# Making More Cars with Less Metal

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Doctor of Philosophy

UNIVERSITY OF CAMBRIDGE

## Preface

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Preface and specified in the text. It is not substantially the same as any that I have submitted, or is being concurrently submitted, for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my thesis has already been submitted, or is being concurrently submitted, for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text.

This thesis is 52,846 words in length and contains 146 figures, which is within the limits set by the engineering department.

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## Abstract

Reducing sheet metal yield losses in automotive manufacturing would reduce material demand, providing both environmental and financial benefits. This thesis explores material efficiency in automotive manufacturing from four perspectives; the opportunity for improvement, the potential to realise this opportunity, the requirement for effective target setting to achieve material efficiency within the circular economy, and finally design for material efficiency.

The opportunity to reduce material losses in automotive manufacturing is currently unclear since there is limited knowledge of how much scrap is generated, the cost of scrap and why yield losses occur. Through an industry study, it is estimated that yield losses account for 44% of sheet metal used in the production of passenger vehicles and the amount of sheet metal currently used to manufacture automotive components worldwide could be reduced by at least 14% if all car manufactures performed at the best practice level of material utilisation. Improving production material efficiency to best practice could save 25 million tonnes of $CO_2$, and £8 billion per year. Evaluation of every sheet metal component in a case study vehicle reveals that yield losses occur when a blank is simplified to a regular shape, or increased in size due to the design of the part, blank holder, and addendum surfaces. A study of business processes identifies that yield losses are increased to meet part design and manufacturing requirements. Nine strategies for sheet metal scrap reduction are proposed.

Despite the available cost and $CO_2$ savings, the automotive industry has not realised the full potential of these material efficiency opportunities. To understand why, a practical case study was set up with an automotive manufacturer. The trial identified a realistic opportunity to improve material utilisation by 20%, and save £9million and 5 kilotonnes of $CO_2$ annually. The greatest saving opportunities were found early in the product development cycle, before the production method is determined by component geometry. Of these, 3% were actually implemented on the production vehicle, saving £1.8million and 1.5 kilotonnes of $CO_2$ annually. The case study identified significant barriers for implementing material efficiency strategies in an industrial setting. To overcome these barriers material utilisation should be considered earlier in the product design process.

Implementation of material efficiency is often considered to be a lower priority than recycling for automotive manufacturers. Since a more efficient production process generates less scrap, the opportunity for closed-loop recycling reduces when material demand reduces. A comprehensive analysis of material efficiency within the circular economy is therefore undertaken to clarify the environmental benefits of material utilisation. Performance metrics for material efficiency and recycling are identified and the interaction between material demand reduction and closed loop recycling is investigated for a case study vehicle. Whilst the greatest environmental and financial savings occur when both strategies are implemented together, it is shown that a 'recycled content' target does not capture these saving opportunities. It is recommended that automotive manufacturers set targets for both material utilisation and recycling process efficiency. This would promote both closed-loop recycling and material demand reduction.

The geometry of a component influences the amount of material required to manufacture it. Knowledge of geometry based forming limits would be beneficial early in the product development process to enable design for manufacture and process selection in sheet metal forming processes. This thesis investigates the influence of corner, die and punch radii on the

maximum part depth for drawing an isolated flanged shrink corner from aluminium sheet, with and without a blank holder. Trends are identified to establish whether complex component geometry can be analysed to provide a guide for process limits for drawing. The failure draw depth is determined experimentally, with a configurable tool, for 96 different drawing scenarios. The analysis is extended using a validated Finite Element Analysis model to consider a further 432 scenarios. The results demonstrate that a trend could be obtained through plotting the failure draw depth against the average radii of a shrink corner. Assuming this can be extrapolated to full parts, the trend could be useful in the early stages of component design to guide decision making for the component's shape and selecting the most appropriate manufacturing process to improve material utilisation.

By approaching material utilisation from these perspectives, this thesis can inform automotive engineers on how to implement material utilisation improvement opportunities in an industrial setting; reducing material demand, emissions and cost. It also provides future researchers in material efficiency with a greatly expanded evidence base and demonstrates a new pathway for material efficient production technology.

## Key Words

The work presented in this PhD thesis can be categorised into the research areas of:

Material Efficiency

Sheet Metal

Forming

Yield Losses

## Acknowledgements

I would like to thank my supervisor Professor Julian Allwood for his expertise and guidance in the research topic as well as his care for my wellbeing and professional development.

The PhD was sponsored by Jaguar Land Rover and the support given by the industrial partner was critical to the success of the project. I would particularly like to thank Paul Cassel, Mark Clifton, Gethin Davies, Andrew Foster, Jim Harper and Anthony Riley for their help and suggestions at each step of the PhD. As well as wider members of the organisation who provided information or were willing volunteers in my implementation case study.

Thank you to Kirsten Saward and Karin Arnold for ensuring our research group ran smoothly. I am grateful to the wider Use Less Group for their technical suggestions and communication techniques, particularly Christopher Cleaver, Adam Nagy and Johannes Lohmar for teaching me to build Abaqus models with Python scripts – a technique which saved me months in simulation time.

I would like to thank Dan Marinac from Forming Technologies and Trevor Dutton and Paul Richardson from Dutton Simulations for providing software licences and forming simulation expertise throughout the PhD.

The physical experiments to determine forming limits were undertaken at Whiston's Industries, who shared their knowledge of press tool design and generously gave their time and presses so I could conduct the experiments in an industrial setting. The metal blanks were cut by the Department of Engineering workshop within Cambridge University. I am grateful to Alistair Ross and Steve Robinson for not turning me away when I presented them with 300 different blank shapes to cut out on the water jet.

Finally, I would like to thank my family for remaining enthusiastic about sheet metal forming and for their unwavering support throughout.

## Publications

Some of the material presented in this thesis has been published in the following journal articles:

Horton, P, Allwood, J (2017), Yield improvement opportunities for manufacturing automotive sheet metal components, Journal of Material Processing Technology, 249, 78-88.

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Horton, P, Allwood, J , Cassell, P, Edwards, C, Tautscher, A, (2018), Material Demand Reduction and Closed-Loop Recycling Automotive Aluminium, MRS Advances, 25, 1393-1398.

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Horton, P, Allwood, J, Cleaver, C, (2019), Implementing material efficiency in practice: a case study to improve the material utilisation of automotive sheet metal components, Journal of Resources Conservation & Recycling, 145, 49-66.

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Horton, P, Allwood, J, Cleaver, C, Nagy, A, (2019), To what extent can sheet metal forming limits be predicted from component geometry? Journal of Material Processing Technology, (Submitted, March 2019)

# Contents

# Chapter 1 Introduction

Carbon dioxide emissions need to be reduced on a global scale to mitigate climate change. This fact has been widely understood and accepted by global leaders, but implementing carbon reduction strategies is challenging. To date, climate change policies have focused on energy supply, promoting renewable energy generation methods over the use of fossil fuels. Mackay (2009) found that large scale implementation of renewable energy is limited by land availability, infrastructure and global politics. His work has shown this change of strategy in energy production is required to reduce carbon emissions, but alone it is not enough.

A report on future energy strategies by the International Energy Agency (2009) claims that 40% of global $CO_2$ emissions related to energy use are produced in industrial activity, the majority of which are from the manufacture of primary materials such as steel and aluminium. To minimise the effect of climate change, global leaders at the 2008 Hokkaido G8 summit have committed to halve $CO_2$ emissions by 2050; yet with population increases and economic development, global demand for these energy intensive materials is set to more than double in this time frame. Current strategies to achieve industrial decarbonisation are set out as: improving the process efficiency of material production; implementing carbon capture and storage technologies; substituting energy intensive materials; and increasing recycling. Through an industry survey, Allwood et al (2010) reviewed the opportunity for energy efficiency strategies in the production of primary materials. Their findings highlighted historic process improvements driven by cost reduction, and show that further process efficiencies are unlikely to provide sufficient energy savings whilst meeting growing consumer demands. Carbon capture and storage for steel making has been shown to be technically possible by Meijer et al (2009). However, Allwood et al (2013) assess the high energy costs for carbon separation and lengthy timescales for implementation, concluding that this technology is not the solution for reducing industrial emissions within the timescales recommended by climate scientists. In the same report, Allwood et al. dismiss material substitution as a method of reducing industrial carbon emissions due to the widespread and optimised application of existing primary materials. Recycling provides an opportunity to reduce primary material production, but stocks of recycled material are unable to meet a growing material demand, and there are challenges in the collection and separation of scrap to maintain high quality material. Since none of the existing emission reduction strategies have proved to be successful, an alternative approach is required.

Allwood et al (2010) proposed material efficiency as a method of reducing industrial emissions. Material efficiency aims to reduce production of primary materials by meeting service requirements with less material. For example, designers of sheet metal components could save cost and reduce environmental impact by placing greater emphasis on the material efficiency throughout the product development cycle. Engert & Baumgartner (2016) identified a gap between sustainability strategies and implementation in an industrial setting. This thesis aims to bridge this gap. Working in partnership with an automotive manufacturer, the thesis explores the scale of the material efficiency saving opportunities, evaluates how much of the potential saving opportunity can be realised in practice, how setting effective targets can support implementation and finally how design for material efficiency can be applied to the product development cycle. This consideration of implementing material efficiency opportunities is crucial in the urgent aspirations to reduce industrial $CO_2$ emissions.

To provide context for improving sheet metal material utilisation in the automotive industry the background to motivations for material efficiency and sheet metal forming in the automotive industry are now presented.

## 1.1 Motivation for sheet metal efficiency in the automotive industry

Steel and aluminium are the greatest contributors to the embodied emissions of a passenger vehicle. They have a greater environmental impact than other materials, such as rubber, glass and plastic, because they are both energy intensive to produce and are used in large quantities. Through mapping global flows of material, Allwood & Cullen (2012) estimate that 12% of steel and 30% of aluminium produced globally is used in the automotive industry, much of which is in the form of sheet metal. A typical car is made up of more than 300 sheet metal components. The components are joined and are collectively called the Body in White, as shown in figure 1.1. This thesis focuses on reducing emissions associated with meeting the automotive industry's demand for sheet metal through material efficiency.

**Figure 1.1 Metal body structure of the Jaguar XE, known as the Body In White (BIW). Image from Business In The Community (2014).**

Material efficiency strategies are process innovations which aim to provide the same service with less material. Allwood et al (2013) outline six approaches in which this could be achieved, these are:

- Light-weight design
- Longer life products
- More intense use
- Re-using components
- Diverting manufacturing scrap
- Reducing Yield losses

The first four of these strategies would reduce material demand in the automotive industry. However, implementation requires a strategic change in the way cars are designed, sold and used. These changes would be visible to the customer and affect the way they currently buy and use cars. Therefore, these strategies are not considered an early priority for material efficiency and are not investigated in this thesis. Through industrial surveys, Allwood et al (2013) identified that the business case for diverting manufacturing scrap is limited to isolated parts, and almost all process scrap is collected and re-melted to become a source of secondary material. Material efficiency achieved through reducing yield losses is not visible to the customer and is not limited to isolated parts. This strategy therefore should be a priority for implementation in the automotive industry. Reducing production yield losses will reduce the demand for energy intensive materials in the automotive industry without impacting the level of service provided.

International legislation and consumer pressure is promoting a reduction in automotive related emissions.  Current strategies focus on reducing energy conversion emissions, commonly known as tailpipe emissions. Lightweight materials and more efficient engines improve the fuel efficiency of the car relative to its size. The development of hybrid and electric vehicles allows alternate, cleaner energy sources to be used. Assuming a cleaner source of energy is available to the automotive industry; reducing the tailpipe emissions reduces the proportion of emissions allocated to the 'use' stage in the vehicle's life cycle analysis. As a result, the embodied emissions of the vehicle's material are becoming increasingly important, as shown in Figure 1.2.

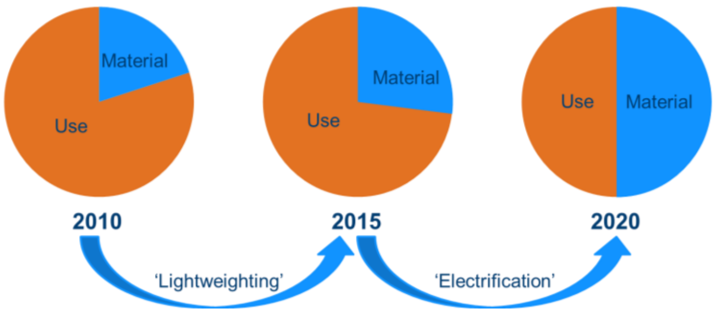



**Figure 1.2** **The dominant life cycle stage in the automotive industry is predicted to shift from the 'use' phase of the life cycle to the 'material' phase. Numbers sourced from J.Shaw, (2016).**

Improving the production efficiencies in the manufacture of automotive sheet metal components would reduce demand for primary material, reducing the embodied carbon of the vehicle. A reduction in material requirement could also reduce material costs, providing a financial saving opportunity.

Previous research has identified environmental and financial motivation to improve the material utilisation of sheet metal components. For example, Ingarao et al. (2011) capture the environmental motivation to reduce production yield losses in their review of sustainability issues associated with automotive sheet metal forming, and Linton et al. (2007) recognised that manufacturing by-products should be considered in the evaluation of sustainable product design. Baumgartner et al. (2017) reviewed sustainability strategies and developed a checklist for considering sustainability in the automotive industry. Material efficiency is included within this checklist. Material demand reduction is being promoted by the Aluminium Stewardship Initiative (ASI 2014). Raw material, in particular sheet metal, is the greatest cost driver for automotive manufacturers. This cost is even greater if aluminium is used in place of steel, (Kallstrom 2015). The motivation to improve material utilisation is reflected in its use as a key performance indicator in the production of sheet metal components, as identified by Behrens & Lau (2008) through a survey of manufacturing organisations.

The automotive industry has motivation to improve material efficiency in sheet metal forming, but how can it be achieved? The manufacturing process of sheet metal automotive components is now described to provide context for why yield losses occur.

## 1.2 Sheet metal scrap generation in automotive manufacturing

The sheet metal manufacturing process transforms liquid metal into a useful three dimensional component. The process can broadly be split into five stages, as shown in figure 1.3. Liquid metal is cast into steel slabs or aluminium ingots. The end surfaces of the casting are removed to eliminate impurities. The ingot or slab is then transported to a rolling mill, where through a series of hot and cold rolling process it is reduced in section to a sheet of the desired thickness. The sheet is then slit to a specified width and uneven edges are removed before it is coiled into a cylinder. The coil is an intermediate product which allows the transportation and distribution of sheet metal to downstream production processes. The sheet metal is de-coiled to a flat sheet, shapes known as blanks are cut out and any remaining material is scraped. The blanks are formed to a three dimensional component and trimmed to produce the final component.

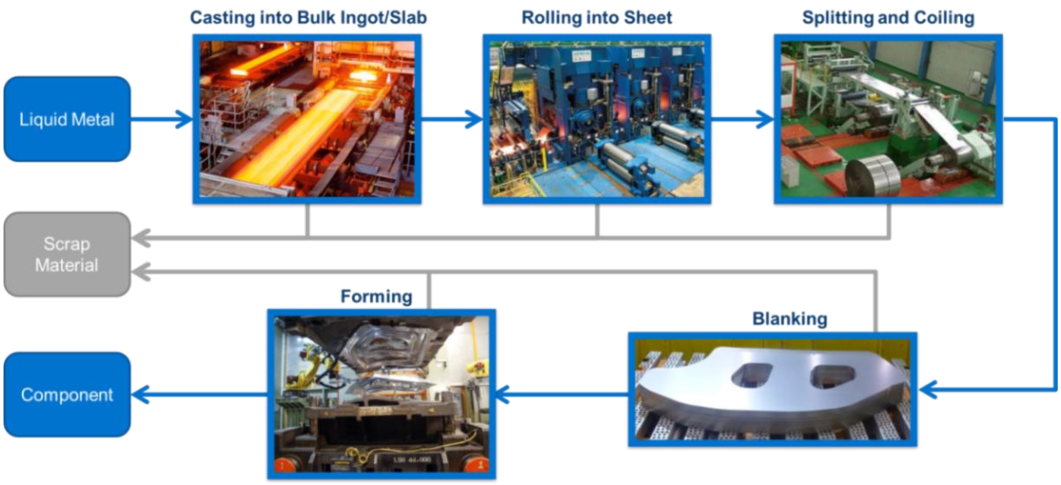



Figure 1.3 Sheet metal production processes, converting liquid metal into a useful component and scrap.

Yield losses occur at each stage of production. Milford et al (2011) estimated that approximately 10% of the liquid metal is scrapped in coil manufacture. The remaining yield losses occur in the downstream processes of blanking and forming. This thesis focuses on these downstream processes, evaluating how efficiently the coil is used to make a component. These processes will now be introduced.

The blanking process, shown in figure 1.4, unwinds and flattens the coil of metal then cuts the continuous sheet into smaller sheets, 'blanks', which are suitable for subsequent forming. For small production volumes the cutting operation can be performed by hand tools such as power snips, jig saws or power shear tools. On a larger scale, blanks are cut using automated tools with simple blades, custom shaped dies or laser cutting.

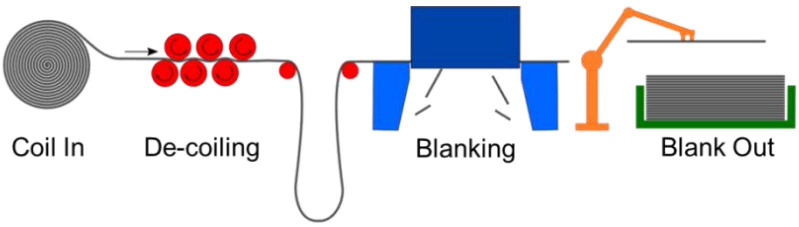



**Figure 1.4** **The blanking process. Scrap is generated as shaped blanks are cut from a coil of sheet metal.**

The sheet metal blanks are then shaped by a forming process to produce three-dimensional components. The shape is generated through plastically deforming the sheet using dies (stamping) or rolls (roll forming) and can be performed hot or cold. Alternative forming methods include hydroforming, explosive forming and electromagnetic forming. The most commonly used process to form automotive components is cold stamping with rigid dies. This process is the focus of this study. The stamping production line has four major process steps, as shown in figure 1.5. A blank is first drawn and plastically deformed into a three dimensional shape using a large heavy press. Smaller subsequent presses trim away scrap, pierce holes, flange edges over and re-strike the component to provide the final dimensions.


**Figure 1.5** **The stamping process. Scrap is generated to allow material to flow in the drawing process and is removed in subsequent trimming operations.**

The yield losses generated in blanking and stamping of sheet metal automotive components can be collected and sold to be recycled. Environmental and financial savings would be greater if yield losses were prevented rather than recycled. This principle is the focus of this research.

The structure of this thesis is now outlined.

## 1.3 Structure of the thesis

This PhD is supported and sponsored by the automotive manufacturer Jaguar Land Rover. It aims to explore why sheet metal production losses occur and propose strategies to improve material efficiency. The project focuses primarily on automotive sheet steel and aluminium processing, but the analysis and findings are transferable to many other applications of sheet metal. The structure of this document is described in Figure 1.6.

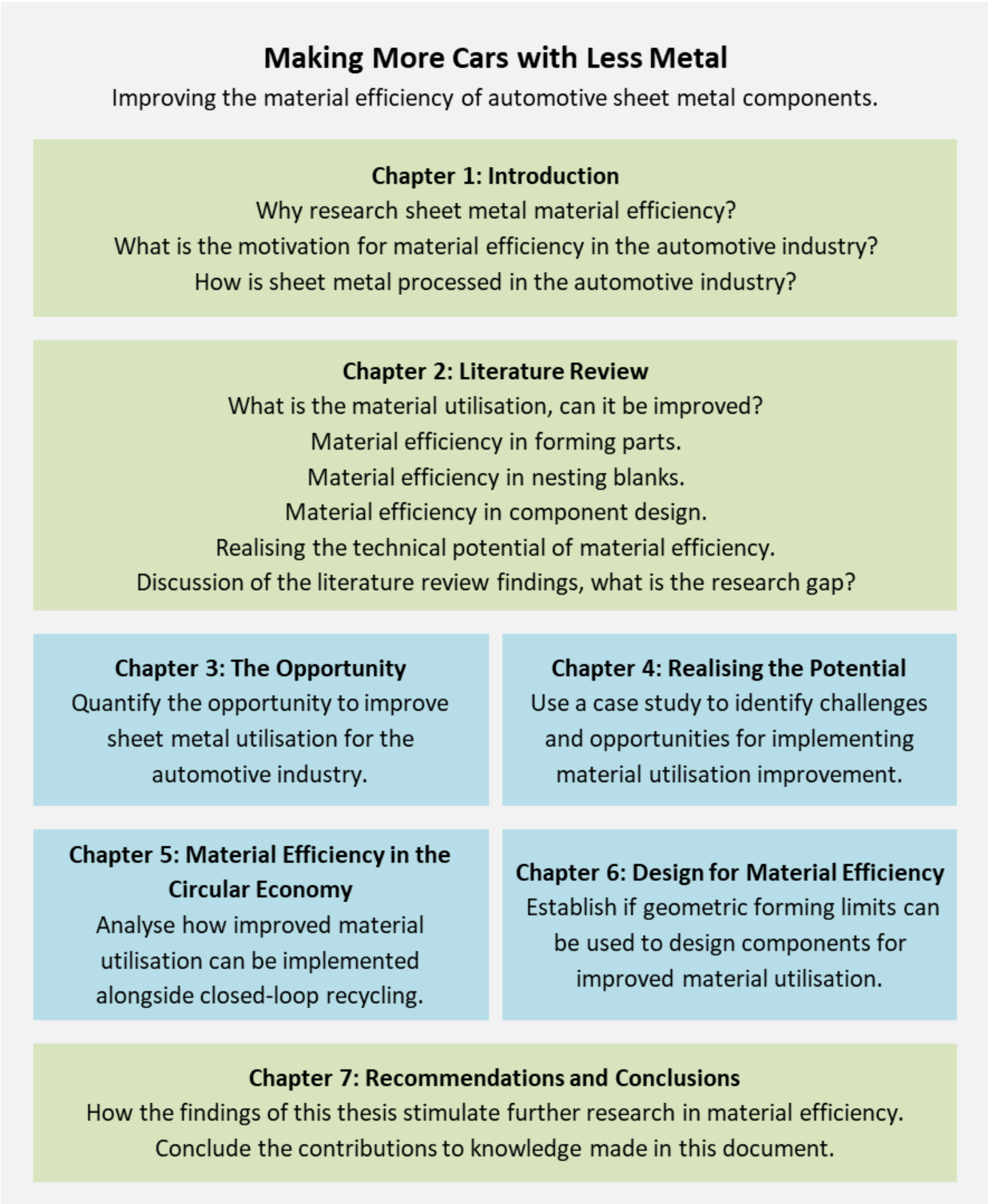



**Figure 1.6 Structure of this document.**

# Chapter 2 Literature Review

This chapter reviews previous research on material efficiency, achieved through reducing yield losses, in the manufacture of sheet metal automotive components. Section 2.1 identifies existing estimates for the material utilisation of automotive sheet metal components and highlights any previously identified opportunities for improvement. Section 2.2 evaluates current sheet metal forming technology and analyses how existing knowledge can be exploited to improve material efficiency in forming. Section 2.3 explores best practice for material efficiency in blanking through evaluation of nesting algorithms.  Section 2.4 discusses previous research into automotive component design to identify how the component geometry can be modified to improve material efficiency. Section 2.5 evaluates the extent in which the material efficiency opportunities identified in sections 2.1-2.4 have already been implemented and reviews previous studies which observe potential barriers for implementing material efficiency in an industrial environment. Finally, section 2.6 outlines the research opportunities in the field of sheet metal material efficiency which the remainder of the thesis will address.

