entire rolling system [2] (see Figure 1).

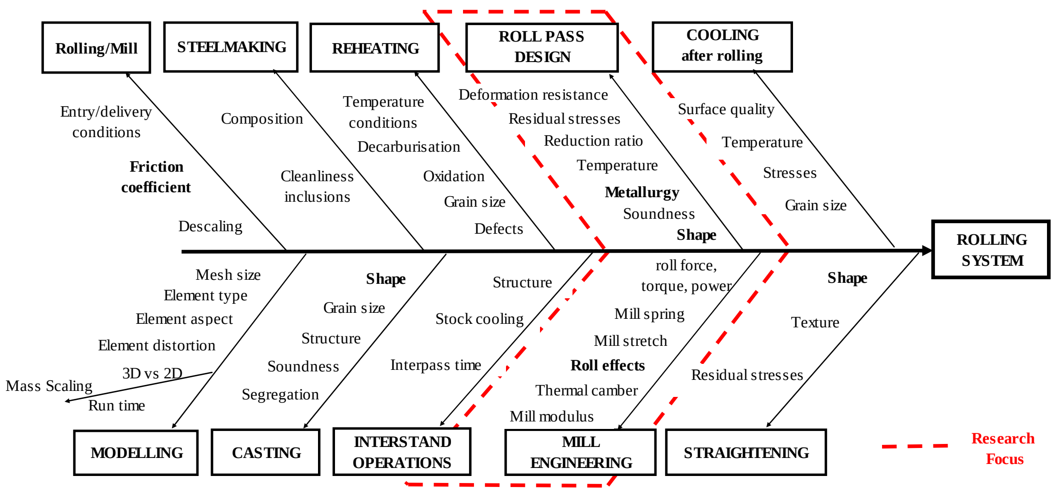

Figure 1: Fishbone Diagram of the Rolling System

The rolling system as a whole is multidisciplinary in nature consisting of reheating, inter-stand operations, mill engineering, roll pass design, straightening etc. Figure 1 shows a fishbone diagram that classifies the rolling system components for this paper. The fishbone diagram was developed by the authors in collaboration with rolling system engineers and by reviewing the literature [1]. It is also important to note that in rolling system analysis it is also common to include the influence of historical behaviours from steelmaking and casting processes. The rolling system components are classified under general headings to show how the individual components of the complex system can be decomposed. It should be noted that the relationships amongst each individual components are not mutually exclusive but in fact a complex interaction of these components forms the inherent source of the rolling system complexity. Figure 1 shows how the highly complex nature of the rolling system is composed of the product and process that interact with multifaceted disciplines. The RSD problem is an important component of the rolling process. The following sections introduce RSD and identifies the challenges posed by the RSD optimisation.

2.1. Features of Rolling System Design Problems

RSD problems like most real world process problems can be characterised as having chaotic disturbances, randomness, and complex non-linear dynamics. This is due to the elastic-plastic material behaviour and potentially large deformation behaviour [3]. It is widely accepted that the rolling processes are usually large scale, highly dimensional, non-linear, highly uncertain and involves complex interaction of highly experienced engineers to apply empirical design knowledge to develop roll schedules [4]. Some of the main considerations of RSD problems are listed below, and are summarised in Figure 2.

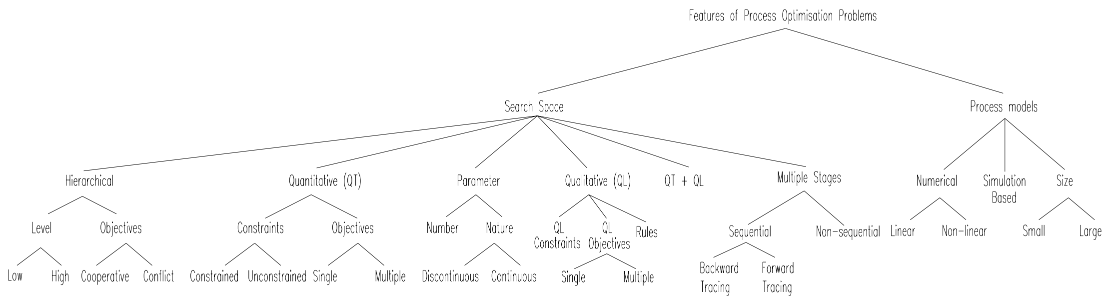

Figure 2: Features of Rolling System Design Problem

<u>Search Space</u>

RSD can be formulated as a process optimisation problem, where the search space represents all possible designs. Here, processing parameters can be chosen to maximise productivity, minimise product defect subject to the complex synergies between the material flow, composition, thermal dependencies, and intricate interactions between the draughting section rolling. Like most real-world process optimisation problems, RSD poses significant challenges for traditional optimisation algorithms. The main features of the problem space is summarised in this section using the classification given by [5].

The complexity of the search space is due to the number and nature of objectives and constraints. The presence of multiple hard constraints significantly affects the performance of any optimization algorithm including evolutionary search methods [6] making it difficult to find optimal solutions. The objective and constraint functions can be non-smooth, severely non-linear, discontinuous or even ill-defined/undefined in some region of the parameter space [7]. The existence of several local extrema (multi-modality) is also quite common. Most real-world process problems also have very large number of parameters resulting in exponential increase in interactions [8]. This effect was described by [9] as the 'Curse of Dimensionality'. The search space can also be quantitative (Q^T) or qualitative (Q^L) in nature or both [10]. Q^T describes the behaviour of the problem using suitable numerical terms. However, this can be incomplete and even there are certain behaviours (e.g. manufacturability) which are not easily described using analytical means. In such cases human based reasoning can be formulated into rules for Q^L models to express such behaviours.

The following paragraph explores some of the RSD features that are likely to influence optimisation algorithms. This also demonstrates that the RSD is similar to other process optimisation problems.

Multi-staged

By definition, multiple passes is an ordered multi-stage process. This is similar to the sequential process described for process problems where the output stock of one mill stand is fed as input stock into the subsequent mill stand. Solving the sequential design problem increases the problem size (number of variables), introduces hierarchical search space problems and relationship between passes. These relationships are expressed in terms of variables, parameters, objective and constraints. The nature of the problem can be static or dynamic, Q^T, Q^L or semi-Q^T depending on the level of knowledge available. These features present several challenges for an algorithmic approach to the process optimisation.

Hierarchical

The optimisation of a rolling system is a hierarchical problem in which different competing technological and quality objectives have to be solved at each level of optimisation [11]. For instance, at the top levels, productivity of the rolling mill is one of many issues to be considered, while at lower levels, for example, the determination of the number of passes and the form of grooves must be obtained ([12], [13], [14]). A parameter or an objective function can also be of singular or multiple hierarchical level in nature. For example a geometrical parameter might be of lower level such as CAD entities, or of a higher abstract level such as feature-based, or might be a switch between both. It is observed that roll designs switch levels in this way within the current unstructured design process.