## 2.1 Existing utilisation estimates for automotive sheet metal

As detailed in the introduction, sheet metal is transformed into automotive components through a series of cutting and shaping operations. The sheet metal is first cut from the coil in a process known as blanking; this blank is then drawn into a three dimensional shape through a forming process. Excess material is then trimmed from the formed part to produce the final component. Minimising the production yield losses which occur during these operations would reduce the demand for raw material, generating financial and environmental savings.

The automotive industry measure the material efficiency of this production process using the metric ‘Material Utilisation’ which is defined by equation 2.1.

$$\text{Material Utilisation (\%)} = (1 - \text{Production Yield Loss}) \times 100 \quad (2.1)$$

Where;

$$\text{Production Yield Loss} = \frac{\sum \text{Manufacturing Scrap}}{\sum \text{Coil Mass}} \quad (2.2)$$

Previous research is now reviewed to establish current estimates for automotive sheet metal material utilisation and the known available opportunities for improvement.

When considering the material utilisation of steel and aluminium in all forms, sheet, plate and bulk, Milford et al. (2011) quantified that material utilisation is an average of 74% for steel and 59% for aluminium. In their consideration of the material efficiency of five sheet metal components, used across multiple industries, Milford et al. (2011) calculate blanking and forming losses as 10% and 30% respectively, they estimate the total material efficiency of sheet metal forming as 60%. In contrast, Carruth & Allwood (2013) estimate that sheet metal material utilisation across multiple industries is approximately 50%. When focusing on the production of beverage cans, Carruth & Allwood (2013) observe greater blanking losses than Milford et al. (2011) and estimate that up to 50% of sheet metal is scrapped during blanking. To date there has been only one estimate published for the material efficiency of automotive sheet metal components. In their map of global steel flows, Cullen et al. (2012) estimate the material efficiency of a passenger vehicle as 60%. Their analysis uses a single case study vehicle and is not an industry average. Previous research which considers the opportunity to improve sheet metal material efficiency is now reviewed.

Milford et al. (2011) describe two opportunities for improving the material efficiency of sheet metal components. These are:

1. **Reducing the gripping area in forming:** Sheet metal components are formed from two dimensional blanks. During forming, material around the periphery of the blank is gripped to increase tension and prevent wrinkling in the part. After the blank has been formed this gripping

material is removed and recycled. Reducing the size of this gripping area would reduce the manufacturing yield losses and improve the material efficiency of the component.

2. **Improve nesting on the coil in blanking:** Sheet metal blanks are cut from a coil of metal. The coil material in between the blanks is removed and recycled after blanking. Improving the positioning of the blanks, known as the nesting, to tessellate better on the coil would reduce the yield losses which occur in blanking and improve the material efficiency of the components.

From industry interviews Milford et al. (2013) estimate that automotive yield losses could be reduced by 10% through implementing these strategies. However, specific methodologies for implementing these improvements are not evaluated. Greater evaluation of yield losses in the automotive industry is required to improve the accuracy of this estimate.

Reviewing previous research has revealed many different estimates for sheet metal material efficiency. The estimated material utilisation values vary depending on the components and industry being analysed. The existing estimate of 60% for the sheet metal material utilisation of a whole vehicle automotive is a starting point for analysis, but further research would be required to generate a more detailed value. Previous research has highlighted a potential improvement opportunity to increase the material efficiency of automotive sheet metal components by 10%. However, these opportunities have not been evaluated in depth to determine how they could be achieved, or to quantify the potential environmental and financial benefits. To further explore the material efficiency opportunities of reducing the gripping area in forming and improving the nest in blanking, the processes of forming and blanking are reviewed in turn.

## 2.2 Material efficiency in forming

As described in section 1.2, the forming process draws the blank into a three dimensional shape using a press tool which is able to grip the edge of the blank. This additional material is removed during a subsequent trimming process. Yield improvements in forming could be gained through reducing the ‘gripping area’. An example of the gripping area required to stamp an automotive component is shown in figure 2.1. The area in blue is an approximation of final component and the remaining grey material is the gripping area.

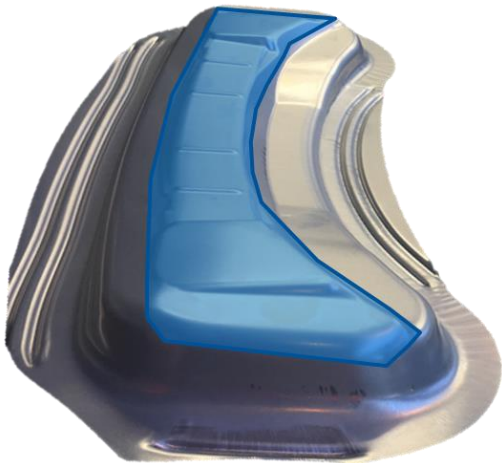


Figure 2.1 Example of scrap generated in the gripping area. Image from factory visits made for section 3.4.

Section 2.2.1 will reveal the purpose and key components of the gripping area. These components are then analysed in turn to identify whether they have been optimised to minimise scrap. Opportunities for future yield loss reduction are discussed in section 2.2.6.

### 2.2.1 Introduction to Material Flow in Forming

This introduction explains how material flows during forming. It explores how additional gripping material is added to control material flow and prevent failure.

Whether a material can flow into a desired shape without failure is known as the material property ‘formability’. Formability has been extensively studied to increase the complexity of shapes which can be formed. In a review of sheet metal formability, Emmens (2011) identifies that formability is not strictly a material property, but a combined result of the material properties, tool properties and process variables in the forming operation. Emmens identifies that any mechanism which exerts a pulling force on material will increase formability. The gripping area in forming is designed to achieve this through applying a tensile force on the part to control the flow of material as the flat blank is plastically deformed into a three dimensional shape. A summary of this process can be found in Altan & Tekkaya (2012), and is redrawn in figure 2.2. In this example the gripping area used is a blank holder, which applies a force to the perimeter of the blank. The blank is stamped into a part through impacting a punch into a die. The material between the punch and the die is stretched. When the stretching limit is reached additional material is drawn into the die from the blank holder area. Forces generated by the punch and blank holder should be designed to control the tension in the wall (zone D-E) and maintain material flow. If there is too much tension in the wall this zone will thin and may fracture. If there is too little tension too much material will flow and wrinkling may occur. The longer the wall the more difficult this process is.  The transition at point F is where fractures are most likely to occur as this area has not been work hardened and is subject to large tensile forces.

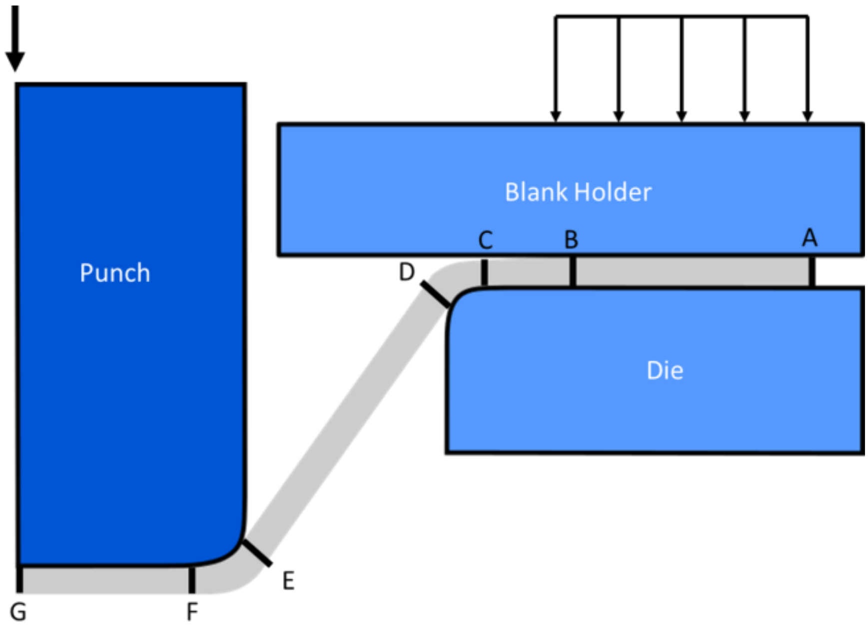



**Figure 2.2 Deformation zones in forming a round cup: A-B flange thickens as drawn into a smaller diameter, B-C flange thins due to tension from punch drawing, C-D die radius material elongates, D-E wall transmits force from the punch to the flange, E-F material work hardens as it passes over punch radius, F-G limited deformation due to high frictional forces at the bottom of the punch.**

The gripping material consists of multiple features which control material flow and improve formability. In addition to the blank holder used in the previous example, Lange (1985) describes how material flow can be controlled using draw beads, a feature in the tool which increases the tension provided by the blank holder; and through cutting holes in the blank shape, to relive stresses during forming. Schenk & Hillmann (2004) demonstrated that the shape of the die surface also affects material flow in forming and can been optimised to improve formability. The die surface is made up of the desired component geometry and a surface which connects the geometry to the blank holder, known as the addendum surface, as shown in figure 2.3. The design of the gripping area is therefore made up of the blank holder, draw beads, the blank shape, the addendum surface and the component geometry. For simplicity these features are collectively referred to as 'forming design variables' in this thesis.

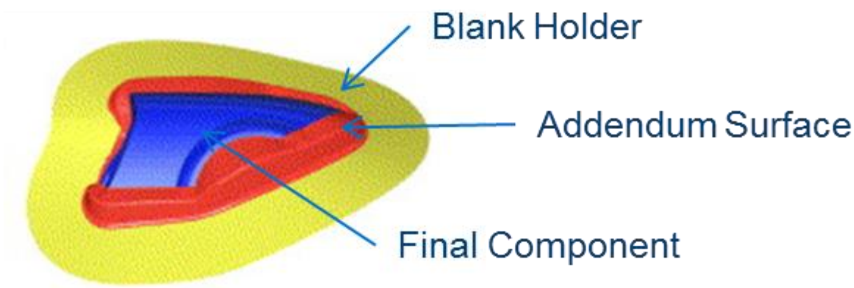



**Figure 2.3** **Image adapted from (Schenk & Hillmann 2004) showing the addendum surface. The addendum surface and component geometry affect the material flow in forming.**

It has been shown by Emmens (2013) that material flow in stamping is affected by the material properties, tool properties, process variables and forming design variables, as summarised in figure 2.4. The forming design variables have the greatest effect on stamping scrap since the design of these variables change the blank size to control material flow. These variables are therefore the focus of this literature review. Although the final component geometry affects material flow, it is not scrapped so is not considered for optimisation at this point in the thesis. The effect of component geometry will be considered in the analysis of the remaining variables. The blank holder, draw bead, addendum surface and blank shape design will now be explored in turn to understand why they are used and whether they can be optimised to reduce yield losses.

| | |
|---|---|
| **Material Properties:**<br>Composition<br>Temperature<br>Deformation History<br>Material Thickness<br>Strain Rate Sensitivity, m<br>Strain Hardening Factor, n<br>Anisotropy, r | **Tool Properties:**<br>Punch & Die Radii<br>Shut Height<br>Surface Finish<br>Stiffness<br>Thermal Properties |
| **Process Variables:**<br>Punch Speed<br>Punch Force<br>Tool Path<br>Lubrication<br>Operating Temperature<br>Number of Operations | **Forming Design Variables:**<br>Component Geometry<br>Blank Holder Design<br>Draw Bead Design<br>Addendum Surface Design<br>Blank Shape Design |

**Figure 2.4 Summary of factors which influence material flow control in forming.**

### 2.2.2 Controlling Material Flow with the Blank Holder

The blank holder, also known as the binder or flange, is the blank area which the press restrains to stretch the part. This section reviews literature which has evaluated how the blank holder works, identifying variables which affect the blank holder restraining force. Previous research in blank holder force optimisation is reviewed and opportunities to reduce yield losses through eliminating or reducing the blank holder area are identified. Optimisation of the size of the blank holder is reviewed in section 2.2.5 when the blank shape is considered in greater depth.

Using finite element analysis of a square cup, Sattari et al (2007) evaluate how material is drawn from the blank holder. As the part is formed the size of the blank holder area reduces, as shown in figure 2.5. The blank holder area which remains at the end of the forming stroke is trimmed off as scrap.

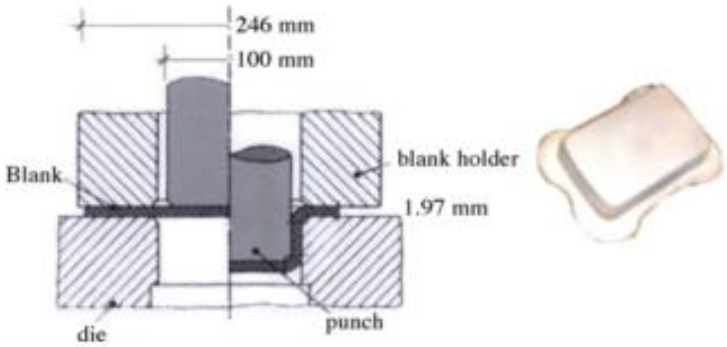



Figure 2.5 Blank holder area before and after drawing Sattari et al. (2007).

The blank holder controls material flow through applying a force to the blank holder area. The resulting pressure provides sufficient tension to prevent wrinkling and splitting. Siebel & Beisswanger (1955) mathematically estimated the required blank holder force for a cup, given in equations 2.3 and 2.4.

$$F_{BH} = p_{BH} \times A_{BH} \tag{2.3}$$

Where:

$A_{BH}$ is the blank holder area
$F_{BH}$ is the blank holder force
$p_{BH}$ is the blank holder pressure

$$p_{BH} = 10^{-3} c \left[ (DR - 1)^3 + \frac{0.005 d_0}{s_0} \right] S_u \tag{2.4}$$

Where:

c is the empirical factor, usually 2 to 3
$d_0$ is the blank diameter
DR is the draw ratio (blank diameter/cup diameter)
$p_{BH}$ is the blank holder pressure
$S_0$ is the blank thickness
$S_u$ is the ultimate tensile strength of the sheet material

This formula shows that the size of the blank holder, and gripping scrap, is affected by the force applied to the blank holder and the required pressure. The pressure requirement depends on the geometry of the component. There has been no published evaluation of the required blank holder pressure for a generic geometry. Therefore the blank holder design is developed experimentally through simulations and physical trials. The blank holder size, shape and force can be varied to control material flow and prevent forming failure. Optimisation of blank holder force will now be discussed.

The blank holder force provides tension during forming. Altan & Tekkaya (2012) estimate that the blank holder force required is usually between 0.5 and 1% of the drawing force. Using finite element simulation software, Zhong-qin et al (2007) identify a specific window for the blank holder force (BHF) which prevents failure for a specific part geometry, as shown in figure 2.6. There has been no investigation into the forming window for a generic geometry.

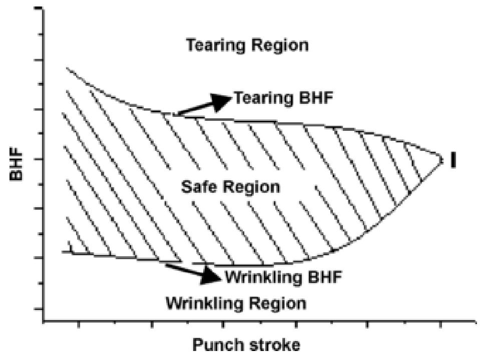



**Figure 2.6** Example of safe blank holder force window from Zhong-qin et al. (2007). The forming simulation aims to calculate a safe forming window for the blank holder force in which neither splits nor wrinkles occur.

Doege & Sommer (1983) identified that the blank holder force can be varied with time during forming to reduce failure. Obermeyer & Majlessi (1998) reviewed blank holder technologies, observing disagreements within the academic community of whether a variable blank holder force should match the press force, or oppose it. The variety and contrasting nature in results of optimising the variable blank holder force is likely to be a result of differing part geometry. This has not been investigated. Instead, research focus shifts to control loops which adjust the blank holder force when thinning begins to occur. For example, Zhong-qin et al (2007) optimise a variable blank holder force to form an example component using finite element analysis and physical trials, shown in figure 2.7. Controlling the blank holder force has not been completely understood; instead the process is designed to react to the onset of failure.


**Figure 2.7** Improved forming results using control systems for time variable blank holder force Zhong-quin et al. (2007). This can be a successful method of forming, but it does not give understanding of how the blank and part geometry impacts the blank holder force.

Blank holder force optimisation is reviewed by Zhang et al (2004). They find that spatially variable blank holder forces have been developed to increase the geometrical complexity and draw depth of a part which can be formed without failure. Palaniswamy et al (2006) develop a spatially variable blank holder force, through physical trials, to reduce the development time to produce an automotive door panel, as shown in figure 2.8.

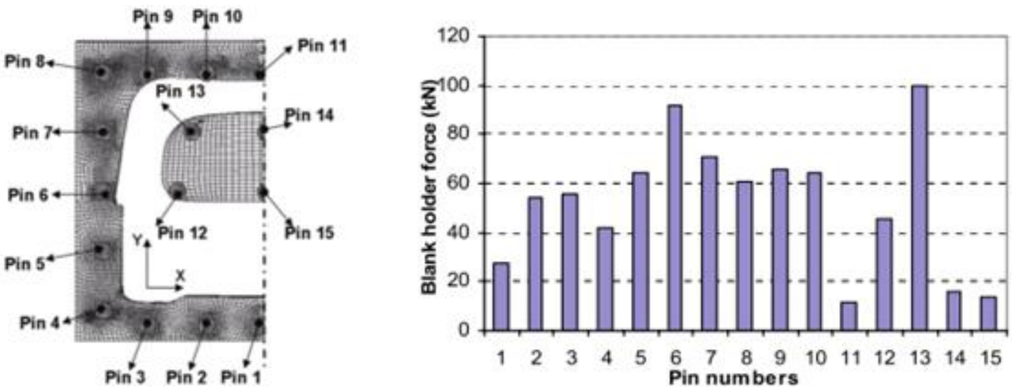



**Figure 2.8** Spatially Variable Blank Holder from Palaniswamy et al. (2006).

Further developments of the blank holder force include a pulsating blank holder by Kitayama et al (2015) and electromagnetically assisted sheet metal stamping by Tekkaya et al (2015). Finite element studies for example parts have shown that these methodologies have merit in improving formability, but there has been no consideration of the impact of blank holder size and material efficiency in the development of these technologies.

The blank holder is eliminated in a process called crash forming, also known as solid forming. Crash forming deforms material using a punch and die, but since there is no blank holder area to grip the blank, the control of material flow reduces, so complex parts can split and wrinkle. The geometrical limits of crash forming have not been identified. It is possible that crash forming is underutilised. Increasing the application of crash forming could reduce yield losses in stamping.

The blank holder has been extensively optimised to control material flow more accurately and reduce forming failure. The blank holder force has been optimised to be variable with time, spatially and applied in pulses. This optimisation has led to an increased formability of complex parts. To date, blank holder force optimisation studies have only considered individual components. There has been no analysis of different geometries to understand the wider opportunity for implementing these technologies to minimise production scrap.

Opportunity exists to reduce yield losses through minimising the blank holder area, optimising variable blank holder forces and a greater use of crash forming. However, there has been no investigation into the minimum required blank holder area and force to form a generic geometry. This knowledge would facilitate implementation of these saving potentials.

### 2.2.3 Controlling Material Flow with Draw Beads

The draw bead is a physical obstacle built into a tool to increase the restraining force of the blank holder. The addition of draw beads increases the blank size, which increases scrap. This section explains how draw beads control material flow, how they have been optimised and identifies whether they can be reduced or eliminated to reduce yield losses.

Using mathematical analysis correlated with physical testing, Samuel (2002) demonstrates the additional effort required to overcome the draw bead increases the restraining force on the flange, as shown in figure 2.9. Heinle (2012) identifies through industrial observation that holding material in the draw bead for the full stroke duration avoids discontinuities in material flow, but increases scrap material, figure 2.10.

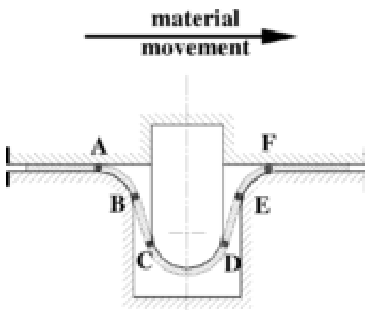



**Figure 2.9** **Bending and unbending as material flows over the draw bead Samuel (2002). As material is drawn down into the die it must plastically deform to bend and unbend three times around the draw bead, these bending points are marked by letters.**

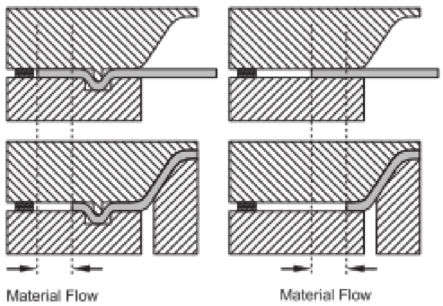



**Figure 2.10** **Comparison of drawing with and without a draw bead Heinle (2012). The draw bead restrains material throughout the stroke to avoid discontinuities in material flow. The addition of draw beads increases the blank size.**

The size and cross sectional shape of the draw bead is designed to provide the required restraining force to form a part without failure. The greater the deformation required to pass through the draw bead the greater the restraining force it provides. A finite element study by Naceur et al (2004) found that the restraining force of a draw bead can be increased through increasing the height or tightening the radii. Makinouchi (1996) surveyed industry processes and found that draw beads are traditionally selected from data bases and experience-based guidelines. More recently, Zwitter et al (2013) noted from industrial observation that the shape of the beads are selected from a database, but can then be adjusted during tool try-out stage by modifying the press tools.

Draw bead optimisation techniques have been proposed by Courvoisier et al (2003) using numerical analysis, scientific experimentation and finite element modelling. These optimisation techniques design the radius and height of the draw bead for the required restraining force. Further optimisation by Emblom & Weinmann (2011) varied the draw bead size spatially and with time to allow the formation of complex geometry and reduced failure, figure 2.11

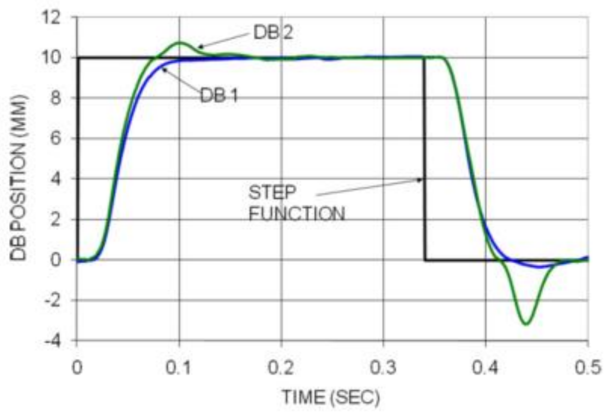



**Figure 2.11 Varying the draw bead height during the stroke to control material flow from Emblom & Weinmann (2011).**

The size of the draw bead has been optimised to provide the required restraining force which avoids failure. Draw beads have been optimised to vary spatially and with time to provide additional control during the drawing stroke. The positioning of draw beads will now be considered to reveal if there is an opportunity to reduce yield losses through optimising the use of draw beads.

Chen & Chiang (1997) and Guo et al (2000) identify through industrial observation that the draw bead is usually positioned at a given offset of the perimeter of the formed part. Kayabasi & Ekici (2007) optimise the value of the constant offset for a component using iterations of finite element analysis, figure 2.12, but there has been no variable placement optimisation of draw beads.

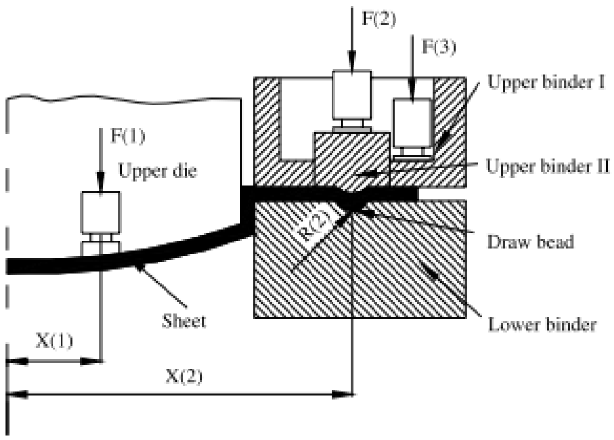



Figure 2.12 Draw bead position optimised with a constant offset, X(2), from (Kayabasi & Ekici 2007)

The opinion of when draw beads are required varies. Samuel (2002) claim that draw beads are required for deep parts. Naceur et al (2004) claim they are required to form complex parts. Whereas Boljanovic (2004) used draw beads to form shallow, simple parts. Ingarao & Lorenzo (2010) recognise that the placement of draw beads, with respect to geometrical features, is achieved through trial and error. There has been no study to better understand which parts or geometries drive the requirement for draw beads.

Shim (2013) proposes 'beadless stamping' to reduce the additional material requirements of draw beads. In contrast to the name, 'beadless stamping' still uses draw beads, but limits their use to the minimum required to form the part, as shown in figure 2.13. Shim (2015) uses finite element forming simulation to optimise a case study component. Small modifications of the component geometry are made to improve the formability of beadless stamping enabling a reduction in blank size by almost a quarter. The results are shown in figure 2.14. The methodology proposed by Shim relies on feedback to component designers to improve manufacturability and a complex initial blank shape. This may limit its immediate application to reduce material utilisation.

Figure 2.13 Beadless stamping proposal, original draw bead route (top) and modified draw bead (bottom). Image from Shim, (2013). Shim proposes replacing draw beads which surround the perimeter of a part, with an optimum blank shape which controls the material flow with less scrap, one draw bead is required to prevent oscillation in the part.

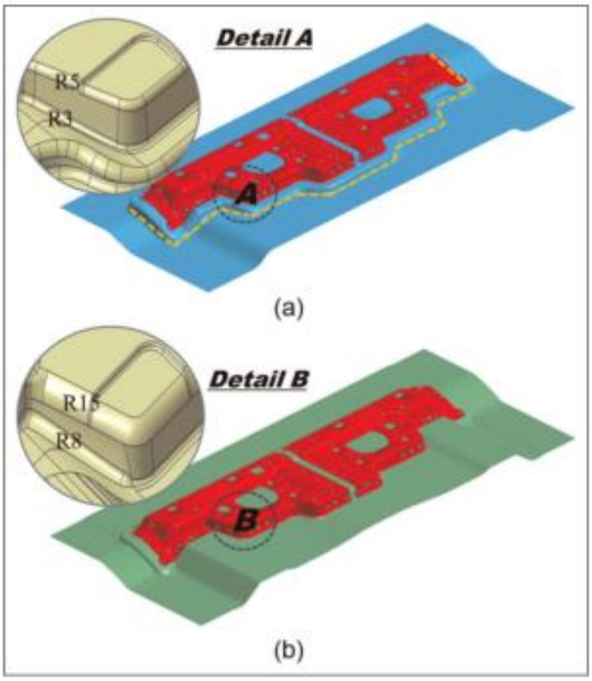



Figure 2.14 Modification of part geometry for forming improvement (a) original design (b) modified design. Image from Shim (2015). The blank size is optimised through widening the corner radii on the part geometry to allow improved formability with minimal use of draw beads.

Draw beads provide additional restraining force to the blank holder so should only be positioned where additional force is required. There is limited understanding of when and how draw beads should be used. Through increasing this understanding and reducing the use of draw beads, stamping scrap could be reduced.

### 2.2.4 Controlling Material Flow with the Addendum Surface

The addendum surface connects the component geometry to the blank holder. The addendum surface is usually trimmed off as scrap after drawing. For some components a second part is used as an addendum surface. This practice is called double attaching. This section explains how the addendum surface has been designed and optimised and identifies opportunities to reduce scrap.

The addendum surface is designed to control tension. Dy et al (2008) categorised the shapes of curves in the addendum surface as general, vertical trimming and bulging, as shown in figure 2.15. These features either locally stretch material or provide additional surface area for excess material, to ensure drawing defects or wrinkles do not enter the final component. Optimisation of the addendum surface design will now be considered.

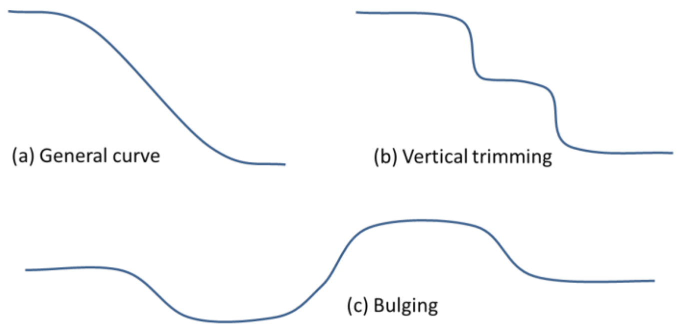



**Figure 2.15 Cross sections of addendum surface feature design. A general curve is used to connect the part to the blank holder when no additional tension is required. A vertical trimming curve is shaped to facilitate easier trimming after the part has been formed. Bulging is used to control material tension and move slip lines away from the part, a row of bulging curves is referred to as a convex hull and a sausage shape bulging curve is referred to as a run-off or a draw bar.**

Through an industry observation, Debray et al (2013) found that addendum surfaces are usually designed by engineers with CAD software and require many trials and corrections. Chen et al (2010) design the addendum surface for an automotive bonnet panel. They use finite element analysis and physical trials to design the addendum surface for optimum formability, but material utilisation is not considered. For complex parts the forces on the die face are not uniform during drawing. This makes forming difficult and increases the chance of part failure. You et al (2011) design the addendum surface to compensate for irregular geometry, to make the die forces more uniform during forming. Optimisation algorithms have been developed by Heinle (2012) with the aim of shortening die development time to reduce development costs. Again material utilisation is not considered in this optimisation.

Addendum optimisation techniques have been shown to reduce failure in forming, and reduce development time. However this optimisation has led to a growth in the addendum size and therefore an increase in yield losses. This is evident in figure 2.16, figure 2.17 and figure 2.18, which show that for a very similar part the addendum surface has grown in each attempt at optimisation. The automotive fender addendum surface has been optimised by Makinouchi (1996), Shi (2004), and You (2001). In each case, no clear evidence is provided as to why the larger addendum surface is more effective. It is possible that the increase in addendum size is no better, just quicker to design.

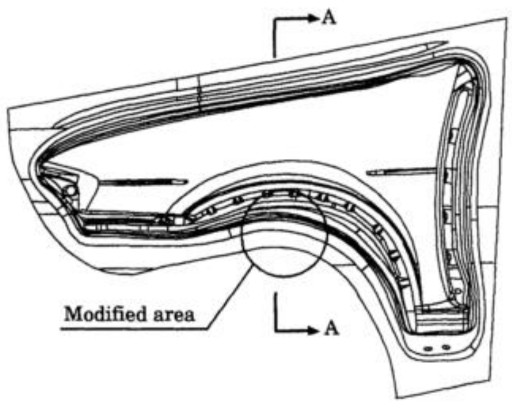



Figure 2.16 Fender addendum surface optimisation Makinouchi (1996).

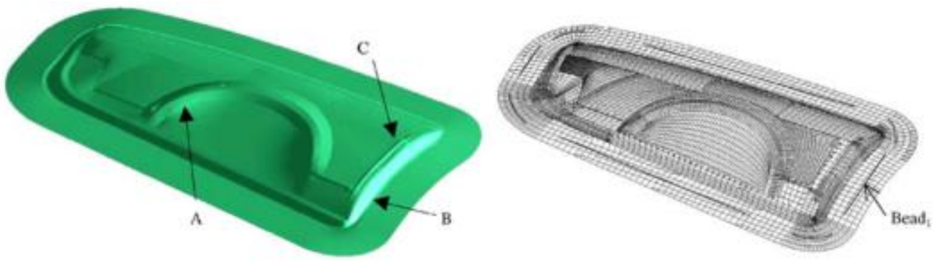



Figure 2.17 Fender addendum surface optimisation Shi et al, (2004).

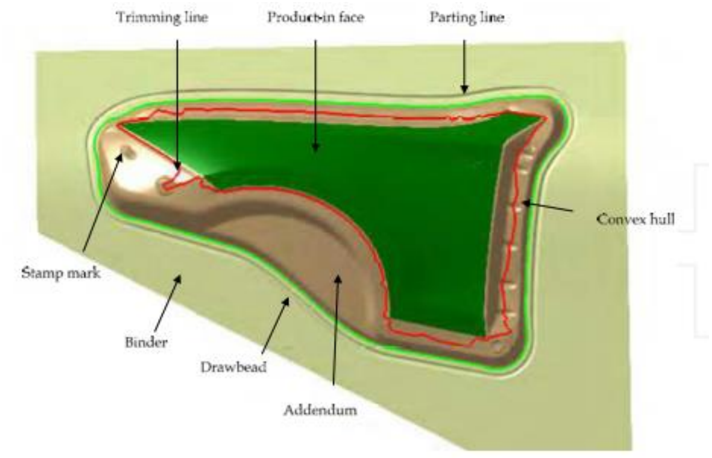



Figure 2.18 Fender addendum surface optimisation You et al. (2011).

Debray et al (2013) recognise that a good addendum surface should be designed to minimise material utilisation. However, their optimised design still includes excess material, as shown in figure 2.19. The addendum surface on this part could be reduced through forming the flanged material in the blank holder area rather than increasing the draw depth, as shown in figure 2.20.

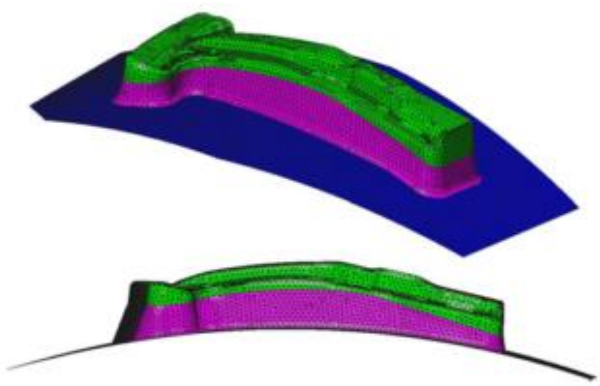


Figure 2.19 Addendum surface optimised for splits and wrinkles not material utilisation, Debray et al. (2013).

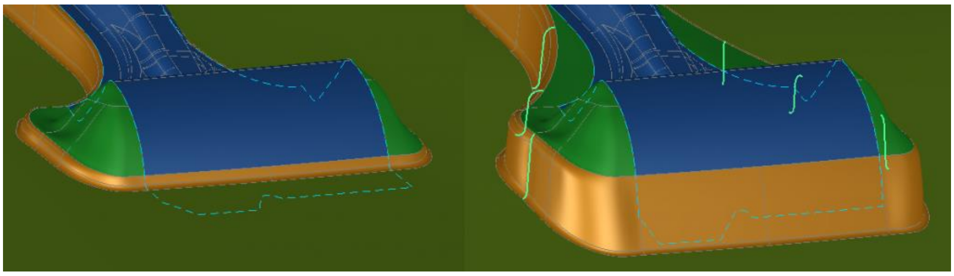


Figure 2.20 Reducing draw depth and addendum surface through forming the flange. (Heston 2010).

The addendum surface is greater for irregular parts which have large differences in height at the edges of the part. A variable blank holder height has been developed by Ingarao & Lorenzo (2010), to improve material flow control in forming an automotive component but their analysis did not consider the benefit of reduced material requirement. The component analysed is shown in figure 2.21. In the analysis of beadless stamping, Shim (2015) demonstrated that a variable height binder can reduce the size of the addendum surface through reducing the distance required to connect the part geometry to the blank holder. The use of variable blank holder heights in industry is limited to set shapes which are able to distribute the force evenly across the die. There is no academic discussion on the limits of variable binder height for industrial applications.

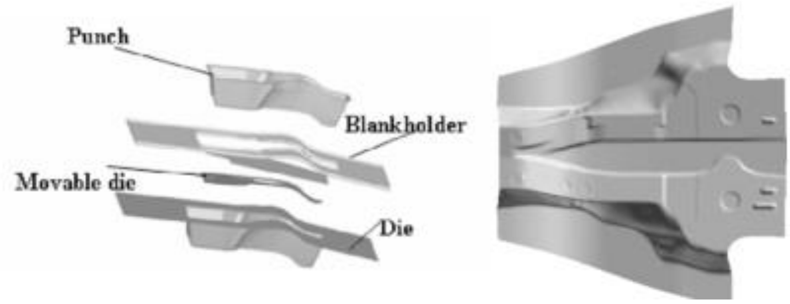



**Figure 2.21 Varied height binder surface shown in the blank holder punch and die Ingarao & Lorenzo (2010).**

The addendum surface has been optimised to reduce the time required to design a part which is free from failures. This has led to an increase in material use and addendum surface scrap. Existing techniques for designing flanges to reduce draw depth, and using a variable blank holder height provide opportunities to reduce the addendum size and scrap. Further research is required to fully understand the scale of the opportunity in implementing these techniques.

Material efficiency opportunities for the blank shape design are now considered.

### 2.2.5 Controlling Material Flow with the Blank Shape

The size and shape of the blank affects material flow. Excess material can be locally removed or added to the blank to prevent the formation of wrinkles or to allow material to flow to prevent splits. Previous research into the size of the blank is now reviewed to identify opportunities for material efficiency. Blank shape features, such as holes and contours, are then considered.

Toh & Kobayashi (1984) used experimental and numerical analysis to identify how the size of the blank affects the formability of a shaped part. They found if the blank holder area is too large the material flow into the die is restricted causing thinning or splits in the part, but if the blank holder area is too small the restraining force is insufficient, causing wrinkling. Gea & Ramamurthy (1998) demonstrated that by optimising the shape of the blank iteratively they could significantly increase the failure draw depth of a square cup, from 25mm to 55mm. In their development of an optimum blank shape for a square cup using finite element analysis, Park et al (1999) recognise that this relationship enables design of the blank size to prevent failure of the part during forming. The drawback of these optimisation methods is that authors tend to optimise the blank shape for formability and accept a good blank design, which does not result on part failure, as soon as it is found. These studies do not look to minimise the blank size to improve material efficiency. This can be seen in figure 2.22, where Gronostajski et al (2004) have optimised the blank size of a complex component using CAE, however the final blank still has excess material which will be scrapped after forming.

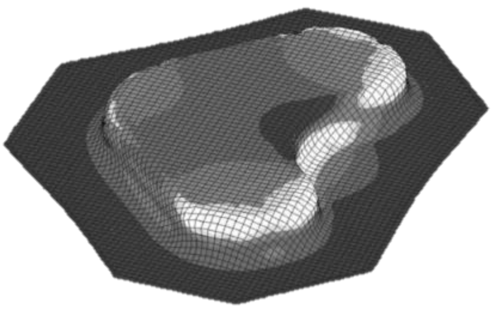


**Figure 2.22** **An optimised blank shape post forming from Gronostajski et al. (2004). The large regular blank holder area after forming suggests the size of the blank has not been minimised.**

Naceur et al (2004), Shim (2004) and Sattari et al (2007) develop the minimum required blank size to form specific part geometry. Naceur et al (2004) and Sattari et al (2007) minimise the blank holder area to form a square cup using finite element analysis. Both methods reduce the blank size iteratively until part failure and produce similar results. Results from the iterative passes by Naceur et al are shown in shown in figure 2.23. Shim (2004) identifies the minimum theoretical blank shape for a complex part from the automotive industry, as shown in figure 2.24, but feasibility is not considered and the minimum blank is later increased in Shim (2015).

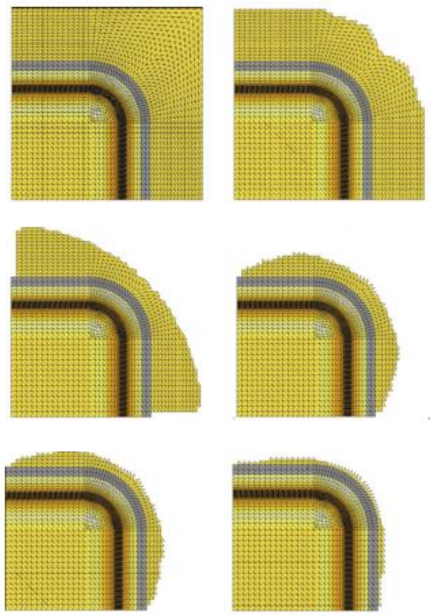


**Figure 2.23 Optimising the blank holder shape using an evolutionary algorithm. Naceur uses an evolutionary algorithm to analyse the corner of a square cup. The algorithm identifies a blank shape required to form a good part with no splits and wrinkles, then minimises the blank holder area iteratively until it impacts the formability of the part.**

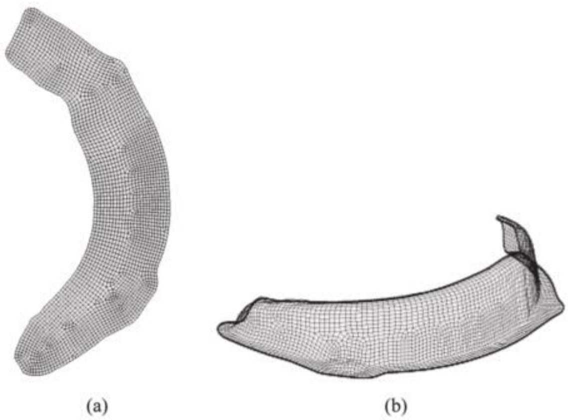



**Figure 2.24 Optimum blank shape (a) for complex formed part (b) Shim (2004). Blank size is minimised but the formability has not been considered, the blank size is increased to eliminate part failure in forming Shim, (2015).**

Work by Neceur, Shim and Sattari demonstrate an opportunity to reduce yield losses through minimising the size of the blank. However, these investigations do not go as far as identifying relationships between the part geometry and the material required to form the parts. Establishing this relationship would increase opportunities to minimise the blank holder area.

Blank design features identified in industrial applications are holes, slits, and a shaped perimeter of the blank. The design of these features will now be reviewed and opportunities for improving material utilisation identified.

A burst hole removes material inside the blank. This allows material to flow from multiple directions through an expansion of the hole during forming. Van der Hoven et al (1991) identified the need to add holes to improve drawing performance for a complex component. The size and shape of the holes in this study were developed through trial and error. Tailor welded blanks include holes in a complex blank shape produced from multiple small components. Figure 2.25 shows an example of tailor welded blanks used to make an automotive body side panel, published by the European Aluminium Association (2013).

**Figure 2.25 An automotive body side part and blank with a cut out. This part was developed for tailored welded blanks and has minimised material utilisation, image from European Aluminium Association (2013).**

It can be seen with this example, that investigation into tailor welding blanks has indirectly maximised blank cut outs and improved material utilisation. Cut outs and holes in the blank shape have been successfully used to improve formability and material utilisation. However, there has been no mathematical optimisation in the design of holes used to improve formability. This could provide an opportunity to minimise scrap through designing a blank which requires less material to form a component.

In a review of industrial best practice, Lascoe (1998) describes using slits to control material flow in a progressive die strip. The slit prevents material flow between two components on a continuous strip of material. The slit is expanded during forming as material is drawn from both sides, as shown in the example part in figure 2.26. This reduces material demand as the components can be manufactured on a long strip, reducing the blank holder area. There is an opportunity for conventional drawing to use slits to improve material flow control and reduce material demand. This opportunity has not yet been explored.

Figure 2.26 Use of slits to control material flow in progressive stamping. Image from Comec (2016).

Lo & Lee (1998) propose a theory of using contours in the design of the blank shape to improve the formability of a cup. They show mathematically that the shape of the blank perimeter can be designed to improve formability. This research has been extended in unpublished work by Charles Caristan, Taylan Altan and Serhat Kaya undertaken in 2006 at Ohio State University (referred to by Heston (2010)). Their study created a blank contour, for the corner of a square cup, which removed areas of excess material to prevent wrinkling, the contour designs for both studies are as shown in figure 2.27.

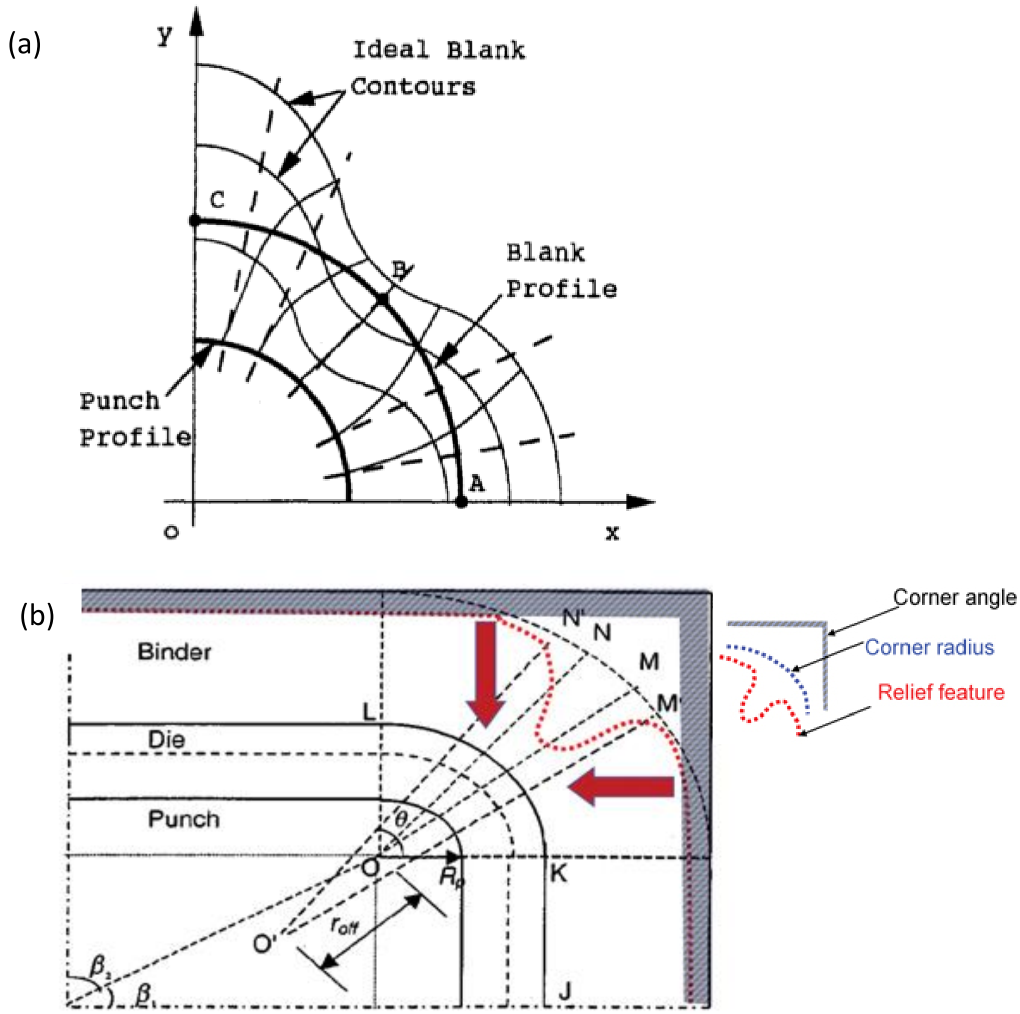



**Figure 2.27 Design of blank contour to prevent wrinkling. Images from (a)** Lo & Lee (1998)**, (b)** Heston (2010)**.**

Material at the corner of a cup is drawn in from the top and the side. Without restraining features such as draw beads, too much material can flow into the corner, causing wrinkles. Removing excess material through designing a blank contour prevents wrinkles without the need for these additional restraining features. Designing the shape of the blank to control material flow provides significant opportunity for reducing material requirement in stamping, but very little research has been published to exploit this opportunity.