Multi-disciplinary

RSD is characterised by complex interactions occurring amongst various disciplines. For example, material flow/composition, thermal, pass design, mill capabilities, inter-stand dependencies, and process controls all combine to determine the shape and property of the product. Combining different models across various disciplines have an important influence on the optimisation algorithm. It is necessary to ensure models have equivalent scales so that they can be integrated and the optimisation algorithm can be utilised.

Multidimensional

RSD is characterised by various process and product variables such as forming sequence, shape evolution, forming speed, reduction ratio, temperature distribution, friction conditions, thermal and mechanical conditions of the work-piece and the die [15].

Qualitative Knowledge in Rolling System Design

Rolling system design is a knowledge intensive task and can be qualitative (Q^L) in nature [16]. Traditional RSD has been undertaken by individual experts using a mixture of empirical knowledge, based on sound engineering and rolling practices acquired over many years of experience. This knowledge is not always explicit and is not so easy to capture such knowledge for generic re-use. In many instances, there are no clear rules to design a particular pass shape [17]. They tend to be too specific and it is difficult to decouple the process, product and mill engineering knowledge [18].

3. ROLLING SYSTEM DESIGN APPROACHES

This section presents a comprehensive review of approaches for dealing with RSD problems in terms of modelling and optimisation. This section presents a critical analysis of the RSD optimisation approaches in terms of developing approximate Q^T models and approximate Q^L models, manual search methods, handling Q^L information, multi-pass optimisation problems, and Soft Computing approaches in RSD.

3.1. Approximate Q^T Modelling Methods

Section 2.1 stated that a pre-requisite to any optimisation problem is the availability of a process model. This is required to evaluate the quality of a given solution. Since physical experimentation is slow, expensive and disrupts production runs, approximate Q^T models are developed to represent the process behaviour so that off-line studies can be carried out in order to gain better understanding of the process. Several modelling methods have been developed for simulating the behaviour of the rolling process. These approaches aim to find a suitable representation for the underlying process behaviour. This section reviews the following Q^T based modelling approaches, classical rolling theories, recent mathematical methods, finite element methods and approximate finite element strategies.

3.1.1.Classical Rolling Theories on Load and Torque

Much efforts were devoted to develop theoretical model to predict roll pressure distribution, rolling load, torque, yield stress of the material being rolled and the coefficient of friction between the rolls and the material. Most rolling mathematical models of hot-strip rolling are concerned with the force of equilibrium of vertical cross-sections in the roll gap. Siebel [19] and Von Karman [20] in 1925 first introduced the concept of homogeneous compression of vertical strip segments as they move through the roll gap. These early authors made the fundamental assumptions of a neutral plane cross-section and a neutral point occurs along the contact arc between the rolls and the deforming metal. Ekelund later developed a formula [21] (equation 2.1) based on the study of material flow during plastic deformation. Ekelund's approach consisted of contact area, friction hill factor and the yield stress. It was very popular in the early years due to the embodiment of the essential rolling variables and it was considered to be a convenient form for calculation.

$$P = w_m \sqrt{R(h_1 - h_2)} \times \left[1 + \frac{1.6\mu\sqrt{R(h_1 - h_2)} - 1.2(h - h_2)}{h_1 + h_2} \right] \times \left[J + \frac{2\nu\varepsilon\sqrt{\frac{h_1 - h_2}{R}}}{h_1 + h_2} \right]$$

Equation 3.1

where: P = rolling load, w_m = mean width of the material in the arc of contact, h_1 = height of material before the pass, h= height of material after the pass, R = roll radius, ν = peripheral velocity of the rolls at the bottom of the pass, μ = coefficient of friction between the materials and roll. Ekelund derived values of $\mu = 0.848 - 0.000222tF$ from experiments for steel rolls, tF = temperature of rolled material. ε = coefficient of viscosity derived as 0.01 (20164 – 7.89tF), J is the static compressive strength of hot steel derived as $100\varepsilon(1.4 + C + Mn + 0.3\ Cr)$. Where C, Mn and Cr are the carbon, manganese and chromium content of steel respectively. Limitations in Ekelund's formula are due to large approximations. According to Ekelund's formula, if the temperature is increased to 1400°C, the yield stress would be equal to zero. This implies that the rolled stock would begin to melt. A critical analysis of Ekelund's formula is presented by [1].

Siebel and Lueg [22] performed experimental studies on annealed aluminium and measured roll pressure distribution. Their results were used to compare early theories. Orowan [23] discarded most of the mathematical approximations and assumptions of the rolling theories and developed the most comprehensive model. Orowan recognised that the flow stress of the material varies in rolling due to the variation of effective strain, effective strain rate and temperature and considered these variations in his model. Orowan also abandoned the assumptions of slipping friction and homogeneous compression. He showed that the coefficient of friction can be sufficiently high for the tangential stress to reach the shear yield stress of the material and that the strip sticks to the roll. He was interested in developing an accurate theory that can be used as a benchmark for assessing simplified theories regardless of its complexity. Subsequently, several authors simplified the Orowan's model, notably [24]. Sims assumed sticking friction over the whole arc of contact and made allowances for homogeneous deformation. Sims's formula shown in equation 3.2 consistently under-predicts values predicted by the Ekelund formula [21] [25].

$$P = K.\sqrt{R'(h_1 - h_2)}.Q_p$$

Equation 3.2

$$Q_p = \left[\frac{\pi}{2}\sqrt{\frac{1-r}{r}}\tan^{-1}\sqrt{\frac{r}{1-r}} - \frac{\pi}{4} - \sqrt{\frac{1-r}{r}}\sqrt{\frac{R'}{h_2}}\ln.\left(\frac{h_N}{h_2}\right) + \frac{1}{2}\sqrt{\frac{1-r}{r}}\sqrt{\frac{R'}{h_2}}\ln.\left(\frac{1}{1-r}\right)\right]$$

Equation 3.3

where *R'* is radius of curvature of the elastically deformed roll, Q_P is a complex function of the roll gap given by equation 3.3, and $r = \frac{h_1 - h_2}{h_1}$, h_1 and h_2 is the initial and final thickness of rolled strip respectively.

<u>Classical Rolling Theories: Observations</u>

Although applications of classical rolling theories have been relatively successful in delivering roll design solutions, their limitations influence the RSD in terms of the quality of solutions, and poor response to a broad range of problems. They tend to be related to specific disciplines. Typical classical rolling theories tend to consider spread, elongation, and load. This limits the information obtainable from such methods since rolling processes are influenced by many more factors such as metallurgical and thermo-mechanical properties. Since limited number of rolling design variables are considered, this can result in unrealistic design solutions.

Several authors ([26], [27], [28]) have investigated the performance of a number of classical rolling theories and found that in most cases the rolling load and torque are severely underestimated. Alexander [29] conducted experimental studies on annealed copper strip with front tension and made comparison on earlier theories. It was concluded that previous rolling theories were not capable of predicting the roll torque with adequate precision. The fundamental stress equilibrium approach for which the rolling theories were based fails to take account of the non-homogeneity of the deformation. For this reason, under-estimates of the rolling loads resulted in many cases. Most of the empirical rules tend to focus on flow mechanism related to spread and elongation for various roll groove geometries without considering the temperature and strain rate effects. Research efforts have focused on applying the Finite Element Analysis (FEA) to the metal forming processes to address some of the above mentioned issues.

3.1.2.Finite Element Methods in RSD

The concept of Finite Elements (FE) was originally introduced in the 1950's as a method of structural analysis for the aircraft industry [30]. Since then, it has evolved and its wide application covers various classes of metal forming problems such as rolling. The FE technique can be used to simulate the metal forming before performing actual experiments, which can reduce the cost and development time for the process design. However, due to the computational burden of the FE method there are still few challenges for using the FE method as embedded optimisers for the roll process design problems. This section introduces the FE method, and reviews FE applications to rolling problems.

The aim of FE application to metal forming problems is to predict physical quantities such as stress, strain, velocity, and temperature throughout the deformed solid. This implies that the physical quantities are required at infinite number of points, which defines a problem with infinitely many degrees of freedom. The FE method is based on the idea of discretisation where the deformation zone is divided into a finite number of sub-zones called elements. The elements are connected together at the corners and at selected points at the edges called nodes. For each element, the individual relationship between the applied nodal forces and the resulting nodal variables such as velocity and temperature are calculated and the element stiffness obtained. The global stiffness matrix of the whole body is then assembled by combining the elemental stiffness. A detail description of the FE method is given in [4].

<u>Application of FE Method in Rolling Problems</u>

The fundamentals of the rigid-viscoplastic FE method and the mathematical formulation are well established and given in literature ([31], [32]). Several authors ([33], [34], [35], [36], [37]) have applied the FE method to determine more detailed information of material flow for shape rolling in the analysis process. In 1984, Park and Kobayashi [38] expanded the rigid–viscoplastic FE method to three-dimensional cases. Hacquin *et al.* [39] presented a coupled model of thermo-elastoviscoplastic strip deformation and thermo-elastic roll deformation. The model was used to predict profile defects, strain, and stress maps, including residual stresses in hot and cold rolled strips. In rod rolling 3D finite element was used to determine strain distribution for prediction of micro-structural material evolution ([40], [41], [42]). Several authors ([43], [44], [45], [46], [47]) have used FE to determine the thickness accuracy of the strip products. These studies calculated the required rolling force, torque, and power in terms of other process parameters such as roll speed, thickness, and temperature. Recently, Kim and Im [48] applied a three-dimensional FE program for analyzing shape rolling processes considering heat transfer based on rigid thermo-viscoplastic approach. round–oval, oval-oval, square–oval, and square–diamond passes (Figure 3) were simulated at different friction conditions with and without temperature effects.

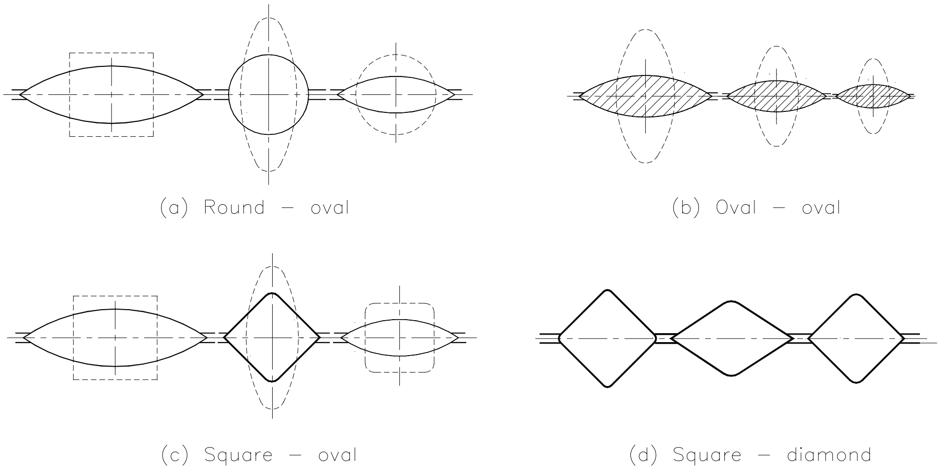

Figure 3: Typical Breakdown Sequence

Inspite of the computational burden, FE models are becoming powerful and are becoming popular for investigating technological windows of different processes in the steel industry. Three-dimensional (3D) FE based codes enable the modelling of large plastic deformation. The FE modelling technique is reported to be more accurate and it provides detailed information of plastic deformation when compared to classical rolling theories. It provides an extensive description of the metal flow in the roll gap and of loads and motion of the whole strip and is thus widely used for simulating and analysing various metal forming processes ([49], [50], [51], [52]). The FE technique has a considerable advantage to the traditional mathematical approaches because it can calculate most of the parameters characterising the process (forces, stresses, velocities, displacements, temperatures etc) in a single simulation.

Approximation Strategies for FE Methods

Wen *et al.*, [53] presented a simplified FE for modelling complex three-dimensional deformation in section rolling. In their work, previous analysis of various passes with the three-dimensional models showed CPU times between 26 and 52 hours compared to pseudo-two-dimensional models of 2 and 3 hours. Kiuchi and Yanagimoto [54] developed a complex element method based on the functional combination of rigid-plastic FE and the slab method. Kim *et al.* [36] further simplified the approach and applied the two- dimensional rigid-plastic FE method for the generalised plane strain condition, and combined it with the slab method. Kim *et al.* [55] extended the work by developing a computer program called TASK which was used by Shivpuri and Shin [56] to investigate RSD. In truss optimisation problems, where similar FE computational burden is also experienced, several approaches were reported to address the problem. Deb and Gulati [57] in design of truss-structures, introduced the concept of basic and non-basic node to emphasise creation of user-satisfactory trusses and reduce computational time. This avoided expensive FEA for unsatisfactory trusses. Quagliarella and Vicini [58] proposed a hierarchical approach for the fitness evaluation. This involves using several solvers with different levels of accuracy, in order to use the more computationally expensive models only when needed. These approaches can be regarded as “good house keeping measures” that improves on the computational expense of large FE runs; however, they fall short of alleviating the problem in the context that makes them applicable to complex real life problems. Siteo [59] developed a Genetic Algorithm with Ancestry Record (GALGAR) within a framework of hybrid techniques based on simple GA, hill-climbing and simulated annealing. The basic idea is to save computational FE simulation cost by storing previously processed information along with the current against some pre-defined criteria. Although this approach intuitively suggests significant reduction of computational cost, storing previous solutions could significantly disrupt the pattern formation during the search.