For a study identifying the benefits of laser blanking, Caristan, Altan and Kaya (referred to by Heston (2010)) combined designing cut outs and the blank shape perimeter to improve the formability of an automotive door inner panel. They aim to enable forming without using draw beads in order to reduce the material required to form the part. Their methodology was not published, but the results are available and are shown in figure 2.28.

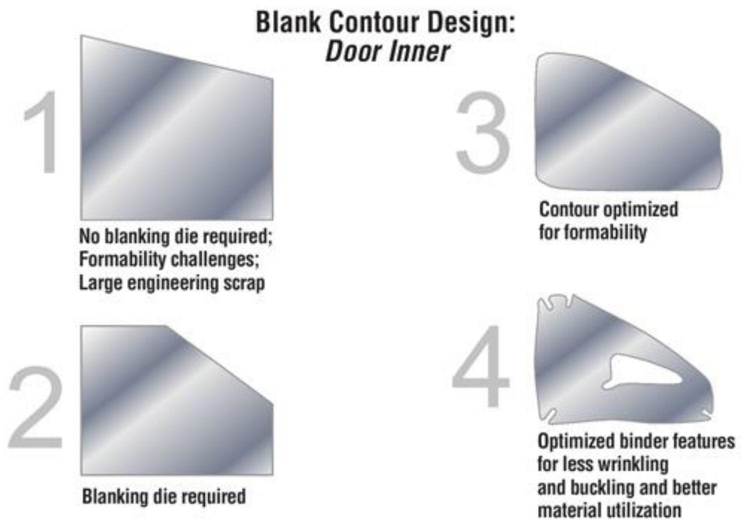



**Figure 2.28 Example of improving formability and material utilisation with holes and blank shape features image from** (Heston 2010)**.**

Material flow is controlled in industrial applications using holes, slits and designing the shape of the blank. However, very little is known about how design features affect material flow and to what extent they can be used to improve material utilisation. Consideration of the blank design for material flow control provides an excellent opportunity to reduce stamping scrap as unlike other forming design features additional material is not required for increased material flow control.

Previous research into the blank holder, draw beads, addendum surface and blank design are now summarised to conclude on the known opportunities for improving material efficiency during forming of sheet metal components.

### 2.2.6 Analysis of Material Flow Control Techniques

Material flow control using a blank holder, draw bead, addendum surface and blank shape has been reviewed. The design of these features directly affects the amount of scrap generated when forming a component. The review has found that these control methods have been developed to reduce costs, reduce development time and improve part quality, but material utilisation has not been fully considered. The control techniques identified are summarised in figure 2.29.

| | |
|---|---|
| **Blank Holder Design:**<br>Designing the size of the blank holder<br>Designing the shape of blank holder<br>Constant blank holder force<br>Time varied blank holder force<br>Spatially varied blank holder force<br>Pulsating/Electromagnetic blank holder<br>No blank holder force (crash form) | **Draw Bead Design:**<br>Designing the size of the draw bead<br>Varying the offset from tool parting line<br>Spatially varied draw bead size<br>Time varied draw bead size |
| **Addendum Design**<br>Optimising addendum surface<br>Forming flange in the blank holder<br>Varied height blank holder<br>Double attached parts | **Blank Shape Design:**<br>Cut outs in blank apertures<br>Contour designed blank outline<br>Blank shape features |

**Figure 2.29 Summary of material control techniques which could be exploited to improve the material efficiency of the forming process.**

The review revealed that there is a considerable opportunity to use these existing control techniques in a manner which reduces yield losses, but this opportunity has not yet been fully investigated. Stamping process scrap could be reduced through:

- Designing the minimum required blank holder area, using a variable blank holder force. If the blank holder size is considered together with the blank holder force, not only would scrap be reduced, it is likely that the formability of the parts would also improve.
- Increasing the use of crash forming. The geometrical limits of crash forming are not documented, so it is likely to be underutilised.
- Minimising the use of draw beads through designing them specifically for the geometry of the part. Draw beads should not be constantly applied around the perimeter, removing this simplification in the design process would reduce the blank size.

- Consideration of material use during addendum optimisation. The addendum surface could be reduced through designing flanges in the blank holder and using a varied height binder.
- Minimising the blank size through designing the blank periphery shape with features to control material flow.

There is an opportunity to improve material efficiency through considering the design of the forming process. This literature review will now consider material efficiency in the blanking process.

## 2.3 Material efficiency in nesting blanks

It has been shown in section 2.2.5 that the design of the blank shape can be optimised in order to improve the material efficiency of forming. In order to capture these opportunities, the blank must be nested efficiently on the coil from which it is cut. Previous research into nesting of blanks is now reviewed to identify opportunities for material efficiency in this area.

The shift from human to computerised processing in this problem field has driven the development of many software solution methodologies, commonly known as nesting algorithms. This review analyses the current capabilities of nesting algorithms, evaluating their effectiveness to minimise material use and identifying opportunities for material efficiency improvements in blanking. The design of the blank for nesting is evaluated in section 2.3.1. In section 2.3.2 the motivation and historical development of nesting algorithms is explored. The types of nesting problems and their characteristics are then identified in section 2.3.3. Algorithms for geometrical representation and optimising the positioning of parts are reviewed in sections 2.3.4 and 2.3.5 respectively. Finally, the opportunities for future improvements in material utilisation are identified in section 2.3.6.

### 2.3.1 Designing Parts to Nest

Nesting algorithms can be used to find the most efficient blank layout, but the blank shape directly affects the maximum possible material utilisation. This is demonstrated by Bennell & Song (2010) who benchmark 16 sets of parts which are commonly used to test nesting algorithms in literature. For some sets of parts they identify the best recorded material utilisation was 100%, but for others the best possible nesting layout still generates scrap. This is shown with two examples in figure 2.30. This section reviews how the blank shape has been modified to improve nesting.

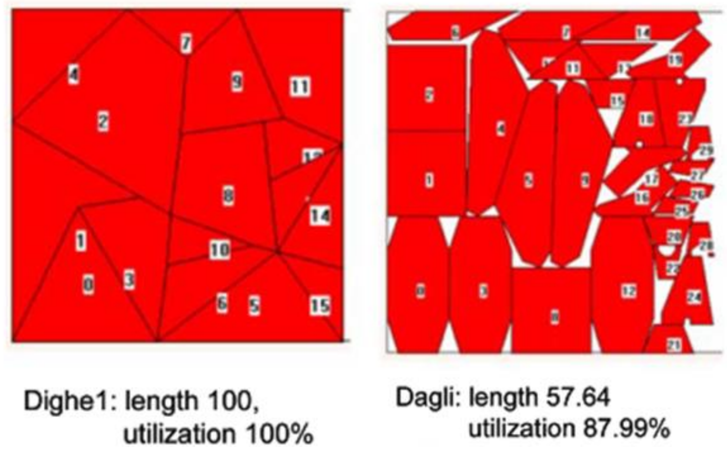



**Figure 2.30 Best possible nesting layouts for two benchmark data sets (Bennell & Song 2010).**

In an exploration of zero-waste-fashion, Rissanen (2013) identifies many examples where shapes of parts in garments are designed to eliminate waste in the nesting layout. An example is shown in figure 2.31. This approach to design will reduce blanking scrap, but it does not necessarily reduce the material demand. Excess material can be designed into the blanks increasing the material intensity of the part.

**Figure 2.31 Zero waste dress by Mark Lui, 2007.**

Through observing one human nester at work, Jones (2014) finds that textile nesters will violate part orientation constraints by a few degrees to allow closer nesting and reduce the material requirement, though this opportunity was not quantified. Relaxing orientation constraints where possible could improve material utilisation.

Mckune & Palanisamy (2007) identify material saving opportunities for specific components in the automotive industry through breaking blanks into smaller shapes to allow closer nesting on the coil. The example shown in figure 2.32 reduces material demand by 25% by producing two smaller blanks which are subsequently laser welded to form the desired blank shape. Mckune & Palanisamy (2007) identify significant opportunities for scrap reduction, as well as increased flexibility in material selection and reduced costs.

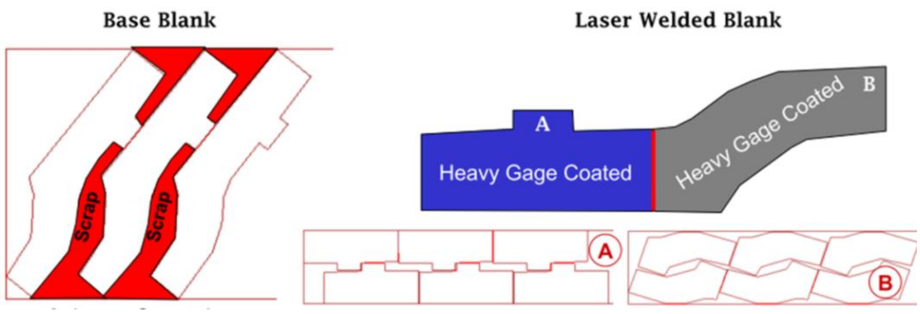



Figure 2.32 An automotive example using laser welded blanks to reduce material demand (Mckune & Palanisamy 2007).

The shape, orientation and construction of blanks have been modified to reduce yield losses in nesting. The literature reviewed shows significant opportunity to design the blank to reduce yield losses and material demand.

Previous research into nesting algorithms is now reviewed to identify the extent in which existing algorithms are able to optimise the layout of a given set of blank shapes.

### 2.3.2 Introduction to Nesting Algorithms

Nesting algorithms are mathematical analysis tools which improve material utilisation when cutting blanks from a sheet stock. Optimising the nest of blanks on the coil forms an area of problem solving called the 'two dimensional irregular cutting stock problem' where nesting layouts are optimised to use as little material as possible, as shown in figure 2.33. The two dimensional irregular cutting stock problem is also known as:

- 2D RCSP (two dimensional residual cutting stock problem)
- Irregular strip packing problem

- Nesting problem
- Leather nesting problem
- Irregular shape packing problem
- Marker making
- Trim Loss Problem

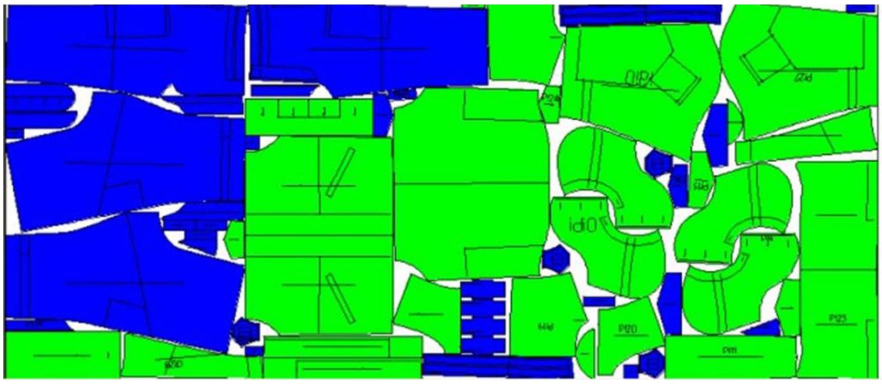


Figure 2.33 Example of a nesting layout in the textiles industry, a process referred to as marker making.

The development of nesting algorithms has been motivated by the opportunity to reduce material costs. Martins & Tsuzuki (2010) observed that a small improvement in material utilisation can create large financial savings for mass-production industries and Licari & Lo Valvo (2011) observed large saving opportunities for applications which use rare or expensive materials. The environmental opportunity associated with material efficiency was identified by Gomes & Oliveira (2006), who stated waste minimisation as a motivation for developing nesting algorithms.

Nesting algorithms can be traced back to paper manufacturing. Brooks et al (1940) developed an efficient way of reducing rolls of paper into sheets, wasting as little material as possible. This work prompted significant research in the field of nesting. In a bibliography of nesting algorithms Sweeney & Paternoster (1992) identified 45 journal articles which were published on this problem across the previous two decades. Haims & Freeman (1970) used nesting algorithms to solve problems in metal and leather cutting. This was the first investigation of nesting irregular shapes. However, Haims & Freeman's methodology approximated irregular shapes as rectangles, so the solution was very similar to those developed for the regular shapes in the paper cutting industries. Nesting algorithms for irregular shapes require more complex mathematics to represent the geometry of the part and detect a collision. Advances made by Pfefferkorn (1975) enabled the representation of irregular parts using convex polygons. Collision detection was developed by Adamowicz & Albano (1976) using method known as the No-Fit-Polygon. These methodologies will be described in section 2.3.3. These mathematical advancements enabled nesting algorithms to be applied to irregular shapes such as those in ship design, and metal cutting, solved by Albano & Sapuppo (1980) and the manufacture of clothing, solved by Farley (1988).

These nesting algorithms, which were developed to improve material utilisation in paper manufacture, have been extended to meet the needs of other industries. For example, the sheet metal and textile industries which nest and cut irregular shapes. The large number of applications creates many varied problems. How these problems are classified based on their characteristics will now be identified.

### 2.3.3 Defining Nesting Problem Characteristics

In their tutorial of nesting problems Bennell & Oliveira (2008) observed a wide range of applications for nesting algorithms. Alves et al (2012) state that nesting algorithms share many characteristics between different applications, making it beneficial to analyse nesting problems by their characteristics rather than their application. This section breaks down these characteristics as objective functions, constraints and performance criteria.

The objective functions for nesting problems are based on material utilisation and time. The majority of papers reviewed aim to maximise material utilisation. Bennell & Song (2010) and Leung et al (2012) developed nesting algorithms which minimised the length of material used, whilst YuPing et al (2009) and Lidong & Jiawei (2010) developed algorithms which maximised the number of parts positioned in a given stock length. Costa et al (2009) and Weng & Kuo (2011) used a combination of both objectives. In some applications, the time to find a solution was stated as being important.

MirHassani & Bashirzadeh (2015) developed a nesting algorithm to solve leather cutting problems with the objective function to minimise the computational time to achieve an acceptable material utilisation. Similarly, Domović et al (2014) developed a nesting algorithm which maximises material utilisation in a given processing time. The trade-off between time and utilisation is managed through the selection of the algorithm methodologies. This is discussed in sections 2.3.4 and 2.3.5.

Problem constraints are rules which govern the specific application of a nesting algorithm. The constraints for nesting algorithms, identified from an extensive review of previous research in this field, are listed with examples in figure 2.34.

| | |
|---|---|
| **Stock Size and Shape Constraints:** | |
| Width variability of the stock. | Slit metal coils |
| Discrete or Continuous stock | Leather hides/fabric roll |
| Regularity of Stock geometry | Leather hides/fabric roll |
| Multiple or singular stock | Small metal offcuts/one large plate. |
| **Part Size and Shape Constraints:** | |
| Number of different parts | Sheet metal blanks/garment pieces |
| Complexity of part geometry | Ship building/leather furniture |
| **Placement Constraints:** | |
| Quality requirements of stock and parts | Defects on leather hides |
| Placement within the stock boundary | All parts. |
| Part overlap | All parts |
| Part orientation | Directional fabric |
| **Implementation Constraints:** | |
| Time restrictions | Automotive leather |
| Part demand requirements | Garment sizes are demand driven |

Figure 2.34 Cutting and packing problem constraints and examples.

The suitability of a nesting algorithm depends on the problem constraints because they determine the size of the problem. Li & Milenkovic (1995) prove that the irregular cutting stock problem is NP hard. This means that the size and complexity of generating a solution increases exponentially with the size of the problem. The constraints which have the biggest impact on the problem size are: the number of different parts as identified by Costa et al

(2009); the complexity of the part geometry as reviewed by Bennell & Oliveira (2008); flexibility in the part orientation, which Martins & Tsuzuki (2010) evaluated as being large since it requires a discrete evaluation of a continuous problem. How each nesting algorithm methodology manages these constraints is identified in sections 2.3.4 and 2.3.5. Whilst the objective function usually maximises material utilisation, the success of an algorithm was often assessed on how quickly the solution is found. Costa et al (2009) and Martins & Tsuzuki (2010) both used this performance criteria to evaluate their nesting algorithms. In contrast, Gomes & Oliveira (2006) and Jones (2014) evaluated how reliably a good result is determined, whereas MirHassani & Bashirzadeh (2015) measured success on how large a problem can be solved. Performance measures for cutting stock problems are a combination of material utilisation, time, reliability and scalability.

The objective functions, constraints and performance measures identified in this section determine the problem characteristics. Identifying these problem characteristics allows comparison between algorithm methodologies when the application is different. The suitability of geometrical representation algorithms and position optimisation algorithms will now be assessed against these problem characteristics.

### 2.3.4 Geometrical Representation in Nesting Algorithms

In order to determine whether a part can be placed in a given position a check must be made to ensure the problem constraints are met. A human nester can easily make this check by looking at the parts, but for a computer a system of geometrical representation is needed to check for collisions and determine the distance between parts. Methods of geometrical representation are:

- Enclosing rectangles,
- Raster representation,
- Direct trigonometry
- No-fit-polygon

These methods are evaluated using the example parts shown in figure 2.35 as a demonstration.

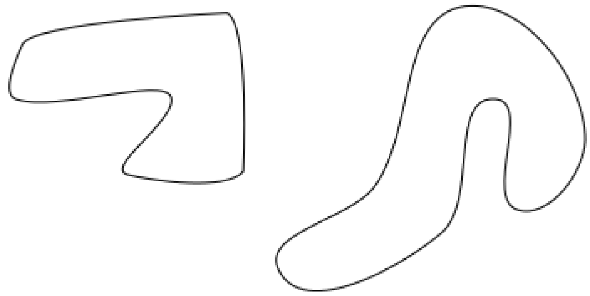


Figure 2.35 Example parts for investigating nesting algorithms.

### Enclosing Rectangles

The method of enclosing rectangles was applied to irregular nesting problems by Haims & Freeman (1970) as a concept for representing irregular parts more simply. Irregular shapes are approximated as the minimum possible enclosing rectangle, figure 2.36. Interaction between parts is determined through checking each line for an intersection.

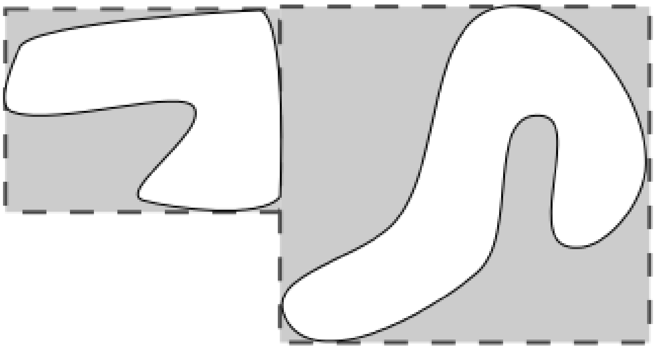


Figure 2.36 Enclosing rectangles geometric representation.

Rounding up the part size to an enclosed rectangle can greatly reduce the material utilisation produced by a nesting algorithm. Lidong & Jiawei (2010) recognise that for plate cutting applications, where shapes are inherently rectangular, these rounding losses are minimal. Simplification to enclosing rectangles enables a quick solution generation, even with complex constraints such as freedom of rotations and large numbers of different parts, as each part has only four vertices to check for a collision.

### Raster Representation

First applied to irregular nesting by Maria & Braga (1986), raster methods represent geometric information as a grid, figure 2.37. Collision detection and the distance between parts are calculated by counting cells in the grid.

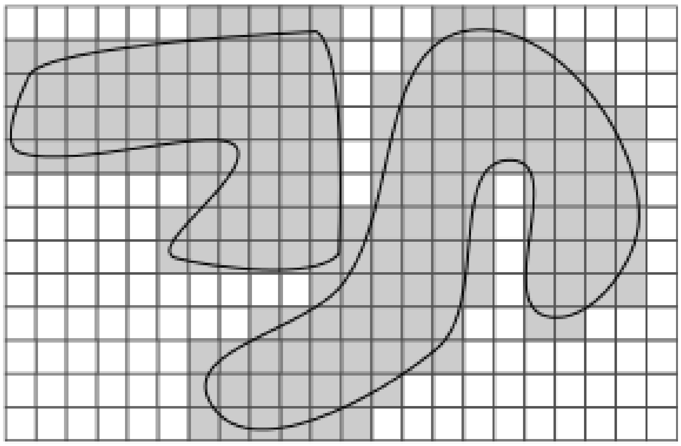


**Figure 2.37 Raster geometric representation.**

Accurate part representation can achieved through a small grid. Siasos & Vosniakos (2014) recognise that this improves material utilisation at the expense of an increased processing time. In raster representation the number of processing steps is linked to the number of grid cells, not the shape of the part. Baldacci et al (2014) exploit this characteristic to develop a nesting algorithm which solves for complex shapes and defects without the requirement for additional processing time. These reduced processing requirements allow large numbers of parts and stock sheets to be processed in the nesting algorithm originally developed by YuPing et al (2009). This method of geometrical representation is becoming increasingly popular. In their review of nesting algorithms MirHassani & Bashirzadeh (2015) found the use of raster representation has increased in recent publications.

### Direct Trigonometry

Proposed by Pfefferkorn (1975) and developed by Albano (1977), the direct trigonometry method represents parts using vertices for polygon approximation, figure 2.38. Trigonometry is then used to determine the interaction between parts through checking each line for an intersection.

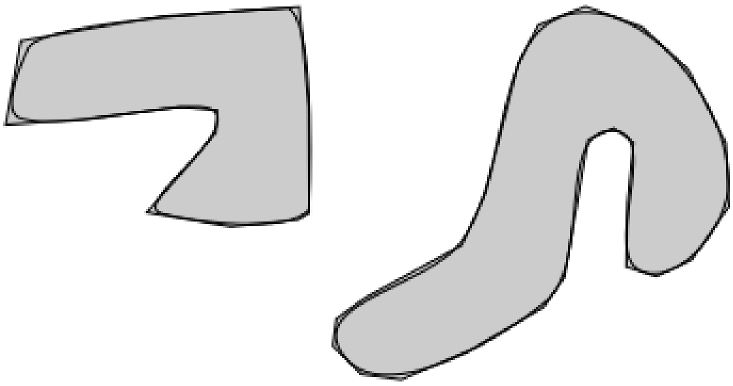


Figure 2.38 Polygonal geometric representation for direct trigonometry.

The resolution can be improved through increasing the number of vertices in the polygonal representation. Accurate representation enables high material utilisation values, but has a high computational cost. Direct trigonometry is therefore not suitable for large problems, complex shapes or multiple orientations. However, it is used by Yuping et al (2013) due to the simplicity of the shapes being nested.

### No-Fit Polygon

The no-fit-polygon is the most commonly used method of geometric representation. First introduced by Adamowicz & Albano (1976), the no-fit-polygon represents the space in which two parts can be positioned without colliding. It is generated by tracking a reference point on one part as it slides around the other part using polygonal geometric representation, figure 2.39. Collisions and distance between parts are detected by an intersection with the no-fit-polygon. Bennell & Song (2010) considered the no-fit polygon to be the best method of geometric representation since the accurate representation of parts maximises the potential material utilisation. The no-fit polygon can be calculated more efficiently than direct trigonometry, through the application of Minkowski Sums (or vector sums) developed by Martin & Stephenson (1988). However, the no-fit polygon must be calculated for every combination of parts and orientation. Therefore Bennell & Oliveira (2009) recognise that it is not suitable for large complex problems.

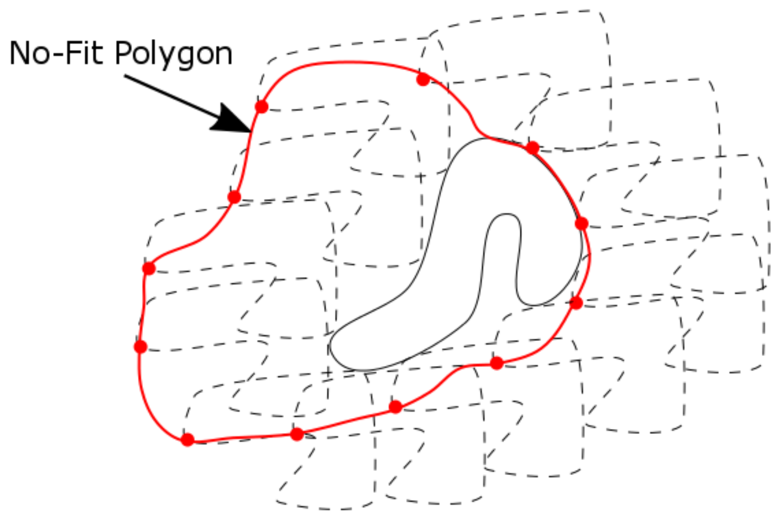



Figure 2.39 Geometrical representation using the No-Fit Polygon.