FE Method in RSD: Observations

FE methods are capable of predicting quite accurate deformation behaviour such as roll contact stresses, rolling load, and rolling torque required for RSD. However, they can be computationally expensive and the time required for a fully converged solution limits its wider application for optimisation problems. CPU time of 4-5 hours for 5000 – 6000 nodes and 1000 time steps is not unusual [60]. The 3-dimensional modelling even with the super computer is still time consuming and quite complex to investigate the influence of all the potential variables ([61], [62], [28]). Although the FE method provides various detailed information, it can be difficult to analyse. The FE based design process often lacks structure and appears to be done sporadically. Since various design parameters are considered simultaneously, quite often practitioners seems to be content with any solution that appears feasible in light of the computational burden. In addition, since this approach is mainly based on Q^T information, it cannot address integrated Q^T and Q^L search space problems [4].

3.1.3.Recent Mathematical Modelling Methods

In spite of reported model accuracy of the FE methods in metal forming problems there is still an increasing interest to use simplified mathematical formulae for predicting complex metal forming behaviours ([63], [64]). There are various reasons why the mathematical approach is still popular in the industry. It is a simplified alternative to the complex FE formulations and it requires less computational efforts. They allow formulation of dependencies between rolling parameters [65]. Rudkins and Evans [25] and Lenard *et al.* [28] performed off-line calculations to aid in the finishing of mill set-ups. In their study they use the [21] and [24] formulae to determine the likely rolling loads for a given reduction pattern and compared the results obtained with Finite Element calculations. They concluded that the FE results gives accurate prediction of mill loads while the Sims model [24] slightly under-predicts the values compared to that predicted using the [21] formula. Joun and Hwang [63] developed an approximate mathematical approach for predicting roll pressure and tangential stress at the roll-strip interface. The authors reported that theoretical predictions agree with FE results and experimental results. Although there was no optimisation study reported in the paper, the authors suggested that the method could be used for optimising rolling parameters. Wusatowski [1] and Chitkara and Hardy [66] applied the groove rolling principle and proposed an empirical formula for determining spread in flat rolling. Mauk [67] adopted a similar method and proposed an iterative approach. Hwang et al. [41] presented an analytical model for predicting the mean effective strain defined as a maximum average effective (equivalent) plastic strain at a given pass in bar (or rod) rolling process. The information obtainable by the mathematical modelling method is limited compared to the FE method since it is difficult to accommodate most of the complex factors. Like the FE method, it is based on Q^T information only, and as a result cannot simultaneously deal with integrated Q^T and Q^L search space problems.

3.2. Approximate Q^L Modelling Methods

Q^L information is a non-numeric method used in reasoning about the behaviour of the physical environment. It is mostly used in the presence of incomplete knowledge. Q^L

models include Q^L abstractions of the relations in a numerical model, the casual dependencies between its variables and explicit representations of the modelling assumptions used to describe a physical system. This section reviews Q^L modelling methods reported in literature to deal with RSD problems.

Pataro and Helman [68] developed an approach to determine sequence of passes for the strip rolling process using fuzzy logic rules. The authors suggested that the rules can be extracted from data obtained from theoretical model, available databases or production data. Jung *et al.* [69] developed a fuzzy control system based on production data and operational knowledge. The fuzzy controller calculates the change of roll force to improve the flatness of the thin strip based on the developed fuzzy rules and fuzzy inference. These approaches are only suitable for readily available data [70], and would incur significant computational cost if used for large simulations.

Shivpuri and Kini [71] in roll pass design, generated a fuzzy model from finite element data using two fuzzified design variables. In the approach adopted, design variables were fuzzified and used directly as inputs in the fuzzy reasoning module. Since the rolling process is highly dimensional, increasing the number of design variables also increase the number of rules required exponentially. This also incurs expensive computational cost since the models are generated from FE data.

3.3. Manual Design Search Methods in RSD

A significant part of RSD carried out in the industry is manual. This relies on adopting existing solution to produce the required design where design variables are changed one at a time. Individual experts carried out traditional RSD by combining empirical knowledge developed through years of experience with rolling theory. Prior to the 1980s, RSD had been largely based on empirical formulae. Several other authors have developed design rules empirically from production data ([72], [73]) and experiments ([74], [75], [76], [77]). Based on such research work, design guidelines and the empirical formulations were developed to speed up the development process and to enable a more structured RSD approach. Although their applications have been relatively successful in delivering roll design solutions, their difference in functional characters render them unsuitable for dealing with complex geometries. In RSD design where the problem involves many variables the design problem becomes too complex due to curse of dimensionality. Since the human can only deal with up to 5-10 variables at any single time [78], the search problem reduces to costly trial and error and it becomes slow and very ineffective.

The manual approach when used in the industry takes on various forms with respect to the type of modelling approach adopted. The classical rolling theories as well as the recent mathematical models when used alone are inherently trial and error search process from an initial design (single point). Each process normally requires significant effort and it results in long process development times and high cost of the products ([79], [80], [81]). It is also observed that attempting to use this traditional approach may result in optimising one criteria at a time [82]. Another important criterion for the RSD is to be able to search a large design space as quickly as possible and to deliver multiple good solutions, which can be beneficial for locating a variety of good solutions. Here the classical methods fail miserably. The manual RSD approach cannot produce multiple good solutions due to its inherent one point solution method. In addition, since this approach is mainly based on Q^T information it cannot simultaneously deal with Q^L aspects in RSD. Although the FE method is a computational technique, a design search conducted using the FE method on its own is a manual process. Designers use their experience to search by adopting existing design within the neighbourhood of a known solution point and use FE simply to evaluate the chosen design point [18]. The computational cost of FEA and the nature of the search method inhibit elaborate exploration of the design space. This can result in low quality solutions as the search is limited. The FE method when used alone is not suitable for generating designs at the initial design stage, where a large number of alternative design solutions are required at low cost and high response time. The FE model based optimisation also gets more complex and time consuming in the presence of large number of design parameters [83]. This section has shown that the manual methods are single point search methods and are not suitable for multiple objective problems and cannot evolve multiple good solutions. The next section considers algorithmic approaches.