A related concept to the no-fit-polygon is the inner-fit-polygon, which represents the area in which one polygon can fit within another. The inner-fit-polygon is used by Costa et al (2009) and Alves et al (2012) to assess spaces on the stock sheet to evaluate if a part can be positioned.

Previous work has revealed that each method of geometrical representation has advantages and disadvantages, and selection depends on the problem characteristics. Raster representation is the best methodology for large complex problems which can accept a reduced material utilisation to achieve a solution in a reasonable time. Whereas the no-fit-polygon is better for small simple problems which require an accurate solution or where time is not limited.

### 2.3.5 Position Optimisation Nesting Algorithms

Position optimisation algorithms use the geometric representation to position parts and generate a layout. There are three main categories of solution methodologies, heuristics, meta-heuristics and exact algorithms. These will be evaluated in turn.

#### Heuristic Methodologies

Heuristic methodologies interpret the geometrical representation and generate an initial feasible solution.  Part selection and positioning is based on a given sequence. Gomes & Oliveira (2006) use the most common heuristic placement method, selecting the largest part first and position it in the bottom left of the stock material, figure 2.40. Lidong & Jiawei (2010) claim a more effective method is to match parts into similar shaped pairs before positioning, figure 2.41.

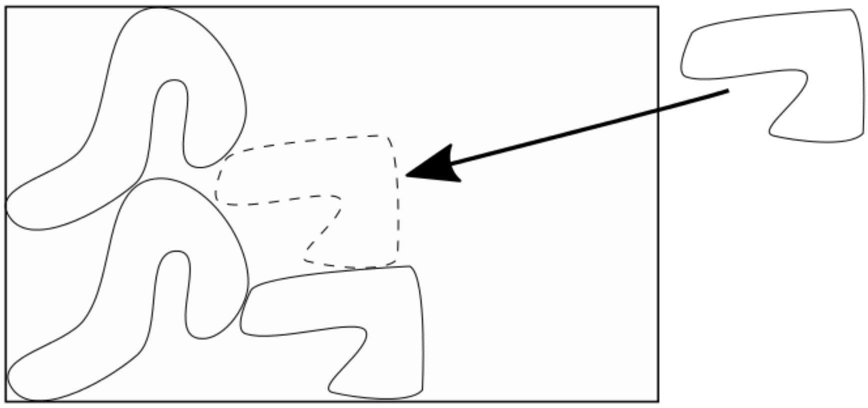


**Figure 2.40 Heuristic placement using largest first and bottom left placement algorithms.**

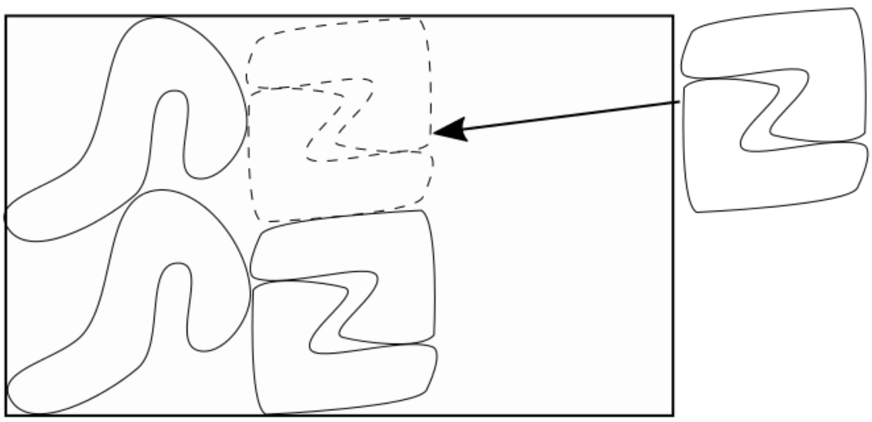


**Figure 2.41 Heuristic placement using matching pairs.**

Heuristics optimise the position of each part as it is placed, locally minimising the utilisation. Baldacci et al (2014) claim that a heuristic algorithm is quicker than a metaheuristic as parts are placed with fewer computational steps. The simplicity of heuristic methodologies allows these algorithms to be scaled up to solve large problems with many constraints.

### Meta-Heuristic Methodologies

Meta heuristics optimise an initial solution through changing the position, orientation or sequence of part placement, as shown in figure 2.42. Meta-heuristics sample the solution space with changes and guide the evaluation process towards good solutions. The meta-heuristics used to solve the irregular cutting stock problem are Search Based Algorithms and Evolutionary Based Algorithms.

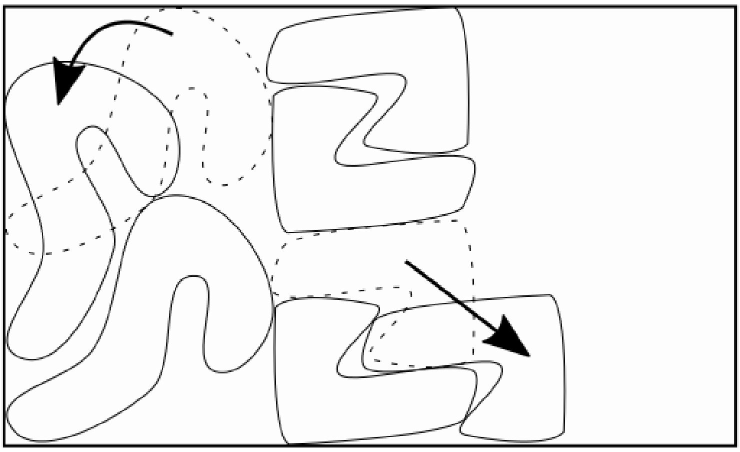


Figure 2.42 Placement improvements using a meta-heuristic.

Through this sampling approach, Hopper & Turton (2001) use a meta-heuristic to produce a better material utilisation than a heuristic algorithm at the expense of an increased processing time. Bennell & Oliveira (2009) found the processing time could be reduced through combining a metaheuristic with a simple geometric representation, and Domović et al (2014) implemented a time limit to ensure the solution was produced within process constraints. Meta-heuristics are less repeatable than heuristics. Different solutions can be found each time the algorithm is run. Meta-heuristics can be unreliable if the algorithm identifies local minima, generating a poorer result. This has been avoided through additional computational steps. Ramakrishnan et al (2008) modified a search based algorithm to escape local minima through the addition of a penalty system and Alves et al (2012) added a randomisation step. Genetic algorithms have been modified by Yuping et al (2012) to avoid local minima through the addition of simulated annealing to the mutation feature.

### Exact Methodologies

For small nesting problems Licari & Lo Valvo (2011) and Dalalah et al (2014) identified all possible placement positions for every sequence selecting the solution with the minimum waste. Through this an exact algorithm finds the global minimum solution. Exact solution methodologies reliably generate the best possible material efficiency for a given part representation, at the cost of a long processing time. The ‘NP hard’ nature of the cutting stock problem means that exact solutions can only be calculated for a very small number of simple parts. MirHassani & Bashirzadeh (2015) found that an exact methodology can solve for a maximum of 7 different parts.

It has been shown that no single optimisation methodology dominates. Exact algorithms are suitable for simple problems with no time constraints. Heuristics are able to manage large complex problems with many constraints, and meta-heuristics are best at solving problems in the middle. The combination of geometrical representation algorithms and position optimisation algorithms should be considered when selecting an algorithm as the nesting performance if affected by both steps.

### 2.3.6 Analysis of Nesting Algorithms

In the 50 years since the introduction of nesting algorithms many different methodologies have been proposed to solve a wide range of problems. Selection of the best methodology depends on the objective, constraints and performance criteria of the application. This section will analyse nesting methodologies with respect to material utilisation and identify opportunities for future improvement.

Whether an algorithm can maximise material utilisation depends on how accurately the parts are represented and how effective the placement optimisation is. The solution methodologies with the best material utilisation are those which combine exact geometric representation (using the no-fit-polygon or direct trigonometry) and an exact optimisation algorithm. This was done by Alvarez-Valdes et al (2013) and Santoro & Lemos (2015). Exact algorithms are able to provide the highest material utilisation, but they have only been developed to solve small problems. There is an opportunity for growth in the size of solution solved by exact algorithms. Meta-heuristics solutions appear to be converging on the likely limit of material utilisation.

Improvements in meta-heuristic algorithms are unlikely to generate significant improvements in material utilisation and would not be a priority for future research. It was observed that human nesters use informed judgement to break problem constraints and design the part geometry to improve the material utilisation of a nest.  This flexibility has not been implemented in algorithms for automated nesting software. There is an opportunity to improve material utilisation through relaxing placement constraints and designing parts for efficient nesting.

Nesting algorithms have been extensively optimised. Current algorithms using polymer representation and exact or meta-heuristic placement strategies are converging on the maximum possible material utilisation. It is unlikely that further algorithm development will significantly improve material utilisation of automotive sheet metal components. The greatest opportunity for improvement is through relaxing problem constraints and designing parts for better nesting.

The literature reviews of nesting blanks and forming parts both identified an opportunity to improve material utilisation through modifying the design of the component.  Existing knowledge of how components can be designed to be material efficient is now reviewed.

## 2.4 Material efficiency in component design

Sections 2.2 and 2.3 identified opportunities to improve component material utilisation through the design of the forming and blanking processes. Previous research conducted in both areas also revealed that the component geometry influences the material efficiency opportunity. Previous research is now reviewed to investigate how material efficiency is considered during the design of component geometry. Section 4.4.1 describes the product development process and identifies stages in which material efficiency is considered during this process. Section 2.4.2 reviews the existence of and potential for design guidelines which could be used to support engineers in the design of component geometry which can be manufactured with improved material efficiency. In order to design component geometry for material efficiency variables which affect the forming limits need to be considered. These variables are reviewed in Section 2.4.3. Section 2.4.4 summarises the known opportunity to improve material efficiency through the design of component geometry.

### 2.4.1 How is material efficiency considered in component design?

Section 1.1 identified financial and environmental benefits for the automotive industry to improve the material efficiency of sheet metal components. The motivation to improve the use of material utilisation is reflected as a key performance indicator in the production of sheet metal components, as identified by Behrens & Lau (2008) through a survey of manufacturing organisations. The product design process is now reviewed to identify how and when material efficiency is considered in the design of component geometry.

Automotive design activities follow a stage-gate process to organise product development from concept to component manufacture, shown in figure 2.43(a), and described in Ettlie & Elsenbach (2007). Automotive engineers design multiple vehicles to be made on one manufacturing platform, as shown in figure 2.43(b). Where possible, parts are designed to be shared between different vehicle lines and models (Verhoef et al. 2012). Decisions which affect material utilisation are made when the platform, vehicle line and model are being designed.

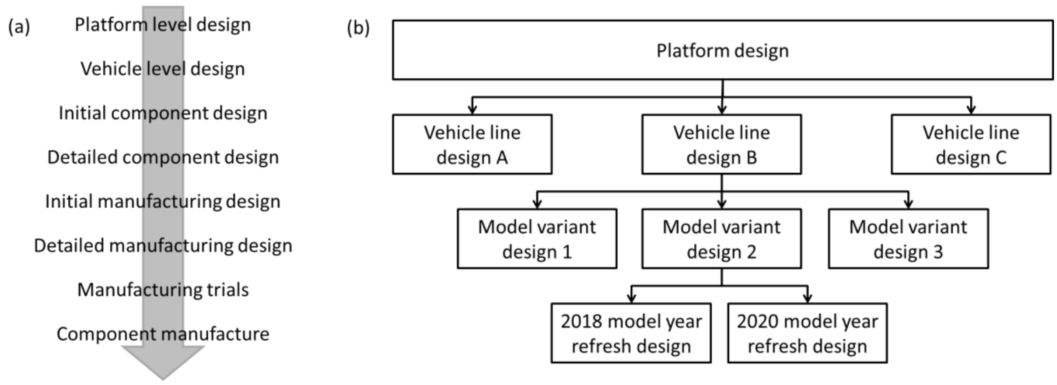



**Figure 2.43 Structure of product design activities in the automotive industry.**

Material utilisation is one of many objectives automotive engineers are required to meet, Belecheanu et al. (2006) map the complexity of multiple design trade-offs in the automotive industry to provide the wider context of product development decision making. For example, parts are designed under time constraints to meet cost and strength requirements. Material efficiency is not specifically included in their review. Azevedo (2013) also evaluates the performance criteria in the design of automotive components and includes environmental cost in their analysis.

In their proposal of a systematic approach to designing components for material and process efficiency, Edwards (2003) observe that design for material utilisation can be achieved with expert knowledge and experience. However, the opportunity at each stage in the product development process has not yet been quantified. Lewis et al. (2001) recognise an increasing 'cost-lock-in' of environmental impact through the product development cycle which dictates that the earlier the decision the greater the improvement opportunity. Despite this knowledge of product design 'lock-in', improvement of material utilisation is typically considered to be a manufacturing activity.

Previous research has identified that component geometry has an impact on material efficiency and material utilisation should be considered throughout the product development cycle. The automotive industry should be motivated to improve material utilisation early in the product development process alongside other product development requirements. Existing research into how this can be achieved through a design guideline is now considered.

### 2.4.2 Guidelines for material efficient design

As described in section 1.1, the automotive industry is motivated to improve material utilisation alongside other product development requirements. It should be possible to reduce the amount of scrap generated in forming sheet metal components by designing within geometric forming limits for material efficient processes. As described in section 2.2, manufacturing a component which can be drawn without a blank holder or draw beads is more material efficient than a component which requires this additional material to be drawn without failure. Determining geometric forming limits for these processes would enable component designers to make decisions for material efficient manufacture

Sheet metal forming limit diagrams are used to predict whether a component can be manufactured without failing. Forming limits are typically predicted prior to manufacturing by combining Finite Element Analysis (FEA) predictions of the strain distribution with experimentally determined forming limit diagrams specific to the work-piece material. This approach requires both the part geometry and the manufacturing process to be fully specified prior to the formability analysis to enable strains to be calculated. Therefore, formability analysis can only takes place late in the product development cycle when the design is near completion, shown in figure 2.44. This is too late to influence design for material efficiency.

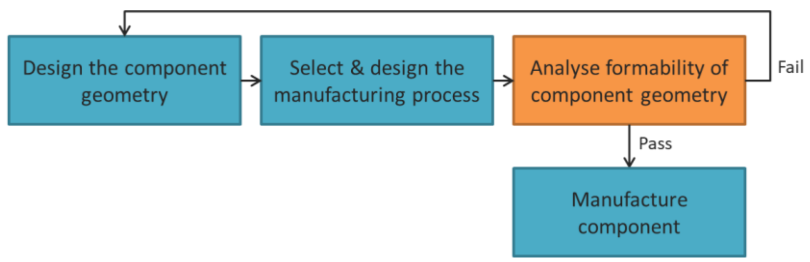



**Figure 2.44 Formability analysis usually takes place after the component has been designed.**

The presence of geometry based formability guidelines would allow failure to be predicted before the component geometry has neared completion and therefore would inform geometry and process selection decisions. Informed decisions would then take place earlier in the product development cycle when there is greater scope for change, as shown in figure 2.45. Early consideration of formability would save time, cost and improve material utilisation by allowing better optimisation of the component design.

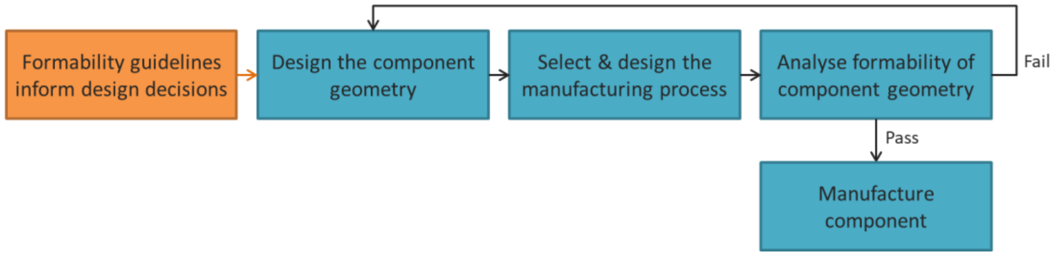



**Figure 2.45 Considering formability early in the production process can support design for manufacture.**

Previous research on the Limiting Drawing Ratio (LDR) and radius based forming limits are now reviewed as existing methods of predicting failure which could be used early in the product development cycle

### Estimating failure depth from component geometry

Guidelines for geometric forming limits are less accurate at predicting failure than Finite Element Analysis (FEA) because they do not predict the forming strains. However, they are useful to inform component designers of process formability in the early stages of product design when a full analysis of forming strains is not possible. Two measurements which could be extended to generate a formability guideline from component geometry are the Limiting Drawing Ratio (LDR) and radius based forming limits. Previous work on these techniques is now considered.

The most commonly used method of predicting failure using the component geometry is the Limiting Drawing Ratio (LDR). Originally developed for analysing forming limits of cylindrical cups, the LDR is described by Chiang & Kobayashi (1966)as the ratio of the blank width and maximum cup height. The theory has been extended to consider the maximum height of square cups, where the LDR is also the ratio of the blank width and the maximum cup height. For example, Marumo et al. (1999) use the LDR to investigate the effect of strain hardening on maximum draw depth, and Özek & Ünal (2011) calculate the LDR to evaluate the impact of changing the blank holder force and the punch radius when drawing square cups. Whilst the LDR has been proven to be a useful tool to evaluate the impact of changing forming variables on the maximum draw depth, it is not an appropriate measure to guide design decisions on component geometry as the calculation depends on the starting blank size not the component geometry size. Inclusion of a flanged region skews the LDR as the starting blank must be larger. The LDR, as applied to-date, is only appropriate when all material is drawn into the part. Therefore it is not suitable for predicting failure in complex shapes when additional material, such as a blank holder, is required.

Formability information for component designers can be found in knowledge based industry guidelines. Zein & Shazly (2013) refer to geometric forming limits for cylindrical cups based on a design code. Their guidelines suggest the maximum value for geometric variables such as the punch and die radius given as a function of material thickness. Similarly, Suschy (2006) provide guidelines for the maximum draw depth for different corner radii, plotted in figure 2.46. Both of these guidelines only considered one variable at a time; and do not provide sufficient certainty over what combination of punch, die and corner radii will result in success or failure during forming.

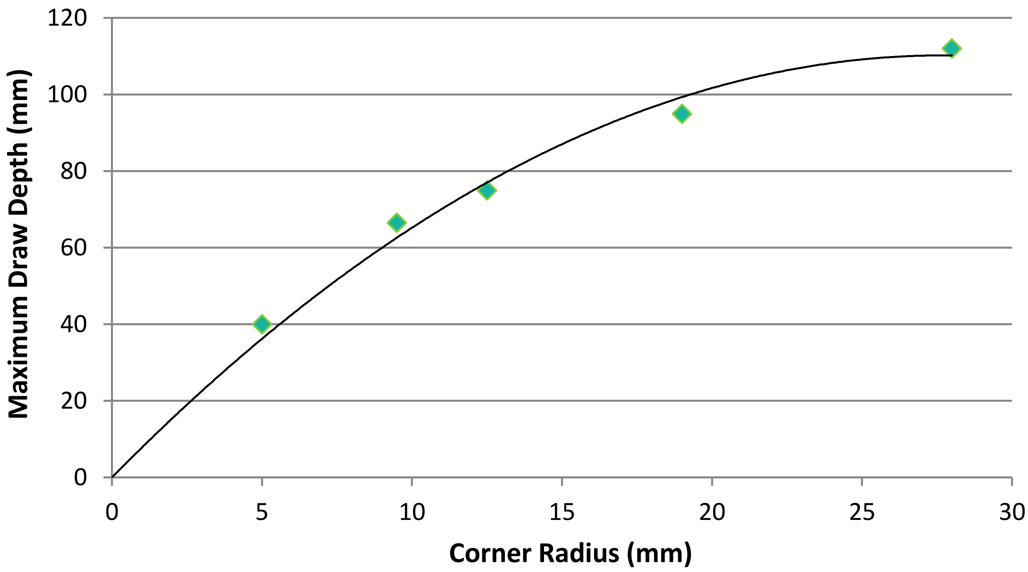



Figure 2.46 Maximum draw depth for increasing corner radius plotted from data in (Suschy 2006)

Sheet metal forming limits are now reviewed to establish if sufficient information can be extracted from previous research to generate a formability guideline which combines multiple geometry based metrics.

## What design guidelines could we infer from existing studies?

Many studies have been undertaken to identify the maximum draw depth of a square cup. The geometries investigated and the corresponding failure depths are summarised in table 2.2.The maximum draw depth from these studies cannot be directly compared because the forming variables are not constant between studies and the failure criteria are different for each paper.

**Table 2.2 Existing studies investigating the maximum draw depth of square cups**

| Study | Material | Yield strength (MPa) | Material thickness (mm) | Punch radius (mm) | Die radius (mm) | Corner radius (mm) | Max. depth (mm) | Failure criteria | |
|---|---|---|---|---|---|---|---|---|---|
| Demirci et al. (2008) | Aluminium | 104 | 2.0 | 10 | 10 | 10 | 38 | wrinkle height | 0.1mm |
| Firat (2012) | Steel | 390 | 1.0 | 12 | 12 | 13 | 49 | thinning strain | necking onset |
| Foudeh et al. (2013) | Aluminium | 104 | 2.0 | 10 | 14 | 10 | 40 | wrinkle height | 0.1mm |
| Hongsheng et al. (2009) | Aluminium | 91 | 1.0 | 3 | 4 | 5 | 27 | thinning strain | fracture |
| Hsu & Lee (1976) | Steel | - | 1.2 | 13 | 6 | 6 | 65 | thinning strain | fracture |
| Huang et al. (2008) | Steel | 163 | 0.6 | 5 | 6 | 5 | 55 | thinning strain | 33% |
| Özek & Ünal (2011) | Steel | 195 | 0.9 | 12 | 12 | 6 | 65 | thinning strain | 27% |
| Saxena & Dixit (2010) | Aluminium | 280 | 0.9 | 8 | 5 | 10 | 5 | wrinkle onset | stress criteria |
| Sener & Kurtaran (2016) | Steel | 309 | 0.8 | 20 | 35 | 47 | 75 | thinning strain | 26% |
| Takuda et al. (2003) | Steel | 590 | 1.2 | 10 | 10 | 10 | 27 | thinning strain | fracture |
| Yao et al. (2000) | Steel | 175 | 0.8 | 10 | 10 | 10 | 31 | thinning strain | fracture |

Whilst many studies have been undertaken into the forming limits in sheet metal drawing, it is not currently possible to analyse this information to identify geometric forming limits for the interaction of the punch, die and corner radius. In order to estimate the maximum draw depth from the component geometry the influence of variables relating to the design of the manufacturing process should be controlled. These variables are now considered.

### 2.4.3 Variables which affect forming limits

Variables within sheet metal forming can be organised into three categories, the manufacturing design parameters, the manufacturing process parameters and the component design parameters. These are now considered in turn.

Manufacturing design parameters include the design of the addendum surface, draw beads and blank shape, which all affect the flow of material during the manufacturing process and can be designed to enable a complex part to be formed without failure. The design of these parameters influences sheet metal forming limits. Chen et al. (2010) provide a detailed review of studies optimising the addendum surface for sheet metal components. Li & Co (2000) demonstrate that the draw bead design can affect the failure draw depth in their development of variable draw beads. Kitayama et al. (2015) and Iseki & Sowerby (1993) demonstrated that optimising the blank shape can increase forming limits and Pranavi et al. (2016) found that reducing the blank size from 200mm square to 150mm square increased the maximum draw depth of a square cup from 13mm to 23mm. To eliminate these manufacturing design parameters, further study should not include an addendum surface or draw beads, and the blank size should be optimized for each geometry being studied.

Manufacturing process parameters are variables which describe the tool set up such as draw speed, tool clearance, lubricant and blank holder force. Changing these variables changes how material flows in the drawing processes and therefore affects the failure depth. Browne & Hillery (2003) found that increasing the draw speed reduced the maximum draw depth of cylindrical cups. Ma & Huang (2014) demonstrate that the clearance between the punch and the die affects the rate of wrinkling and thickening in their investigation of tool clearances for drawing of a complex automotive component. Zein & Shazly (2013) observed that varying the lubricant type and coefficient of friction affected the material thickness after forming. Many studies have evaluated how the blank holder force affects forming limits, and Obermeyer & Majlessi (1998) provide a thorough review of these studies. To control the effect of manufacturing process variables, the blank holder force should be optimised and the draw speed, tool clearance and lubrication remain constant between experiments.

Component design parameters include; material selection, material properties, material thickness, punch radius, die radius, corner radius, distance between corners and draw depth. Each of these parameters affect formability. Tekkaya & Gür (2005) demonstrate that the formability of DDQ mild steel is approximately three times that of aluminium grade 6111-T4 in their analysis of axisymmetric cups. The material properties including material process history such as the rolling direction affect forming limits, as identified by Correia & Ferron( 2004) in their study of forming limits of conical cups. Saxena & Dixit (2010) find that the maximum cup height increases as material thickness increases in their study of wrinkling in aluminium cups. Özek & Ünal (2011) report that increasing the punch and die radius increases the limiting drawing ratio of a square cup. In contrast Zein & Shazly (2013) state that increasing the punch radius has the opposite affect and reduces the limiting draw ratio and Hassan et al. (2014) found that the limiting drawing ratio increases and then reduces as the corner radius is increased from 5mm to 22mm, with the maximum LDR occurring at 10mm. Hongsheng et al. (2009) demonstrate that increasing the separation between corners from 90mm to 140mm more than doubles the maximum draw depth in their experiments drawing aluminium square cups. In order to evaluate the failure draw depth from the component geometry future research should vary component design parameters and control the other variables.

### 2.4.4 Summary of opportunities in component design for manufacture

Previous research has established that the component geometry impacts material utilisation. However there are no existing design guidelines to support design for material efficiency. Whilst many studies have been undertaken into the forming limits in sheet metal drawing, the variables used in these studies are very different so the results cannot be compared. Further research is required to control the manufacturing design and process parameters in order to investigate the effect of component geometry on the failure depth of a part. This information could then be analysed to generate a geometry based formability guideline to support the design of material efficient components.

The extent in which these material efficiency opportunities, in forming, blanking and designing sheet metal components, have already been implemented in industry is now considered.

## 2.5 Realising the technical potential of material efficiency

Material efficiency is a method of reducing industrial $CO_2$ emissions by meeting service requirements with less material. Since using less material reduces the embodied emissions of a product, it ought to be possible for designers of material intensive products (e.g. cars, buildings and infrastructure) to save cost and reduce environmental impact by placing greater emphasis on the material efficiency throughout the product development cycle. Previous research has revealed that technologies exist to improve material efficiency in forming, blanking and product design of automotive sheet metal components. In order to reduce the demand for sheet metal, these material efficiency opportunities must be implemented in an industrial setting. The efficiency opportunities identified in sections 2.2-2.4 are now reviewed in turn to establish the extent in which they can be realised by the automotive industry to save material. Previous research into implementation barriers for material efficiency is then considered.

### 2.5.1 Industrial implementation of material efficiency

Previous research of industry implementation for material efficiency opportunities in forming, blanking and the component design is now considered.

Chapter 2.2 revealed that material utilisation in sheet metal forming can be improved through the design of the blank holder, draw beads and addendum surface. The blank holder force can be optimised to vary spatially and with time as investigated by Zhang et al. (2004) and Zhong-qin et al. (2007) respectively, this technology can be applied to minimise the blank holder area. Shim (2013) demonstrates that careful use of draw beads can reduce the material required to form the part. They also demonstrate that a variable height blank holder can reduce the size of the addendum surface through reducing the distance required to connect the part geometry to the blank holder, (Shim 2015). Whilst previous studies reference the opportunity to improve material efficiency as a benefit of implementing these technologies, there is no formal review describing how these technologies can be implemented in an industrial setting to improve material utilisation. Further research is required to quantify the material efficiency opportunity which could be realised by the automotive industry through improving the sheet metal forming process. This knowledge would be useful to prioritise investment in the material efficiency strategies which provide the most benefit.

Chapter 2.3 demonstrated that optimisation of the blank has been well researched. Naceur et al. (2004), Shim (2004) and Sattari et al. (2007) develop the minimum blank shape required to form components using iterative finite element analysis. Kitayama et al. (2015) optimise the shape of the blank to reduce material requirement and Alvarez-Valdes et al. (2013) demonstrated that, for problems with small numbers of parts, existing algorithms are able to generate nesting layouts to position components with the maximum possible material utilisation. Finn (2019) claim that material utilisation could be improved by 10%-20% through designing optimal blanks and laser cutting complex nesting layouts. However, there are no studies to provide evidence that these algorithms are being implemented to realise these savings in an industrial setting. Further research is required to identify the extent in which material savings from efficient blanking could be realised in an industrial setting.

Chapter 2.4 identified opportunities to improve material efficiency through considering the design of the component geometry. In their proposal of a systematic approach to designing components for material and process efficiency, Edwards (2003) observe that the design for material utilisation can be achieved with expert knowledge and experience. Lewis et al. (2001) recognise that the earlier the decision the greater the improvement opportunity. However, there has been no previous attempt to quantify the potential material saving opportunity for each stage in the product development process. Suschy (2006) propose a geometry based formability guideline which could be further developed to inform component engineers to make geometry and manufacturing process decisions to design parts with improved material efficiency. Further research is required to identify the technical potential for design for material efficiency and the extent in which this opportunity can be realised in an industrial setting.

Whilst opportunities for material efficiency exist there is little evidence that these opportunities have been implemented in an industrial setting. Instead, much of the focus to date has been to improve recycling operations through introducing closed loop recycling of automotive production scrap (Atherton 2007). For example, Shahbazi et al. (2016) focus on scrap separation to improve recycling processes and a successful example of implementation of closed loop recycling has been reported in JLR et al. (2016). Focus on recycling scrap metal to achieve a circular economy, rather than preventing scrap production, may be distracting attention from potential material efficiency initiates which aim to improve material utilisation in an industrial setting. Further research is required to explore the interaction of recycling and material demand reduction strategies to clarify the environmental benefits of material efficiency in the context of the circular economy.

Implementation of material efficiency opportunities is essential if the automotive industry is to succeed in reducing their demand for sheet metal. To provide an insight of why there is no evidence of industrial implementation of material efficiency, potential barriers to implementation are now reviewed.

### 2.5.2 Barriers to implementation of material efficiency strategies

Implementation of the material saving opportunities identified in this review do not require a strategic change in the way cars are designed, made, sold or used. So why haven’t these opportunities been implemented? The known barriers to implementing material efficiency are now reviewed.

There has been no specific study into the implementation barriers for improving sheet metal material utilisation in the automotive industry, but general approaches have been considered. Zaki et al. (2014) recognise that failure to understand implementation challenges of sustainability practices can reduce their effectiveness. Through an extensive literature review Stewart et al. (2016) identified 35 barriers which limit the implementation of sustainability initiatives in the design of a product or production process. Similarly, through an extensive literature review and interviews with subject matter experts, Kumar et al. (2016) classified and mapped the interconnectivity of 21 barriers for implementing 'Green Lean Six Sigma' activities in product development. Analysing data from the Indian automotive industry Luthra et al. (2016) identified 26 critical success factors in implementing 'green supply chain management'. Penna & Geels (2012) consider barriers to implementing sustainability practices in the automotive industry. The barriers identified in previous research are at a high level, therefore the relevance of each barrier for improving sheet metal material utilisation is not known. With so many barriers identified, existing literature offers limited guidance to an organisation looking to improve sheet metal material utilisation.

There has been significant research on implementation barriers for energy efficiency strategies. Trianni & Cagno (2012) identified and grouped implementation barriers into five themes; resources, skills, information, awareness and difficulties. Their study states that the most significant barriers are access to capital and lack of information. Lack of time ranked 6$^{th}$ out of the 11 barriers identified. Veshagh & Li (2015) identify the most significant barriers to efficiency in the automotive sector as being the lack of financial incentives. Existing literature relies heavily on data gathered through questionnaires and interviews. To the author's knowledge no study has yet reported on direct involvement in implementation of material efficiency.

There in an opportunity to investigate the extent in which the automotive industry is able to realise the technical potential of material utilisation improvement strategies. Research in this area could quantify material saving opportunities and identify any barriers which prevent these savings from being implemented.

Material utilisation in the automotive industry is currently estimated as 60% with an improvement opportunity of approximately 10%. There is an opportunity to improve these estimates through a detailed analysis of automotive sheet metal yield losses. Previous research has identified available technology to improve material efficiency in blanking, forming and component design. However, further research is required to quantify the scale of these opportunities. There is very little research exploring the implementation of material efficiency strategies, so there is a gap between theoretical methods of improving material utilisation and the practical implementation of material efficiency strategies. This gap is particularly significant for designing material efficient component geometry. Research proposals undertaken in this thesis to address these research gaps are now described.

## 2.6 Research proposal

Previous research has been reviewed to estimate current and improved material utilisation values for the manufacture of sheet metal automotive components. There is an opportunity to improve these estimates through a detailed analysis of yield losses in the production of sheet metal automotive components. Opportunities for material efficiency have been identified in blanking, forming and the component design process. However, the technical potential of these opportunities has not been fully quantified and there has been little exploration of the industrial implementation to explore the extent in which these material efficiency strategies can be realised in practice. All sections of the literature review are now considered to identify the research gap which this thesis will address. The following four areas for further investigation have been identified.

### Quantifying the material efficiency opportunity for automotive sheet metal

Previous research has quantified sheet metal yield losses in the automotive industry using individual case study examples.  There is limited knowledge of yield loss quantities on an industry level, and no estimation of the cost of these yield losses. It is also unclear from previous studies how yield losses could be reduced, since there has been no detailed analysis of why yield losses occur. Chapter 3 will determine how much, where and why yield losses are generated.

### Realising the technical potential of material efficiency strategies in the design and manufacture of automotive sheet metal components

Previous research has identified opportunities to reduce automotive sheet metal scrap through improving the blank nesting and optimising the gripping area in forming. However, the extent in which these opportunities could be realised in an industrial setting has not been identified. Evaluation of the opportunity and barriers to implementing different material efficiency strategies would enable automotive manufacturers to prioritise activities which generate the maximum return. This research gap is addressed in Chapter 4.

### Effective target setting for material efficiency in the circular economy

Previous research has identified an existing focus on the circular economy. This focus has promoted scrap recycling rather than scrap reduction. The percentage of recycled material used to manufacture a vehicle is an important performance metric for the automotive industry. Therefore, understanding the interaction of recycling metrics with material efficiency metrics is essential for implementing material efficiency strategies in practice. Chapter 5 evaluates a case study vehicle to explore the benefits of implementing both material demand reduction and closed-loop scrap recycling.

### Designing component geometry for improved material efficiency

Analysis of material efficiency usually takes place after the component geometry has been determined. Therefore, designing forming variables for material efficiency relies on the experience of the designer rather than evidence-based design rules. As a result, the use of forming variables such as blank holders and draw beads may be overused.  Identification of the geometric capabilities of forming processes would enable parts to be designed to be manufactured using simpler forming processes for improved material utilisation, similar to the concept of design for manufacture. Whilst many studies have been undertaken into the forming limits in sheet metal drawing, it is not currently possible to analyse this information to identify geometric forming limits for the interaction of the punch, die and corner radius. The study in chapter 6 aims to identify the effect of component geometry on the forming limit with constant forming variables and consistent failure criteria for two forming processes, drawing with a blank holder and drawing without a blank holder.

Addressing these research opportunities would enable sheet metal material efficiency to be implemented within the automotive industry and provide a detailed knowledge base to support future research into material efficiency.

# Chapter 3 The Opportunity

In previous research, sheet metal yield losses in the automotive industry have been estimated using individual case study examples. This work has revealed yield losses in blanking and stamping and identified opportunities to reduce automotive sheet metal scrap in nesting and optimising the gripping area in forming. However, the scale of the opportunity has not yet been fully identified. There is limited knowledge of yield loss quantities on an industry level, and no estimation of the cost of these yield losses. It is also unclear how yield losses could be reduced, since there has been no detailed analysis of why yield losses occur. To address these research gaps, this chapter will investigate the following hypotheses:

- Are the existing assumptions of 60% material utilisation and 10% improvement opportunity good estimates for manufacturing automotive sheet metal components?
- Can the saving opportunity for material efficiency be quantified in terms of financial and environmental savings?
- Are the suggestions of improving material utilisation through the design of the nest on the coil and the gripping area in forming valid?
- Are there any other strategies which could improve the material utilisation of sheet metal components?

Section 3.2 presents the results of an industry wide evaluation of sheet metal yield losses for 46 vehicles; an analysis of every sheet metal component manufactured for a case study vehicle; and results from semi-structured interviews which investigate decision making in the context of material utilisation. The results from all three studies are then analysed in section 3.3 to identify strategies for reducing yield losses in the production of automotive sheet metal component. These strategies are then evaluated using case study components to conclude the implementation potential of each strategy in section 3.4. The methodology for this research is now outlined.

## 3.1 Methodology: Investigating automotive sheet metal yield losses

This chapter has a two stage approach. Firstly, yield losses are identified through industry, vehicle and process investigations. These results are then analysed to propose and evaluate yield improvement strategies and determine their suitability for implementation. The methodology for the industry, vehicle and process investigations is now described in turn.

### 3.1.1 Automotive industry level study

Only one previous case study has been found to identify yield losses in the automotive industry. Cullen et al. (2012) evaluate one vehicle estimate automotive sheet metal material utilisation as 60%. This study extends Cullen's research and evaluates the material utilisation of 46 vehicles. Data for these 46 vehicles is sourced from conference proceedings at the Euro-Car-Body conference between 2009 and 2015. Analysing data from multiple vehicles enables the global yield improvement opportunity to be estimated. Material utilisation for this analysis is defined in formula (3.1) and (3.2).

$$Material\ Utilisation = 1 - Process\ Yield\ Losses \tag{3.1}$$

Where;

$$Process\ Yield\ Loss = \frac{\sum Scrap\ Generated\ in\ Manufacturing\ Process}{\sum Coil\ Mass} \tag{3.2}$$

The industry average material utilisation and yield loss per car is calculated from these self-declared datasets from the automotive manufacturers. The intended production volume is used to calculate a volume adjusted average yield loss value which is extrapolated to estimate global automotive yield losses from the industry as a whole. Average and volume adjusted yield losses are defined in formula (3.3) and (3.4).

$$Average\ Yield\ Loss = \frac{\sum Yield\ Loss\ Per\ Car}{Number\ of\ Models\ in\ Sample} \tag{3.3}$$

$$Volume\ Adjusted\ \mathrm{Average}\ Yield\ Loss = \frac{\sum(Yield\ Loss\ \mathrm{per}\ Car \times Annual\ Volume)}{\sum Annual\ Volume} \tag{3.4}$$

The benchmark vehicle datasets represent 10% of global passenger car production, including a range of vehicle types and manufactures, and are assumed to be representative of the wider automotive industry. Further losses are generated from the production of commercial vehicles. However, because of differences in vehicle sizes and shapes, commercial vehicles are excluded from the analysis. The environmental and financial costs of automotive sheet metal yield losses are estimated to quantify the opportunity for carbon reduction and identify potential financial gain, which could offset investment costs of process improvement strategies. Carbon data is compiled from process estimates published by Milford et al. (2011) and assumes the aluminium coil includes 30% secondary material and the steel coil is 100% primary. Cost estimates are generated using industry average estimates. Sources are shown in table 3.1. Identifying the cost and quantities of yield losses on an industry scale enables the identification of the best practice material utilisation and provides motivation for improvements to be implemented.

**Table 3.1 Sources of information used for industry level calculations**

| Measure | Source Estimated From |
|---|---|
| Global production volume of passenger vehicles | OICA (2015) |
| Annual global steel production | World Steel Association (2014) |
| Percentage of steel which is used in the automotive industry | Forbes (2015) |
| Breakdown of passenger and commercial vehicles | OICA (2015) |
| Breakdown of automotive steel between components | World Steel Association (2016) |
| Breakdown of steel and aluminium used in cars | Ducker Worldwide (2015) |
| Raw material cost of steel | Alibaba (2016) |
| Raw material cost of aluminium | London Metal Exchange (2016) |
| Processing costs for producing coiled automotive steel | Tata Steel (2015) |
| Processing costs for producing coiled automotive aluminium | Alibaba (2016) |
| Production scrap resale value steel | London Metal Exchange (2016) |
| Production scrap resale value aluminium | London Metal Exchange (2016) |
| Carbon costs for production processes | Milford et al. (2011) |

### 3.1.2 Vehicle level study

The vehicle level study investigates the source of yield losses and technical reasons for their occurrence. All components from a currently manufactured passenger vehicle are analysed to quantify material utilisation and identify sources of blanking and stamping scrap. Yield losses are identified through evaluating scrap generation in trimming operations. To calculate the average material utilisation for the vehicle; coil, blank and component weight data is collated. Data is sourced from coil suppliers, component manufactures and component designers. Due to data availability, 87% of parts by weight are analysed. Yield losses are categorised by scrap source and material type. This information facilitates the identification and evaluation of yield improvement strategies. Material removed in trimming is approximately flat, so the shape of each piece of scrap can be mapped onto the raw material coil. These yield losses are analysed in depth to generate a pictorial representation of how material in the blank is used and when material is scrapped and to identify technical reasons for blanking and stamping scrap. The pictorial method of data representation enables the cause of scrap to be more clearly identified than a purely numerical analysis.

### 3.1.3 Business process level study

In the process level study, automotive sheet metal design and manufacture processes are investigated to identify business reasons for sheet metal yield losses. To ensure proposed yield improvement strategies include all influential processes, a holistic approach is taken to the analysis, considering all stages of component design through to manufacture. This is in line with the Design for Manufacture (DfM) techniques identified by Boothroyd (1994). The design process is benchmarked through ten semi-structured interviews and the evaluation of corporate design documentation for five organisations, one automotive manufacturer and four 1st tier stamping suppliers. The findings are first analysed to identify design decisions which affect yield losses in the production of sheet metal components. These decisions are then explored in greater depth to establish underlying motivations for decision making which increase yield losses.

Automotive sheet metal yield losses are now investigated on an industry level, a vehicle level and a business process level, to uncover how much, where and why scrap is generated. Yield improvement strategies are then identified and evaluated in section 3.3.

## 3.2 Results: Understanding automotive sheet metal yield losses

The previous section has outlined the methodology for industry, vehicle and process level studies in automotive scrap generation. In order to address the hypotheses given at the start of this chapter, the results presented in this section estimate how much scrap is generated, where it comes from and why it is used.

In section 3.2.1 industry wide vehicle data is analysed to improve on previous estimates for automotive sheet metal utilisation (60% from Cullen et al. (2012)) and the opportunity for yield improvement (10%, from (Milford et al. 2011)). With improved utilisation values, the environmental and financial cost for automotive production yield losses and the associated saving opportunity is quantified. In section 3.2.2 an in depth evaluation of yield losses is then presented to validate and extend previous research which suggests material efficiency could be achieved through improving in blank nesting and reducing the gripping area in forming. In section 3.2.3 results from industry interviews are presented to reveal why decisions are made which result in reduced material utilisation. These results are then analysed in section 3.3 to identify strategies which could improve the material utilisation of automotive sheet metal components.

### 3.2.1 Calculating sheet metal yield losses across the automotive industry

Material utilisation and yield loss per car are shown for 46 benchmark vehicle models in figure 3.1. Vehicles are numbered and shown as lowest to highest yield loss per car with material utilisation plotted. Material utilisation falls with increasing yield loss per car, but this trend is not perfect due to variations in the size of the car. Aluminium vehicles are evenly distributed across the graph showing no correlation between material selection and yield losses generated per car. The average material utilisation across the 46 models is 55% (with a median of 56%) equating to an average yield loss of 306kg per car. There is a 34% range of material utilisation across all models.

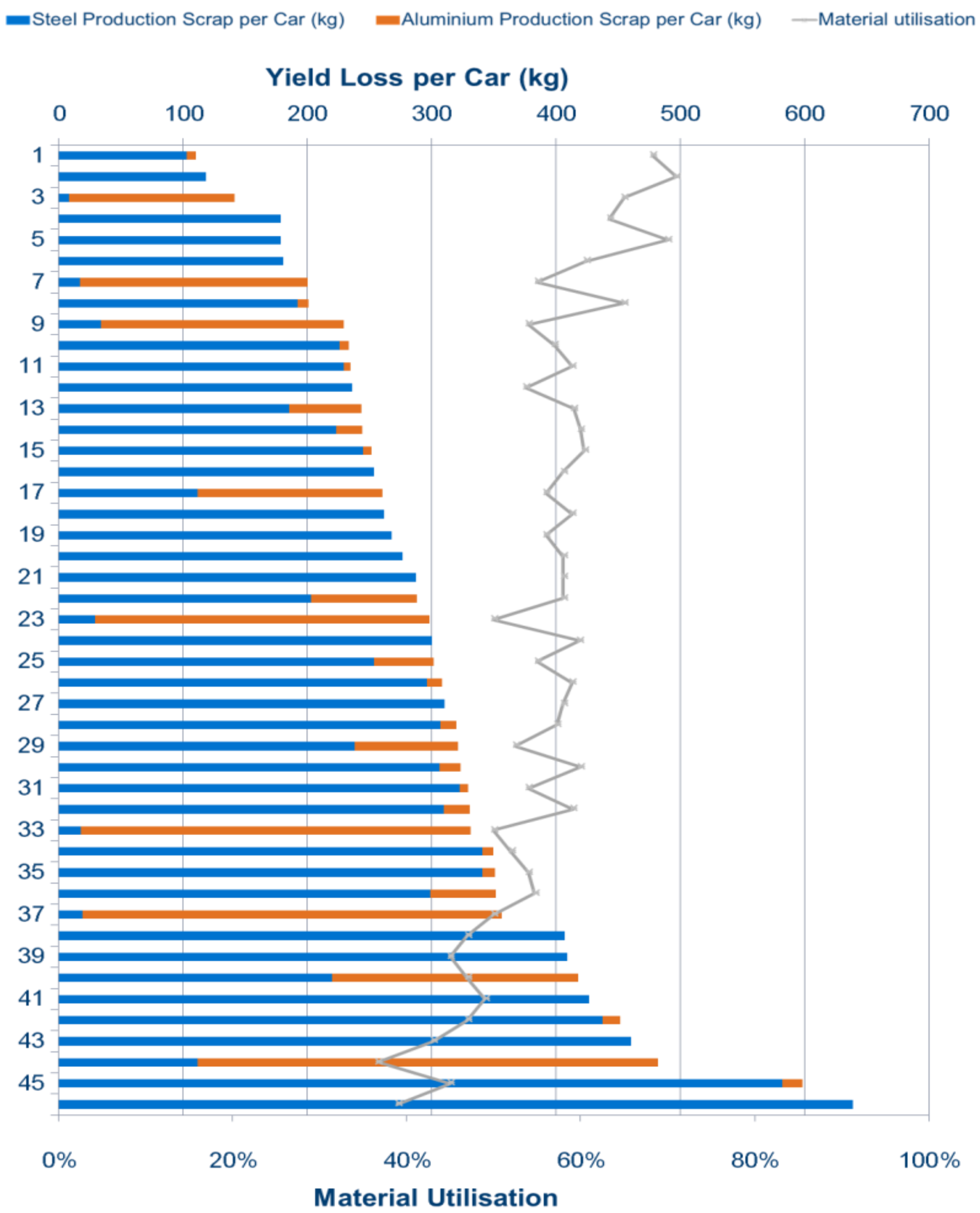



Figure 3.1 Yield loss and material utilisation per car by car model for 46 benchmark models.