3.4. Classical Algorithmic Optimisation Approaches

Classical algorithmic optimisation approaches are alternatives to the manual methods. The aim is to change values to all the design variables simultaneously to achieve a set of objectives while satisfying a set of constraints. Although, it is faster and more effective in exploring a design space than the manual methods, this approach has received very little research interest for RSD problems. Yamada *et al.* [84] developed an algorithm to optimize load distribution using mathematical models for set-up calculation. Lapovok and Thompson [12] formulated a mathematical geometrical problem for tool-form optimisation for roll pass design. The authors used a derivative-based optimisation method to design a breakdown sequence system for rolling simple square profiles. This approach requires the problem to be twice differentiable and the knowledge of the search space. However, these requirements are not always satisfiable due to the complexity of the RSD problems.

3.5. Q^L and Q^T Optimisation Strategies in Metal Forming

Several integrated computational systems have been reported in literature combining computer-aided design (CAD), expert systems (ES), and the FE method in various configurations. The integrated approach can save expensive design time by re-using knowledge. In the 1970s integrated computer-aided systems were developed to incorporate mathematical design techniques and experience based intuitive skills for metal forming process design. The expert system (ES) automated most of the routine and repetitive tasks such as die drawings and design calculations performed by designers. The benefit of the approach is that it reduced the drafting time as well as some of the trial and error in the process design. Subramanian and Altan [85] integrated a CAD and ES system and named it 'DIE FORGE' for die design. The designer interacted with the system through Q^L evaluation of designs obtained from the ES. Although the system reduced repetitive tasks, it is still slow and less accurate. In an attempt to improve the accuracy of such systems, Akerman *et al*. [86] integrated FE method with a more interactive CAD system. The authors developed two computer programs for modelling shape rolling for airfoil designs. The first program predicts lateral spread and the second program simulates rolling of simple parts. The system relied on expensive trial and error FE simulations. Osakada *et al*. [87] later investigated an automatic generation of pass sequences using pattern recognition. The interactive operations use rules to determine the shapes and dimensions of the intermediate products. The authors experienced difficulties in expressing empirical knowledge due to its implicit nature and concluded that simple knowledge engineering may not be adequate for metal forming.

In a parametric optimisation based approach, Perotti and Kapaj [88] proposed a CAD based technique for automatic shape design of square passes. This technique adopts a point-by-point direct search method. The search method finds parameter values of stock shape by iterative calculations using empirical formulae. The method is slow, requires many function evaluations for convergence and tends to get stuck to sub-optimal solutions [89]. Since the shape forming is a highly knowledge intensive task, Osakada *et al.* [90] extended their previous work by building expert system from FE simulations results. The authors integrated expert system, FE method, and neural networks for knowledge acquisition. In similar approaches, several authors ([91], [92], [93], [94]) integrated an expert system with a CAD software for a forming sequence. A number of expert systems have also been developed to produce more efficient solutions in other areas, e.g. steel composition design [95]. While the expert system determined the feasible pre-form sequence for the multistage forging process, the CAD provides the designer with the necessary tools to perform complete analyses for suitability. Predictions from the expert system are further evaluated with FE simulations. Although the developed systems were more accurate, the search method was still slow due to the expensive FE simulations and the inherent trial and error of Q^L evaluation.

Several CAD commercial applications such as LINEBOW [96] and CARD [97] were developed to help improve the design efficiency and increase productivity. These applications are composed of several modules of mathematical pass design models designed to reduce the repetitive task (such as calculations and drawings) performed by the designers. Since the designers evaluate the overall design solution, the evaluation process of the system is still slow and unstructured due to the inherent trial and error nature of the designer interaction. Recent integrated strategies attempt to focus on automatic generation of process design solutions. These strategies aim to provide a more structured design approach free of the ‘on-line’ designer’s Q^L evaluation. Im and Kim [98] developed a knowledge based expert system (KBES) using object oriented programming (OOP) for the design of roll pass, profile sequence and shape rolling of round and square bars. The authors built KBES using empirical design rules adopted from basic design theory and practice. Farrugia and Jennings [18] developed the current state of the art integrated KBES/CAD system. The authors combined KBES, CAD, and FE analysis for automatic generation of roll design solutions. The KBES records, maintains, and automates designs, the CAD generates drawings and the interface software and the FE simulator provide a broad range of advanced analysis capabilities. Although the system can deal with a broad range of problems, the search for good solutions is still based on a point-by-point method. This can present difficulties for problems with large number of variables and evaluation can be time consuming since the solution is analysed by the FE solver. It was also argued that KBES is not suitable for RSD design optimisation because an infinite number of rules are required [13].

This section has shown that there are attempts to combine Q^T and Q^L information in metal forming process design problem. These approaches offer interesting combination of knowledge based systems, CAD, and FE analysis. The KBES approach is capable of producing simulation results quickly and are suitable for metal forming applications where the knowledge is well known. The CAD/KBS reduces repetitive detailing work performed by the designers and saves valuable design time that can used to generate more creative design output. It can also incorporate the Q^L information from the engineers to guide the search for good realistic solutions.

Q^T and Q^L of Integrated Strategies in Metal Forming: Observations

The following issues pose several difficulties for the hybrid approaches mentioned above:

- Development of KBES is a complex task because the metal forming knowledge is often ill-structured, implicit, difficult to systematise and involves a large number of rules ([90], [99]).
- The KBES are not suitable in areas where the knowledge is not well known for example in hot strip rolling areas such as roll damage, roll wear and sheet shape profile [100].
- The approach is not capable of dealing with multi-objective optimisation problems and is not suitable for simultaneously dealing with integrated Q^T and Q^L search space problems. The search method produces single point solutions, which can be slow and tedious due to its inherent trial and error approach.
- These methods do not conduct an algorithmic search and as a result often offer satisfying solutions and not the optimal.

3.6. Multi-Pass RSD Optimisation Approaches

The multi-pass RSD problem is synonymous to the sequential process optimisation problem outlined in section 2. The multi-pass problem aims to provide optimal design solutions for individual passes of the rolling process including both design information such as the geometrical size of a roll and the operating conditions for the mills [1]. This aims to achieve the desired product quality without violating the operating constraints of the overall process. Approaches for addressing this problem includes the FE method, backward tracing [49], forward tracing [101], and a derivative based approach ([102], [103]).