The six plots in figure 3.2 compare the material utilisation values for these 46 vehicles with the following product attributes: number of BIW (Body in White) components; percentage of sheet metal mass used in the BIW; intended annual production volume; geographical region of manufacturer and vehicle segment. This series of graphs show that there is no relationship between these vehicle attributes and material utilisation. Therefore, it is likely that material utilisation is a result of business decisions made during the design and manufacture of the car, rather than the type of car being produced.


**Figure 3.2 Plotting material utilisation values against vehicle attributes to identify trends.**

The volume adjusted average material utilisation is calculated by weighting yield losses with vehicle production volume as described in section 3.1. The volume adjusted average material utilisation for this sample is 56%, equating to a sheet metal yield loss of 288kg per car. The volume adjusted average yield loss is slightly lower than the average yield loss per car since smaller cars are produced in higher volumes. Extrapolating the volume adjusted average yield loss to the global passenger car production in 2015 gives an annual sheet metal yield loss of 20 million tonnes. This value is double-checked through consideration of global steel production, using the sources outlines in section 3.1. Approximately 1500 million tonnes of steel are produced every year, of which 12% is used in the automotive industry. Of the 180 million tonnes of steel produced for the automotive industry, 35% is used to produce commercial vehicles which are not included in this analysis. Of the material used to manufacture passenger vehicles, 66% is used to produce castings and extrusions for the vehicle chassis, suspension components and wheels. The remaining 40 million tonnes of steel is sheet metal used to produce passenger vehicles. Using this value, a production process with an average 56% material utilisation will produce 18 million tonnes of sheet steel scrap per year. Aluminium makes up 10% of the metal used in passenger cars, when this is included total scrap production is estimated as 20 million tonnes per year. This double check matches the value extrapolated from the industry level analysis. The cost of these yield losses will now be considered.

The carbon and financial cost per tonne of yield loss are estimated using the sources outlined in the methodology. Yield loss costs for the benchmark models are shown in figure 3.3 and figure 3.4. Vehicle models are plotted in order of increasing financial and carbon cost per car respectively, using the number allocated in figure 3.1.

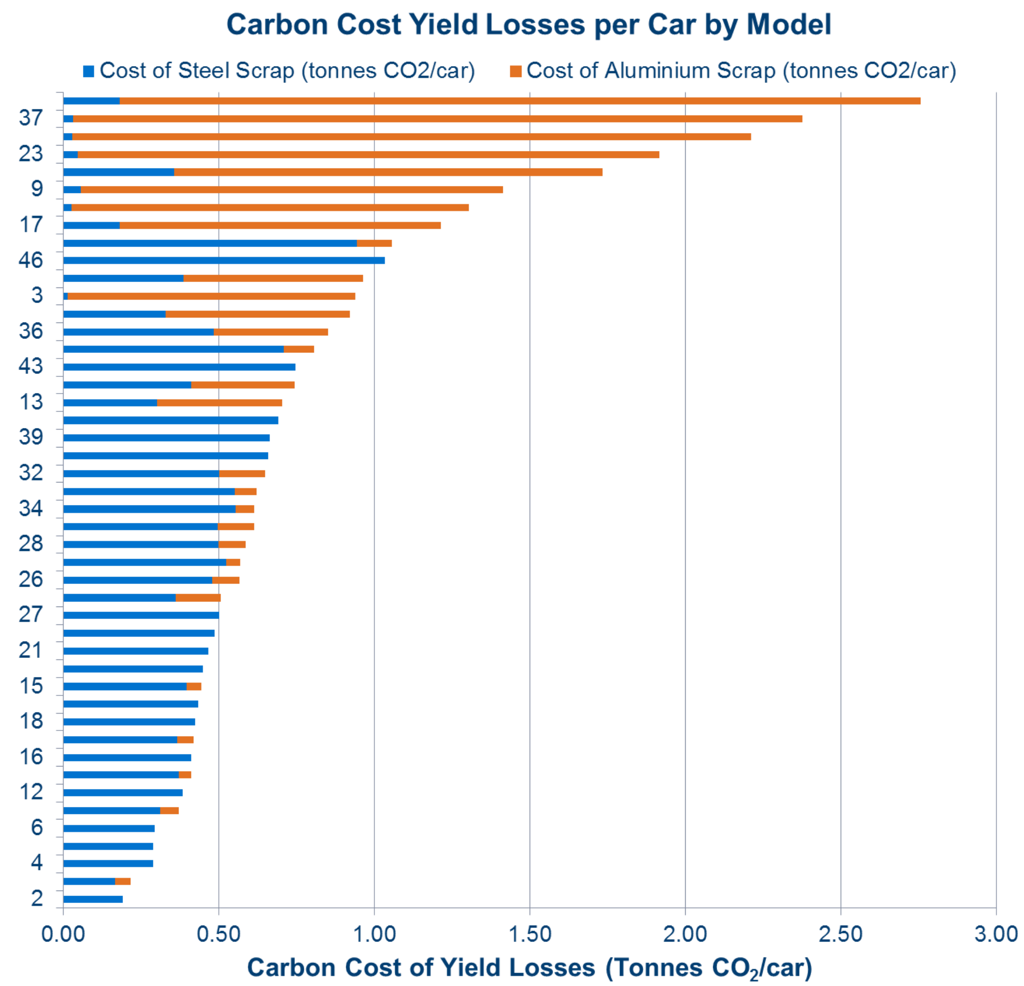


Figure 3.3 Carbon cost of yield losses for 46 benchmark models.

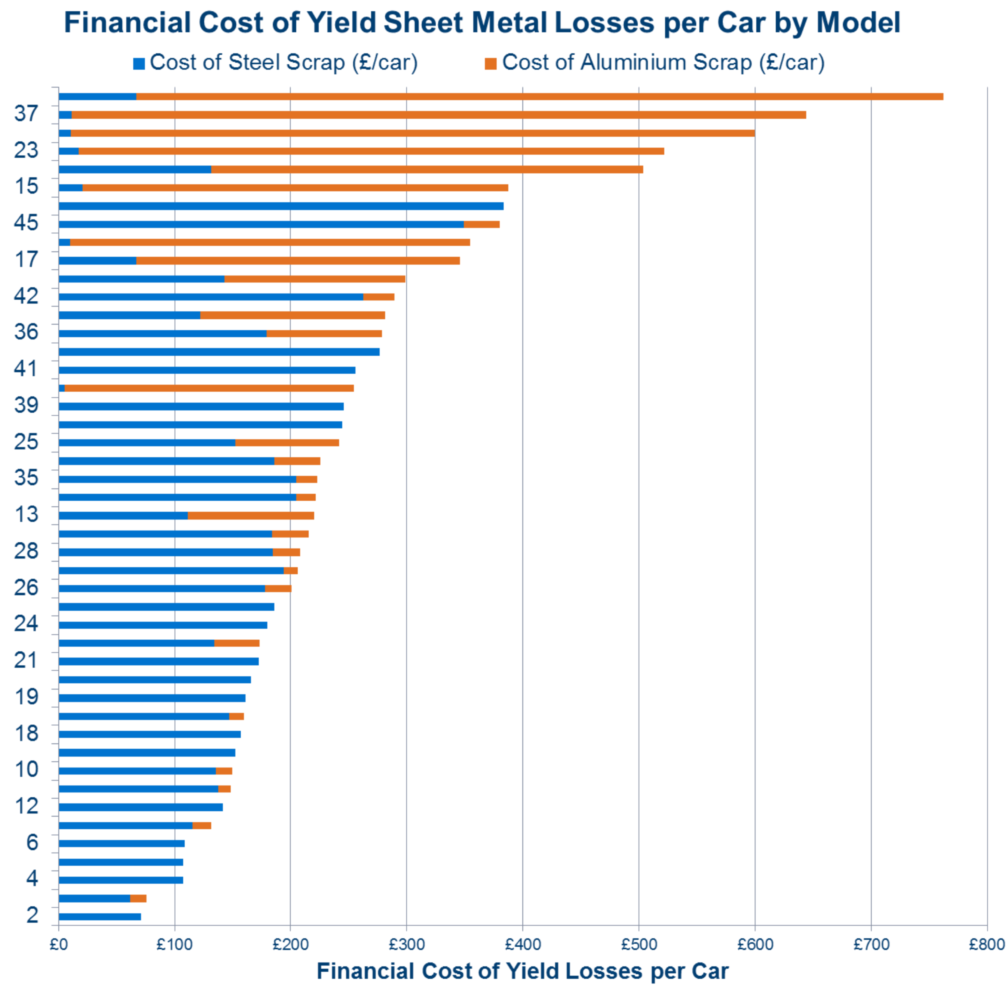



Figure 3.4 Financial cost of yield losses for 46 benchmark vehicle models.

The distribution of orange bars in both cost graphs demonstrates that yield losses are more costly for aluminium dominant cars than for steel dominant cars. This is potentially due to higher raw material and processing costs for producing automotive aluminium coil. The volume adjusted average yield loss cost is £213, and 0.63 tonnes of $CO_2$ per car. This extrapolates to a global annual cost of £15 billion, and 43 million tonnes of $CO_2$. If all passenger vehicles were manufactured with best practice material utilisation, scrapping only 30% of the coil, the volume adjusted average yield loss would reduce by 57% saving £8 billion, and 25 million tonnes of $CO_2$ annually.

Results from this industry level study have improved previous estimates for material utilisation through considering a larger evidence base in the calculations. It has been calculated that the average material utilisation of a vehicle is 56% and there is a potential to improve the average material efficiency by at least 14%, demonstrated by the variability between vehicle models. The annual global cost of these yield losses has been quantified as £15 billion, and 43 million tonnes of $CO_2$. The estimated annual global saving opportunity through improving material utilisation to current best practice is estimated as £8 billion and 25 million tonnes of $CO_2$ annually. These findings are analysed in section 3.3. An in depth vehicle level analysis will now evaluate where in the production process this scrap is generated. This knowledge can validate and extend existing proposals for automotive sheet metal material efficiency.

### 3.2.2 Evaluating sheet metal yield losses for every component in a vehicle

Results in the previous section have identified a significant opportunity for reducing yield losses in the automotive industry. Before this opportunity can be exploited, the sources of the scrap must be examined in more detail to identify how yield losses can be reduced. This section presents results from a vehicle level study to investigate where and why yield losses occur.

Automotive sheet metal yield losses have been evaluated in depth for all sheet metal components from a case study vehicle. The utilisation values for six example parts are shown in figure 3.5. There are large variations in material utilisation between components. Large simple shapes have a higher utilisation than components with small or complex geometries.

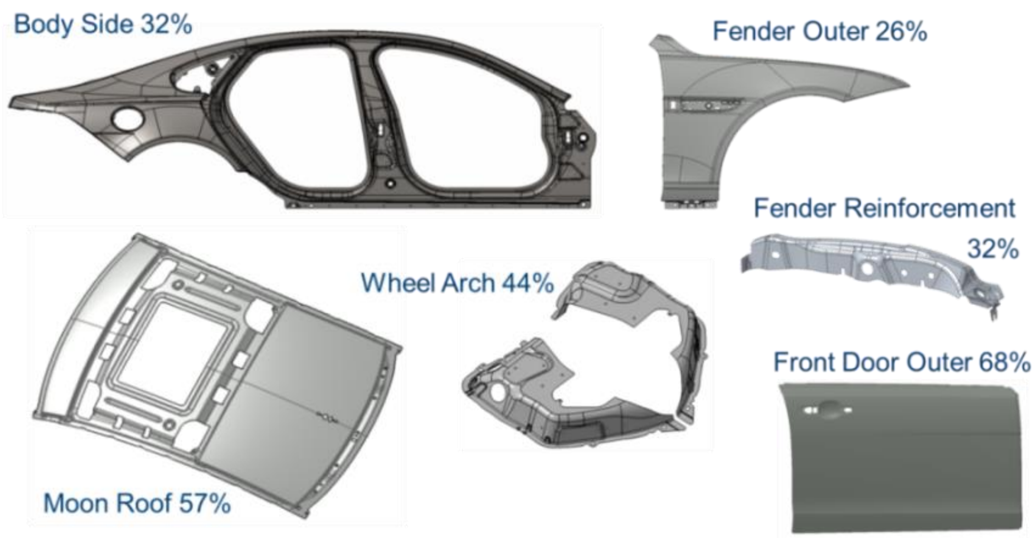


Figure 3.5 Material utilisation values calculated for six case study parts. (Images used with permission from JLR)

A pictorial representation of how the raw material coil is used to make these parts is shown in figure 3.6. They show the size and shape of blanking scrap (blue), stamping scrap (orange) and material which is used to produce the final component (green). Each line represents a cut in the trimming operation.

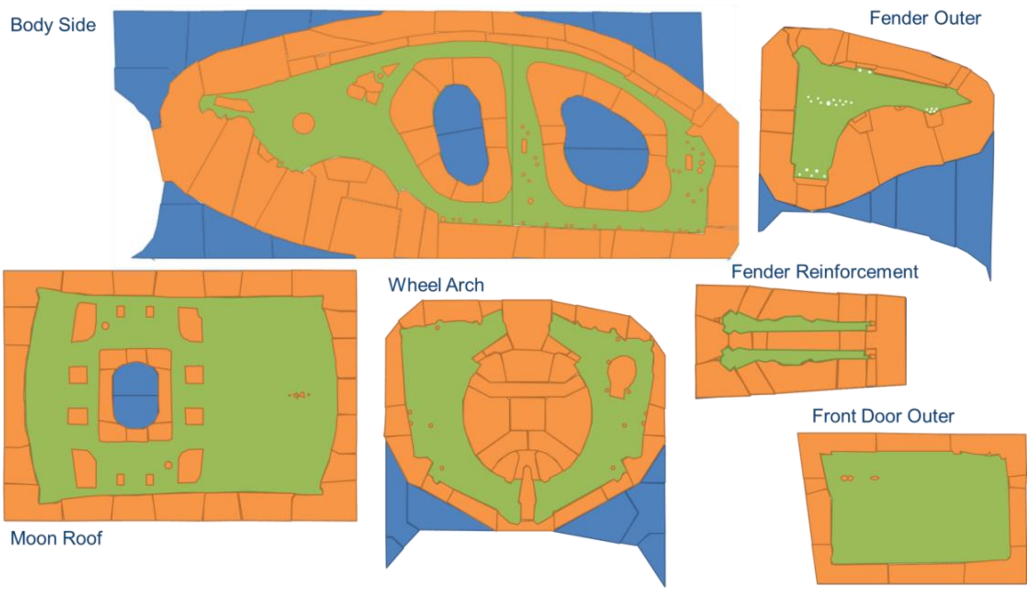



Figure 3.6 Pictorial representation of coil destination for case study parts.

The blanking and stamping scrap is cut into small shapes to be processed downstream. The small size and irregular shape of this scrap limits the potential for reuse. The split between blanking and stamping scrap varies between components. The breakdown of yield losses for all sheet metal components in the case study vehicle is shown as a Sankey diagram in figure 3.7 where the weight of the line is proportional to the material mass. The material utilisation values for components in this vehicle range from 4% to 82%. This range demonstrates that the component geometry has a significant effect on the material utilisation of the part. Approximately 75% of yield losses occur after the stamping operation and the total sheet metal material utilisation is 45%. The industry level analysis reported 47% material utilisation for this car. The self-declared estimate is closer than expected to the actual value considering the difference in detail of the analysis.

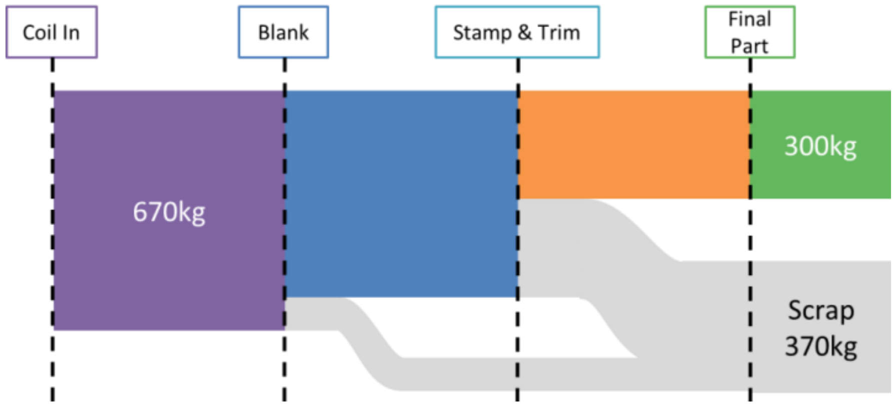



Figure 3.7 Sankey diagram showing sheet metal yield losses for the case study vehicle.

The case study vehicle is made from 15 different steel alloys and six different aluminium alloys. When material gauge, coating and pre-treatment are considered, 100 different sheet metal coils are used to produce 385 components. The production volume for each component differs due to the in service demand, which varies between parts. Figure 3.8 identifies the complex supply chain to produce the sheet metal components in this vehicle, which requires coordination between 21 business units across 13 corporations.

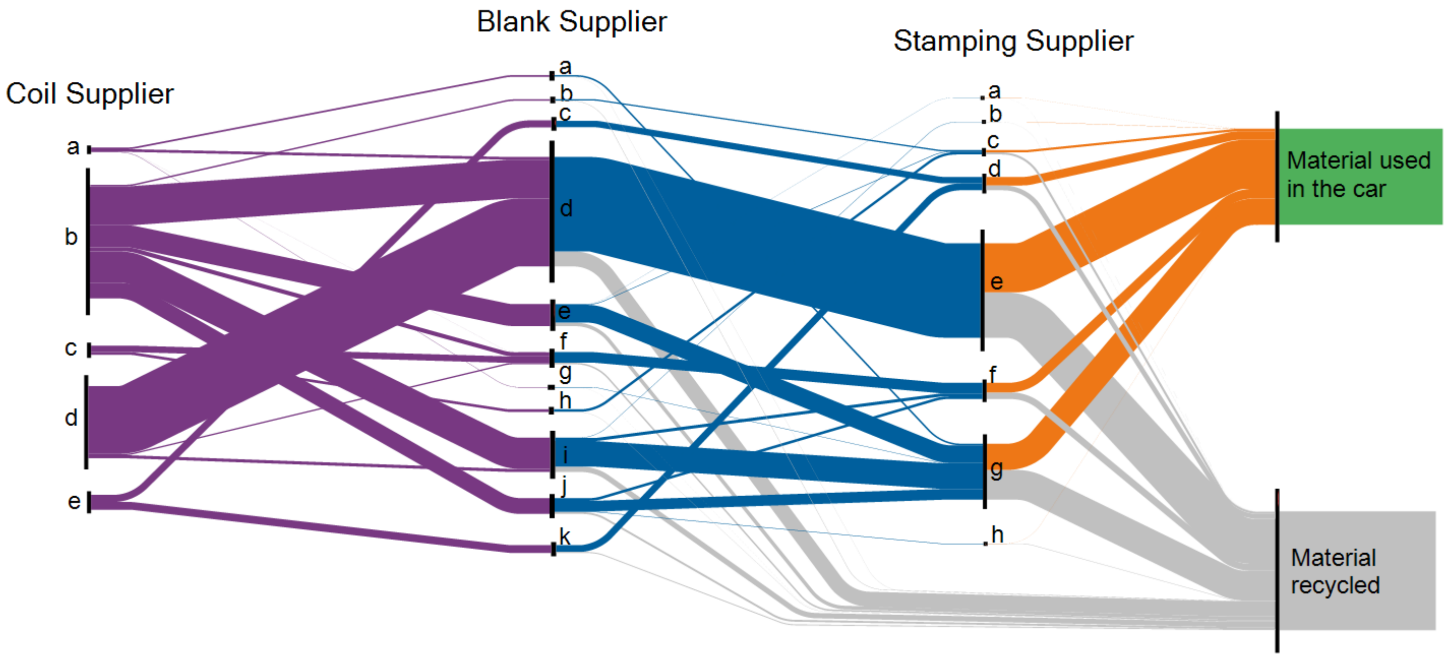



Figure 3.8 Sankey diagram showing sheet metal yield losses by supplier for the case study vehicle

Findings from the vehicle level study are now presented to investigate technical reasons for blanking and stamping yield losses. The fender outer panel and fender reinforcement are used to illustrate these findings.

The evaluation of blanking scrap revealed that the majority of blanking scrap is a result of nesting inefficiencies, generated from gaps between the blank shapes if they do not nest perfectly on the coil. There is a small amount of scrap around the perimeter of the blank since the rough sheared edge and coil edge may generate cracks during forming so is not used in the final component. To illustrate this, the yield losses generated from blanking the fender are shown in figure 3.9. The scale of this nesting scrap is surprising since the literature review identified that nesting algorithms are already able to fully optimise blank lay outs on the coil. The reasons why an optimised blank layouts is not always applied in industry are investigated in the process interviews in section 3.2.3.

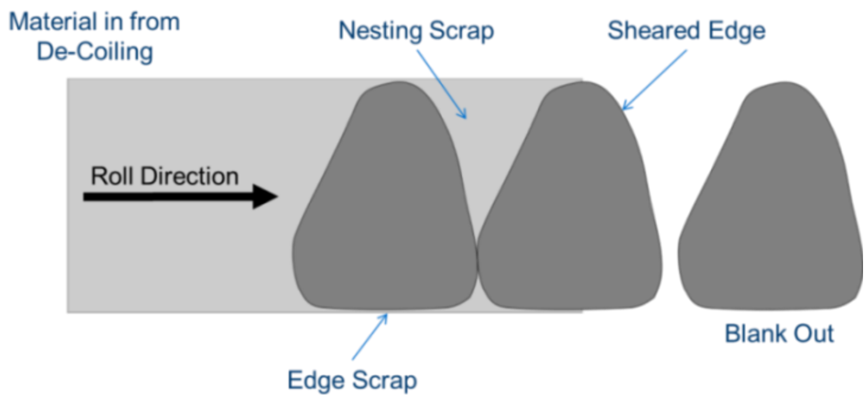



Figure 3.9 Blanking scrap generation

Automotive blanks are commonly simplified into shapes which are easier and cheaper to cut with a standardised blade, rather than using a unique shaped cutting tool, figure 3.10. The blank design is simplified in three of the case study parts; the moon roof, the fender reinforcement and the front door outer panel. Simplifying the blank shape generates a 'hidden blanking' scrap, where yield losses are generated from nesting inefficiencies, but are removed after the forming operation so are incorrectly classified as stamping scrap. It is not possible to measure the quantity of this hidden blanking scrap since the minimum blank shape is never fully developed.

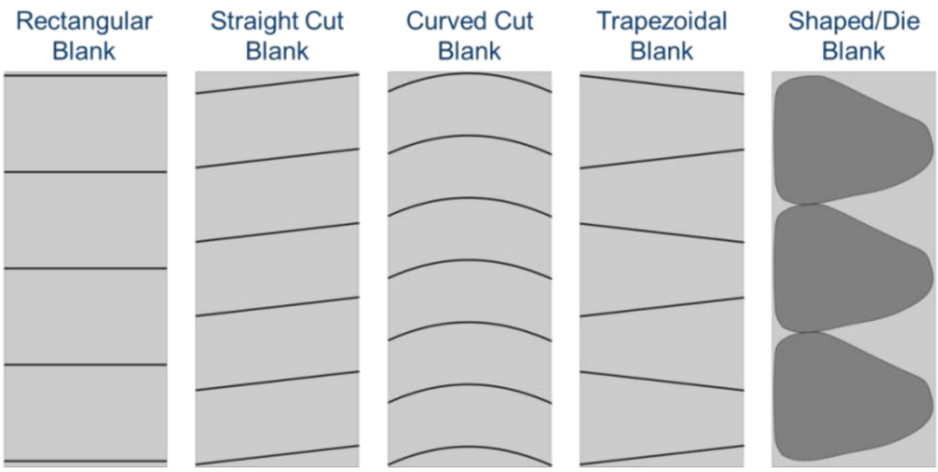



Figure 3.10 Blank shape alternatives

Additional hidden blanking scrap is also generated when internal cut outs are removed after forming, for example holes for fixings, or the fuel filler hole in the wheel arch panel.