Despite the high computational expense, the FE method is still very widely used for solving metal forming multi-pass optimisation problems ([33], [34], [35], [36]). There are various FE based approaches reported in the literature for dealing with process optimisation for metal forming. Two of such approaches are backward tracing and the derivative based approach. The backward tracing starts with the final phase of the deformation stage and traces the loading path (deformation process in non-steady forming) backward to predict optimal pre-form design associated with the finished part. Park *et al.* [49] and Kobayashi [104] applied a backward tracing technique to design a pre-form in a shell housing. The thermo-viscoplastic deformation was modelled as a boundary value problem after the FE discretisation and the solution satisfies the system of non-linear coupled algebraic equations. The backward tracing technique has also been applied to plane-strain rolling problems [105] and disk forging where a uniformly deformed disk is sought under the influence of friction at the interface of the die and work-piece [106]. Although, the technique has been shown to discover the desired final shape in various forming problems, the backward tracing technique, when used alone, cannot uniquely determine the optimal solutions due to the presence of diverse and multiple loading solution paths [107]. The back tracing technique tends to be more efficient when the loading path is known, however this can lead to difficulties in real world problems where the search space is complex and unknown especially when multiple diverse loading paths are present.

Several authors have used the derivative based approach to solve multi-pass optimisation problems. For the derivative approach, the optimal process design problem is initially formulated mathematically based on a penalty rigid-viscoplastic FE method. The solution approach obtains derivatives of the design objective and design constraints with respect to the design variables. Current design variables for a given design iteration in the process optimisation are then evaluated using the values of the derivatives obtained. Joun and Hwang [102], [103] developed a FE based process optimisation technique and applied it to a die profile design extrusion problem. A non-linear iterative optimisation algorithm was adopted to minimise the forming energy. In the proposed algorithm, the authors integrated design sensitivity analysis with finite element analysis for the deformation analysis. The authors extended the work for pass schedule optimal design in multi-pass extrusion and drawing process [108]. Barinarayanan and Zabaras [109] and Forment and Chenot [110], [111] applied the method for optimisation of die and preform shapes in non-steady state forming. In their study, the initial shape of the part as well as the shape of the preform tool was optimised for a two-step forging operation where the shape of the second operation is known. Shapes were described using spline functions and optimal parameter values of the splines were searched in order to produce a part with a prescribed geometric accuracy, optimal metallurgical properties and minimal production cost at the end of the forging sequence. The work was later extended to solve non-isothermal, non steady forming problem [112].

Shin *et al.* [37] conducted a simulation study on I-section beam with four passes. The authors carried out a simplified three-dimensional FE method and a physical experiment with plasticine. Since the technique is inherently a trial and error approach, the development of analysis tool for RSD permitting prediction of the effect of process variables with speed, economy and a level of parameter control can not be attained by conventional experiments [14].

Process sequence design for new materials and complex geometries is not easy to carry out due to the complexity of the process [98]. There are major difficulties involved with systematic process design through the analytical approach due to the non-deterministic nature of the process. For multi-pass designs it is not economically trivial to determine the optimum process sequence without making any deviations from these various paths.

<u>Multi-pass RSD Optimisation Approaches: Observations</u>

Following observations can be made from the study above:

- The tracing techniques require knowledge of the search space to perform efficiently, however this is not always possible since search space can be very complex and unknown.
- These techniques are derivative based and require an initial guess, which can influence the search. This derivative based approach also tends to get stuck in sub-optimal solutions and an algorithm that is efficient in solving one optimisation problem may not be efficient in solving a different optimisation problem [113]**.**
- The techniques cannot also identify multiple optimal solutions in a single run for the multi-objective multi-pass rolling problem. The techniques do not also consider the relationship between passes.

3.7. Soft Computing Techniques in Metal Forming

Soft computing (SC) is a collection of methodologies including, as its main constituents, Evolutionary Computation (EC), Fuzzy Logic (FL), Neuro-computing (NC), and probabilistic computing (PC) [114]. SC aims to exploit tolerance for imprecision, uncertainty and partial truth to achieve tractability, robustness and low cost solutions. It differs from conventional techniques in that, it incorporates human knowledge into the solution methodology. This offers the opportunity to deal with ambiguity and uncertainty in real world problem and can result in more realistic solutions. The application of intelligent SC techniques is increasing with successful applications in many areas including but not limited to: engineering design optimisation, manufacturing system, process control, medical diagnosis, simulation and communication systems [115]. Some of the principal combinations of SC components are: fuzzy logic + genetic algorithm, neural network + genetic algorithm, neural network + chaos theory, neuro computing + fuzzy logic, fuzzy logic + probabilistic reasoning etc [115]. This paper focuses on the combination of fuzzy Logic (FL) + genetic algorithm as a SC technology for the RSD problem.

Although SC techniques are emerging as an alternative for solving real world engineering problems [114], however, its application to metal forming design is still not common [116]. Oduguwa *et al.* [117], [118] presented survey of EC techniques to metal forming. There are two main research trends emerging in literature on the application of SC techniques for metal forming problems. The first aims to automate the search using EC based techniques by adopting a process model, and the second attempts to deal with the complexity of the metal forming domain problem using fuzzy based modelling methodology. The overall aim of these two broad approaches is to develop low-cost computational techniques to guide an algorithmic search for good solutions in real-world process optimisation problems. Most of the applications reported in literature use the FE solver as embedded design evaluation tool for the RSD.

Roy *et al.* [119] implemented an adaptive Micro Genetic Algorithm for shape optimisation of process variables in multi-pass wire drawing processes. A modular based FE package was used to evaluate the objective functions. In a similar approach, Hwang and Chung [120] proposed a modified micro genetic algorithm for the optimisation of design variables for die shape in extrusion. The authors reported that convergence was fast for the first 200 iterations and was slow afterwards. In a recent application of the approach for process optimisation in forging [107] the authors reported that for 1000 FE simulations the search required 200 hours for the convergence.

In an attempt to deal with such large computational cost, several authors have adopted neural network based methods to develop process models for fast and inexpensive predictions. Myllykoski *et al.* [70] developed process models for optimisation of rolling processes. Nolle *et al.* [121] proposed an approach using neural network and GA for the optimisation of roll profiles in strip rolling. Such hybrid approaches require a large number of sample data to develop the neural network model. The approach is not suitable for RSD where the large amount of data required to build the model can be expensive to obtain or are not readily available.

Several authors are now adopting fuzzy logic in RSD for modelling Q^L information. [68] developed an approach to determine sequence of passes for the strip rolling process using fuzzy logic rules. The authors developed fuzzy logic rules from production data. This proposed method, although suitable for generating fuzzy based models with real processing conditions, is not capable of identifying optimal sequences as it has no optimisation capability. Jung and Im [122] developed a fuzzy algorithm to calculate the roll speed variations in order to improve the thickness uniformity of hot-rolled strips considering the complex relationships of process parameters such as roll speed, reduction ratio, strip entry thickness, front and back strip tensions and the deformation of the machinery in the mill system. This work is an interesting example of using SC techniques to deal with complex behaviour, especially if no mathematical model exists to express such behaviour. Since the proposed approach lacks optimisation capability, it is also not capable of identifying optimal roll speed variations.

Shivpuri and Kini [71] developed an optimisation technique using an hybrid of empirical knowledge, FE simulations and fuzzy analysis to improve product quality of RSD. In their approach, simulation points based on experimental design were selected in the neighbourhood of the optimal design region and the optimal solution is then identified from the resulting fuzzy based evaluations. Although this approach offers a semi-automatic method of generating optimal solutions, it has the following drawbacks. In general, the exploratory potential of the hybrid approach is weak due to the absence of an algorithmic search technique. The experimental design used for selecting simulation points is a random sampling plan, and may miss the optimal design points. Recently, Oduguwa and Roy [123] presented an integrated design optimisation approach for Q^T and Q^L search space and applied it to the RSD. The proposed solution approach is based on design of experiment methods and fuzzy logic principles for building the required Q^L models, and evolutionary multi-objective optimisation technique for solving the design problem. The proposed technique was applied to a two objectives rod rolling problem ([124], [125]) and 4 stage multi-pass RSD problem [4]. The authors demonstrated that promising results can be obtained from the proposed approach for dealing with RSD taking into account the related Q^L evaluation of the design problem.

<u>Soft Computing Techniques in Metal Forming: Observations</u>

- Soft Computing techniques can help in addressing a number of limitations of classical approaches, but still have some limitations:
- EC based techniques using the FE solver as embedded design evaluation tool incurs severe computational cost. This problem intensifies since EC techniques require to

evaluate large number of solutions before convergence. This inhibits the use of the EC based optimisation approach to wider range of metal forming problems.

- Fuzzy Logic based design evaluation tools need to model a smaller set of critical process parameters, otherwise the number of rules required for the system can increase exponentially with the increase in the number of parameters.

4. CHALLENGES: IN PRACTICE AND IN RESEARCH

The RSD plays a significant part in delivering timely optimal products to the markets. This paper presents a critical analysis of the RSD optimisation approaches. The review explored how the reported techniques search for good RSD solutions in terms of efficiency and cost of the search approaches. The review also considered the capability of handling multi-objective optimisation problems and integrated Q^L and Q^T search spaces. This section now explores the challenges poised by RSD as an optimisation problem and discusses how the reviewed approaches influence new product development in the steel industry. This discussion section concludes with an outline of interesting research areas identified as a result of this study.

4.1. Challenges posed by Optimisation of RSD

There are several challenges posed by optimisation search procedures for RSD problems. These challenges often inhibit the wider application of these procedures for rolling system design. This section identifies the challenges from both an industrial application viewpoint and an algorithmic perspective.

4.1.1.Challenges of Algorithm based Optimisation in Industry

In spite of the potential benefits achievable from using algorithm based optimisation approaches for generating high quality design solutions, it is very surprising that the application of such approaches is still not grasping the headlines for industrial applications. This section presents industrial perspective based on the authors' observations from a survey conducted in steel industry on the modelling and design activities [4]. These observations have been obtained through a cross-disciplinary data collection approach adopted in this study. This has enriched the knowledge used for generating the observations outlined below.

- Designers lack a full working knowledge of algorithmic optimisation approaches. They often perceive it as a highly theoretical approach, which bears little or no relevance to the day-to-day design activity. This issue is reflected by the comment made by a roll designer during a semi-structured interview including the author, a roll modeller, and the roll designer. These engineers were asked about their viewpoint regarding the potential benefits that optimisation approach could add to roll design. One of the engineers commented that "*optimisation is a different kind of logic which is only good for academics' purposes but not suitable for roll design problems*."
- Formulating the optimisation problem is difficult for the average engineer who is not familiar with the optimisation techniques. The features of the optimisation problems (multiple objectives, constraints etc) and the availability of countless number of possible classical optimisation algorithms contribute to this difficulty. Selecting suitable objectives and formulating the constraints to reflect the real scenario is non-trivial. Classical optimisation algorithms tend to require prior knowledge of the search space and this is not always possible for real life problems due to its inherent complexities.

- There is a cultural misconception inherent in most engineers regarding the role of optimisation in product and process design. It is commonly perceived that since optimisation can automatically generate design solutions, the approach can eventually replace their jobs. This fear of losing their jobs places severe restrictions in the buy-in required from these user groups. This point was reflected in an engineer's comment during an informal interviewing session "*I would rather not use this technique, because you know where this is going, I am going to lose my job*". Also when asked about sharing the optimisation knowledge with other areas of the business, the engineer commented "*we would rather keep the optimisation knowledge within the department as this ensures people always come to us when they have problems*"

4.1.2.Challenges posed by RSD on Optimisation Algorithms

This section identifies some challenges of RSD optimisation poses on the optimisation algorithms.

- The features of the real-life process optimisation problem, such as the presence of multiple objectives, constraints, interaction among decision variables, Q^T and Q^L nature of the information and sequential nature of the design problem create challenges for optimisation algorithms that are currently available for the industry. This discourages the industry to adopt these algorithms.
- A process model that explains the behaviour of the design problem is a pre-requisite of any optimisation problem. It is needed by the optimisation algorithm to evaluate the goodness of the solution. High computational expense (for example FEA) inhibits its application, in addition poor quality models result in engineers having little faith in them. This also makes them sceptical about the results obtained from

the optimisation algorithms. Therefore, developing RSD process models of reasonable computational cost and acceptable quality is an important but quiet difficult task. This point was well captured by a rolling engineer in a discrete event simulation workshop. When asked why optimisation is not part of the design activity for rolling system design, the engineer replied “what is there to optimise?”, implying process models are not available due to the complexity involved in building them.

- Realistic process models infer models not only based on Q^T formulations but also models based on perception based reasoning (Q^L) of the engineers [126]. This shifts the complexity of the search space to a new paradigm and an optimisation algorithm needs to be developed to deal with such complex models.
- An important consideration for obtaining a realistic solution is to ensure the solution strategy closely mimics the nature of the problem. This can ensure that the search preserves the structure of the problem and provides results that can be traced back to its solution mechanism. This also provides more transparency for the engineers since they are able to understand the steps taken to arrive at the result. Developing an algorithm with such features can increase the complexity of the algorithm and compromise its performance.

4.2. Evaluation of RSD Optimisation Approaches for New Product Development

This section presents an evaluation of the RSD techniques reviewed in the previous sections in terms of their suitability for various stages of the new product development (NPD) process. This was considered necessary in order to explore the relationship between the techniques and the different stages of the development process. This can be useful in identifying the most suitable technique for a given stage of the product development process.

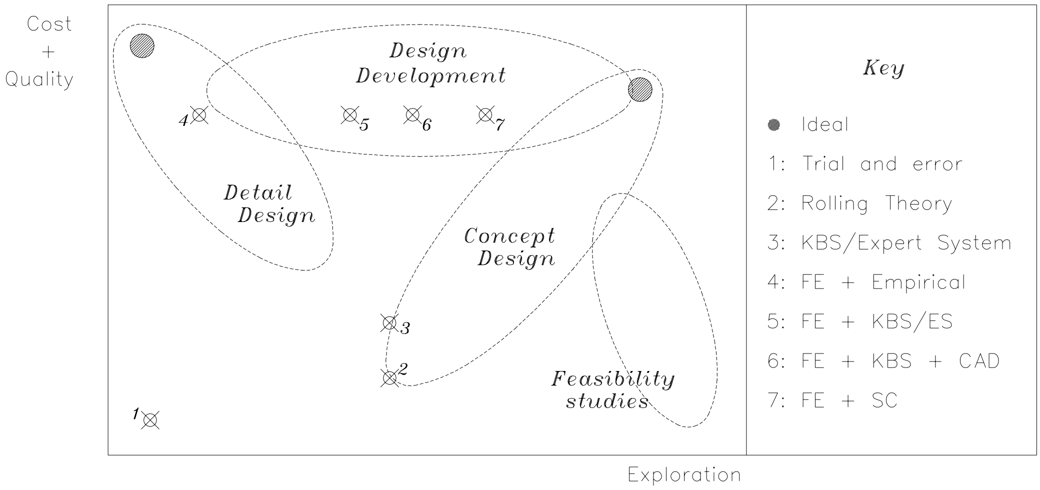

Figure 4: Optimisation approaches and NPD

The review in the previous sections shows that the incremental development of approaches since 1950 has addressed various aspects of the search problem with varying successes. Figure 4 shows a summary of the reviewed approaches and subjective ratings in terms of robustness and exploratory potential for a given technique with respect to the NPD process. A typical product development process consists of the following stages: feasibility studies - concept design - design development and detail design [4]. For such paradigm, the level of design exploration required at each stage of the process increases from right to left, likewise the level of detail and accuracy required increases from left to right. For example, at the feasibility stage, a significant amount of exploration with relatively small accuracy is required to identify any solution alternatives. While for the detail design stage, very little exploration is required since the design is already chosen. Here, the emphasis is on high accuracy and detail to ensure the required objective is specified.

Table 1: Technical Capabilities of the RSD optimisation approaches

Current Approaches	Multi-objective	Q^T and Q^L	Q^T	Q^L	Exploratory Potential
Manual	✗	✗	✓	✗	*
Rolling Theories	✗	✗	✓	✗	*
FE	✗	✗	✓	✗	*
KBS/ES	✗	✓	✓	✓	*
Classical Optimisation	✗	✗	✓	✗	***
SC	✓	✗	✓	✓	****

Table 1 shows the technical capabilities of the optimisation approaches in terms of multi-objective optimisation problems, Q^T and Q^L, Q^T, Q^L and exploratory potential. The exploratory potential signifies the capability to search a design space with reasonable effort. The rating given here is subjective from the authors' viewpoint and is meant to illustrate the relative strength of exploration for the approaches surveyed. Approaches with one star "*" confirms that they are based on manual search. It is clear from this evaluation that SC techniques have the highest exploratory potential and it is capable of handling multi-objective problems. However, most of the reported approaches are computationally expensive as shown by the location of item 7 in Figure 4. It is also observed that most of the FE based approaches (4, 5, 6, and 7) shown in

Figure 4 are ranked with high quality. FE based approaches are computationally expensive but can produce good quality results. The figure also shows the need to develop suitable approaches for the feasibility stage of the RSD. The following sections outline future research directions to deal with these challenges.

4.3. Future Research Directions

Future research directions can be summarised as follows:

- **Approximate strategies for Q^T multi-objective optimisation problems:** Optimisation approaches that require a smaller population for convergence whilst minimising the error between the simulation and the approximate models should be further investigated. Emerging EC based sampling techniques such Kriging, MARS can be explored.
- **Integrated Q^T and Q^L information:** Studies are required to develop optimisation algorithms that can deal with various combinations of Q^T and Q^L information, such as complementary and non-cooperative forms, in a single framework. Scalability of integrated Q^T and Q^L design optimisation strategies to higher dimensional problems is an important success criterion for wider applications. This is influenced by the feature of the problem (large number of parameters) and the nature of the resulting search space (discontinuous).
- Techniques are required for representing the native parameter space of the Q^L information within the optimisation framework. This could provide capabilities for tuning the correlation between the granularities of the Q^L models with the measurement scale of the Q^T models. Search algorithms that consider such features of the problem should give better performance.

- Within the multi-pass optimisation contribution from the several stages may even out fluctuation caused by many of the underlying factors influencing the search directions, this may not always be the case and could result in deceptions in the search problem. Further study could consider investigating the behaviour between different rolling stages during the evolutionary search. Such information could be valuable in understanding the convergence behaviour of the search space, which could result in improved algorithms.
- An inherent feature of the process optimisation problem is the hierarchical nature. There is a need to develop a hierarchical optimisation approaches that can recognise differences at the subsystem level (each mill stand) but performs a system level optimisation (e.g. for the rolling operation as a whole).

5. CONCLUSIONS

The key conclusions from the review can be summarised as follows:

- Classical rolling theories have limited success in delivering roll design solutions. Their limitations can influence optimal RSD in terms of the quality of solutions, and poor response to a broad range of problems.
- The FE method provides a variety of detailed and high quality information, however the FE based design process often lacks structure and appears to be done sporadically. It is computationally expensive and often tends to inhibit its application to a broader range of RSD problems.
- When generating a fuzzy model from FE data, increasing the number of design variables used in developing the fuzzy model also increases the number of rules

exponentially. This incurs expensive computational cost. Very little research has been reported to deal with the Q^T and Q^L RSD problems. Most of the soft computing based efforts in RSD either focus on evolutionary computing or fuzzy logic based techniques.

- There has been little focus in developing optimisation approaches with high exploratory potential that generate a large number of alternative optimal RSD solutions or have the capability to deliver the required quality of solutions for the concept and feasibility design stage of the new product development.

This paper has presented a comprehensive review of approaches for rolling system design optimisation and discussed their advantages and disadvantages. The review has critically analysed how each approach contributes to developing timely low cost optimal solutions and how they influence new product development strategies for the steel industry. The challenges posed by the RSD problem and the future research directions are also identified.

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A review of rolling system design optimisation

Oduguwa, Victor

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