Stamping scrap has previously been referred to as the gripping material. A detailed breakdown of stamping scrap for the fender reinforcement is shown in figure 3.11. Material is categorised as the final part (green), blank holder scrap (grey), draw bead scrap (blue line) and addendum scrap (red). The white area outside the draw bead is hidden nesting scrap and is not required for stamping. Figure 3.11 demonstrates that stamping scrap does more than grip the part. Stamping scrap is made up of multiple elements which are used control material flow, improving the formability and quality of the part.

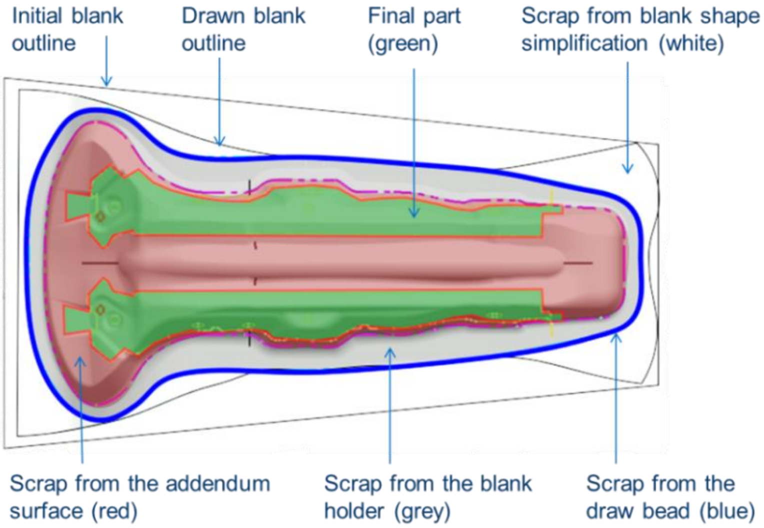



Figure 3.11 Stamping scrap for the fender reinforcement.

The blank holder performs the gripping function, restraining the part to increase the drawing tension. Draw beads increase the restraining force of the blank holder and allow different forces in different areas to increase formability for complex part geometry. Draw beads are also used to stop material defects which result from material being drawn in quickly at the end of the process. The addendum surface provides a connection between the blank holder and the edge of the part since the blank holder geometry is limited to simple curvatures. The addendum surface uses shaped features to soak additional material or provide a source of material. Addendum surface features also move tool contact areas away from critical areas of the part to remove visible slip lines. The addendum surface is designed to reduce changes in section length of line to improve formability and balance forces across the die to reduce die damage.

The vehicle level study has shown that yield losses vary significantly between components in a vehicle; therefore the component geometry must influence the material utilisation value of the part. Scrap is generated from both blanking and stamping operations and whilst most yield losses occur after stamping, the split varies for different component geometries. Yield losses occur across the supply chain and include many different materials. It has been shown that existing cutting and forming technology used in the automotive industry requires additional material to economically produce components of the required quality. These findings are taken into consideration in the analysis in section 3.3 to identify opportunities for improved material utilisation.

### 3.2.3 Understanding decision making which increase yield losses

Yield losses occur in the production of sheet metal components. In section 3.1 it was shown that the scale of these yield losses varies between vehicle models depending on business behaviours of the manufacturer. In Section 3.2, figure 3.6 demonstrates that yield losses vary between different components manufactured for the same vehicle. This section investigates the business processes which may account for these differences in material utilisation on a component and vehicle level. Design decisions which impact yield losses are identified and examined from interviews and design process documentation, as described in the methodology.

The design and manufacture of sheet metal automotive components consists of multiple stages, with each process undertaken by different people, departments and often different organisations. The interviews and review of process documentation presented four key stages where design decisions affect material utilisation. These stages are classified as; design strategy, component strategy, manufacturing design and component manufacture. Table 3.2 details the decisions made and the observed impact of these decisions on material utilisation for each of these four stages as recorded in the interviews. This study of industrial decision making revealed that material utilisation is only formally considered in two stages of product development, as shown in figure 3.12 and explored in table 3.2.

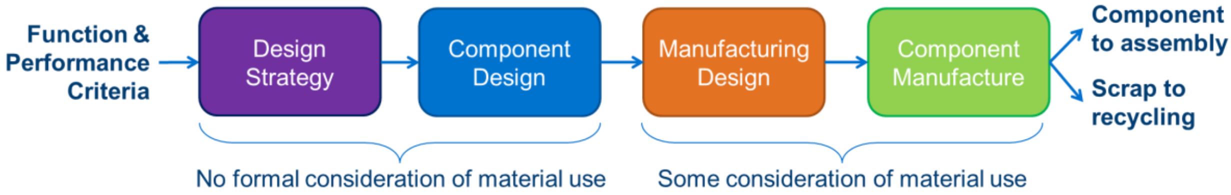



Figure 3.12 Production processes which consider material utilisation in decision making.

The design strategy and component geometry stages are not formally governed by material utilisation guidelines. The interviews revealed a cultural trend to increase component capability through designing and manufacturing complex component geometry. Complex component geometries have greater yield losses as they require larger addendum and blank holder surfaces to ensure they can be formed without failures. Designer preference for complex geometries combined with a lack of clarity about how the geometry influences yield losses, drives increases in yield losses in the design strategy and component design stages.

Table 3.2 Results from interviews identifying decision making which affects material utilisation

| Process Stage Decisions | Observed Impact on Material Efficiency |
|---|---|
| **Design Strategy:** Determines the number of components in an assembly, which supplier will manufacture the components, and which technologies will be used. | Material utilisation was not formally considered in decision making for the design strategy. One interviewee observed that selecting a supplier at this stage can increase yield losses since the choice of manufacturing process is limited to that supplier's capability. Another commented that increasing the number of components in an assembly can increase yield losses. All organisations reduced the risk of process failure through requiring the use of surrogate data, where design decisions are based on previous products which have been successfully manufactured. |
| **Component Design:** Defines the component geometry and selects the material. | None of the organisations interviewed considered material utilisation as an influencing factor at this stage in the design process. One stamping supplier identified parts which could be made with less material if the component geometry was simplified in a way which did not compromise functionality. Another commented how engineers who design the component geometry may not have the training or experience to know how it could be modified to be manufactured with less material. All five organisations interviewed modified the component geometry for formability, but not for material utilisation. |
| **Manufacturing Design:** The blank design, nesting layout and stamping features are specified at this stage. | All organisations recognised that manufacturing process design affects material utilisation, and process documentation was in place to improve material efficiency. However, recommendations varied between organisations and were rarely implemented. Additional material was used to improve other performance criteria, such as dimensional accuracy, surface finish, and production reliability, and to reduce investment costs and development times. It was remarked by one stamping supplier that some customers (vehicle manufacturers) dictate material utilisation targets, but others do not; and if no target exists they do not consider material utilisation a priority. |
| **Component Manufacture:** Changes to the blank and stamping process variables are made during physical trials of the production process. | Material utilisation in component manufacture was considered by all organisations, but approaches varied. One supplier minimised yield losses through reducing the blank size to initiate failure, then increased the blank iteratively to produce a successful part from the smallest possible blank. In contrast, another interviewee described the necessity to increase the blank size to eliminate forming failures during this tool try-out stage. One interviewee remarked that tool makers are not always an active partner in material utilisation due to the risk of part failure if the blank is minimised. |

The interviews revealed that all stages of component design and manufacture rely on surrogate data to provide confidence that a component will meet the required performance criteria. This risk adverse approach prevents the implementation of process improvements to reduce material requirement. Best practice guidelines in manufacturing for material utilisation were in place for all organisations interviewed. However, these recommendations were rarely implemented since material utilisation was considered to be a low priority in stamping design. The interviews found that additional material is often used to improve other performance criteria, such as to reduce the risk of part splitting when complex geometries are formed. This material is rarely considered a yield loss and was referred to as '*process offal*', losing any notion of process inefficiencies. An example of process offal is shown in figure 3.13.

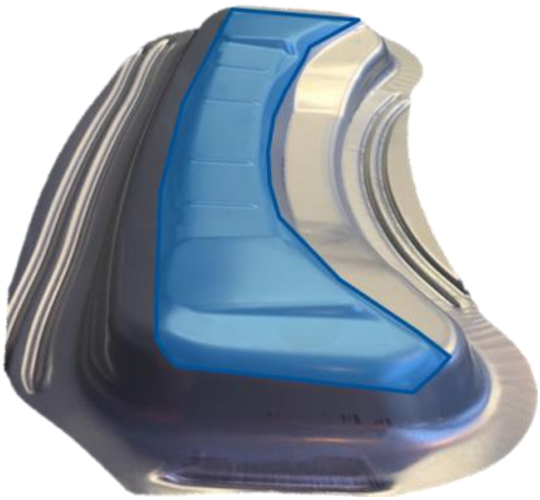


**Figure 3.13 Example of process offal. The area in blue is an approximation of final component and the remaining grey material is referred to as process offal so is not always considered a yield loss.**

Variations in the design and manufacturing process were identified between organisations and individuals within the same organisation. One contributor to these variations is that guidelines are not evidence based, so best practice varies between organisations. Design and manufacturing guidelines also lack details such as specific material utilisation targets and a maximum allowable material use. This allows over-estimation of material requirement. Another contributor to process variation is the limited coverage of guidelines, which do not influence decision making in design strategy and component geometry stages, or those made by other organisations. The absence of industry best practice guidelines to design and manufacture components with minimum yield loss prevents decision making to improve material efficiency.

It has been identified that the decisions made throughout the design and manufacturing process affect sheet metal yield losses in the automotive industry. Three reasons for high yield losses have been identified. Firstly, all components have inherent yield losses due to their complex geometry. Yield losses are then increased to satisfy competing performance criteria. Finally, the design and manufacturing process is not standardised and best practice is not well defined so yield losses are increased further. These factors are shown in figure 3.14.

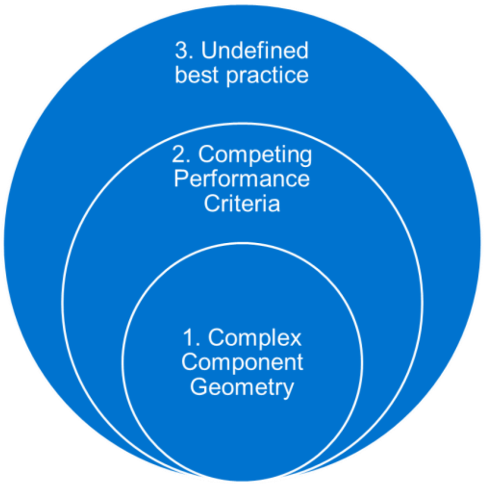



**Figure 3.14 Underlying reasons behind decision making which increases yield losses in the design and manufacturing processes for automotive sheet metal components.**

The results from the industry level study, vehicle level study and this process level study are now considered together to identify and evaluate yield improvement opportunities in automotive sheet metal design and manufacture.

## 3.3 Analysis: Identifying and evaluating yield improvement strategies in the automotive industry

The previous section has investigated automotive yield losses, revealing how much scrap is generated, where it comes from and why it is used. This knowledge will now be reviewed to identify and evaluate yield improvement strategies. Previous research by Milford et al. (2011) proposed an opportunity to improve material utilisation through improved nesting and reducing the gripping area in forming. The evidence from the previous section is analysed to validate and extend Milford's proposal to consider all available opportunities to reduce yield losses in the production of automotive sheet metal components.

### 3.3.1 Identifying yield improvement strategies

The industry, vehicle and process level studies demonstrate an opportunity for material efficiency through yield improvement in the production of sheet metal components in the automotive industry. The results from the industry level study have shown that sheet metal scrap production in the automotive industry varies substantially between vehicle models and organisations. Industry wide yield losses could be reduced if all organisations performed at best practice and there may be opportunities for further yield improvements through advancing best practice. The analysis shows that reducing sheet metal yield losses is an effective strategy for carbon reduction. The financial cost of scrap provides further motivation and opportunity to implement changes required for process improvement.

The vehicle level study identified that yield losses occur when the blank shape is simplified to a regular shape, and when the blank size is increased due to the design of the blank holder and addendum surface. These yield losses could be reduced through improving the design to a shaped blank and reducing the size of the blank holder and addendum surface. Scrap is also generated when there are spaces between blanks on the coil and when parts have unused cut outs which are removed after forming. Generating better nesting designs or increasing nesting options by manufacturing multiple blanks together would reduce this scrap. The results have demonstrated that the component geometry affects the material utilisation of the part. Therefore, material efficiency strategies which consider the component geometry should also be evaluated. The geometry of the component could be modified to improve nesting and reduce the requirement for additional gripping material in forming.

Strategies for improving material utilisation are therefore categorised as improving the part design, the part nesting and increasing nesting options. The business process analysis identified that business decisions influence the yield losses in automotive sheet metal production. Strategies for improving material utilisation should therefore consider the design of the blanking process, the stamping process and the component geometry. These opportunities for yield improvement are outlined in the matrix in figure 3.15. The matrix shows categories for improving material utilisation in the left hand column against design processes on the first row, to identify nine strategies for yield improvement.

| | Design of Blanking Process | Design of Stamping Process | Design of Component |
|---|---|---|---|
| Part Shape | Represent blank shapes more accurately | Minimise blank size through reducing the blank holder and addendum surface | Consider feature impact on blank design |
| Part Nesting | Improve nesting of blanks on the coil | Nest parts to reduce the blank holder and addendum surfaces | Combine parts to reduce material overlap |
| Increase Nesting Options | Nest multiple different blanks | Nest multiple different components | Design parts to nest |

**Figure 3.15 Identifying strategies for reducing automotive sheet metal yield losses.**

### 3.3.2 Evaluating yield improvement strategies with case studies

The proposed yield improvement strategies from section 3.3.1 are evaluated using four applications from the Jaguar XF. For this analysis the strategies are grouped as the blanking process, the stamping process, impact of nesting and component design as shown in figure 3.16. Case study parts were selected to allow the nine yield improvement strategies from figure 3.15 to be investigated and better understood.

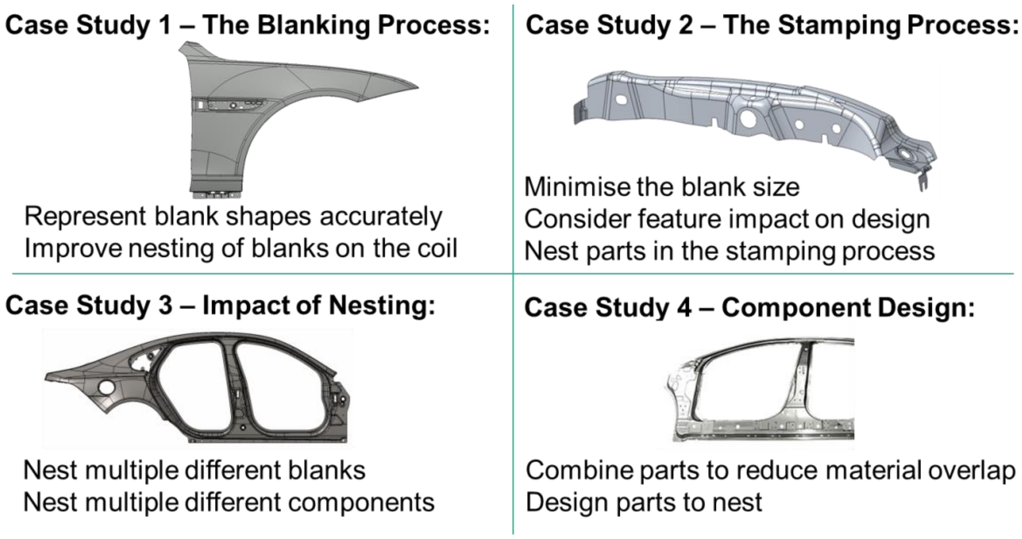



**Figure 3.16 Outline of case studies used to evaluate yield improvement strategies.**

Each case study will explain how the proposals have been implemented to improve material utilisation, the savings which could be realised and the obstacles or costs which limit potential savings. Each strategy is then individually evaluated to determine its potential. This enables the most promising strategies to be identified and suggestions for further research to be made.

#### Case Study 1: The Blanking Process

Case Study 1 evaluates the scrap reduction strategies of '*represent blank shapes more accurately*' and '*improve nesting of blanks on the coil*' to improve the material utilisation of the Jaguar XF fender. The fender blanks are currently cut from a coil strip in a repeating pattern, with all parts positioned in the same orientation, as shown in figure 3.17. If the parts were simplified to a rectangle improvements in blanking could not be implemented. Since the fender is made from a unique shaped blank, known as a developed blank, the nesting layout can be improved reducing the material requirement by 12%, shown in figure 3.17.

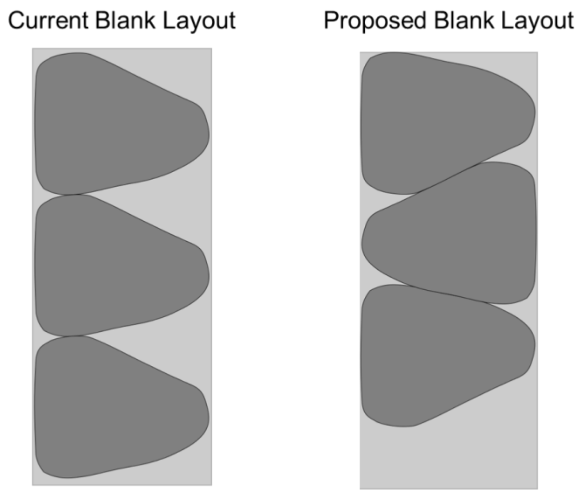



**Figure 3.17 Results from case study 1, improving the blanking process for the Jaguar X260 fender panel.**

In addition to material savings, the literature review in section 2.3 identified that using a developed blank improves the drawing performance in stamping compared to a rectangular or trapezoidal blank, reducing the chance of failure in stamping. However, blanking developed shapes requires a unique die tool to cut the parts. Die tools are more expensive than a straight or curved edged blade which can be used to produce a simple blank. For very complex shapes, laser cutting is required. Laser cutting is more expensive and time consuming per part than using hard blanking tools. The alternating orientation of parts in the proposed blank layout complicates the unloading process. The cut blanks would need to be unloaded into two separate stacks, from different directions. Investment into press shop facilities would be required to implement this change. From this case study, the potential of these yield improvements strategies are evaluated as:

- **Representing blank shapes more accurately:** Using a shaped blank would minimise the blank size to enable tighter nesting and reduce the requirement for additional material in forming. However shaped blanks are more expensive and time consuming to produce. There are no technological barriers to implementing this strategy and it should be implemented whenever it is economically viable. Future developments into laser blanking are likely to reduce in cost and subsequently increase the opportunity for this strategy to be implemented.

- **Improving nesting of blanks on the coil:** The literature review in section 2.3 identified nesting algorithms which are able to optimally nest blanks on a coil for maximum material utilisation. However, these nesting solutions are not always implemented due to limitations in blanking facilities. Improvements can be made through investing in unloading equipment to allow more flexibility in nesting orientations. Investment costs can be offset by material savings from multiple parts.

### Case Study 2: The Stamping Process

Case Study 2 evaluates scrap reduction strategies of 'minimising the blank size through reducing the blank holder and addendum surface', 'nest parts to reduce the blank holder and addendum surface' and 'consider feature impact on blank design' to improve the material utilisation of an automotive fender reinforcement. The current stamping process forms two parts in one drawing process as double attached parts. The blank is trapezoidal with a large blank holder area and large addendum surface, as shown in figure 3.18. The material requirement could be reduced by 55% through forming four parts together with a minimised shaped blank, also shown in figure 3.18. The blank size is reduced through removing the tabs as separate components, reducing the addendum surface between the parts (to the minimum distance allowable by the Jaguar's design rules), and minimising the blank holder area by reducing the use of draw beads and shaping the blank. Separating the tabs reduces the size of the blank, but also reduces the geometrical accuracy of the assembly and requires additional joining work and cost. Increasing the number of parts nested on the blank reduces the blank holder and addendum scrap per part and increases the parts produced per hit, improving production capacity. However, the tool size would increase, which increases the investment cost of tooling.

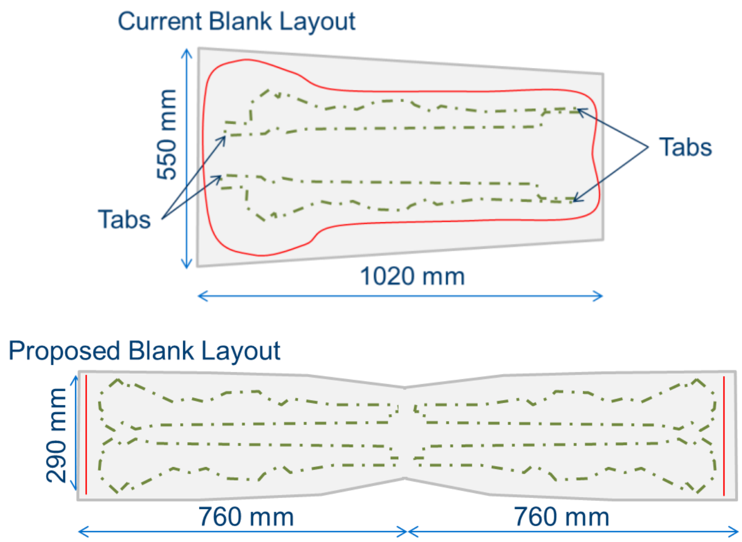



**Figure 3.18** **Results from case study 3, improving the stamping process for the XF fender reinforcement. The green dotted line is the outline of the formed part, the remaining grey area is the blank holder and addendum material and the red lines mark the position of draw beads.**

Forming the component with fewer draw beads reduces the size of the blank holder and addendum surface. Initial studies in section 2.2 show this method of stamping design produces high quality parts, but the technique is new to the organisation so there is a high risk of part failure in implementing this design strategy. From this case study, the potential of these yield improvements strategies are evaluated as:

- **Minimise blank size through reducing the blank holder and addendum surface:** Minimising the blank holder and addendum surfaces reduces the size of the blank and improves material utilisation. However, implementation is limited by the current stamping design process, which increases the blank size to meet other performance criteria such as to reduce development time and reduce the risk of part failure. This strategy requires further research into the minimum material required to form a complex component geometry to be implemented.
- **Nesting parts to reduce the blank holder and addendum surface:** Double attaching, the process of stamping two of the same parts together, is common practice and could be extended to higher multiples to gain further material savings through reducing the size of

blank holder and addendum surfaces. Nesting multiple parts together can improve material utilisation. This strategy does not require further research and should be implemented wherever it is economically viable.

- **Consider feature impact on blank design:** Changing the geometry of the final component can effectively reduce material demand, but can also have a detrimental effect on other performance criteria. The relationship between the geometry of the component and the blank requirements is not currently understood, further research is required to enable design decisions to be made to implement this strategy.

## Case Study 3: Impact of Nesting

Case Study 3 evaluates the improvement strategies of '*nest multiple different blanks'* and '*nest multiple different components'* in the stamping process to improve the material utilisation of an automotive body side. The current process forms the components in this case study from eight separate blanks, shown in figure 3.19. In the proposed process, scrap between the body side blanks is used to make another blank.

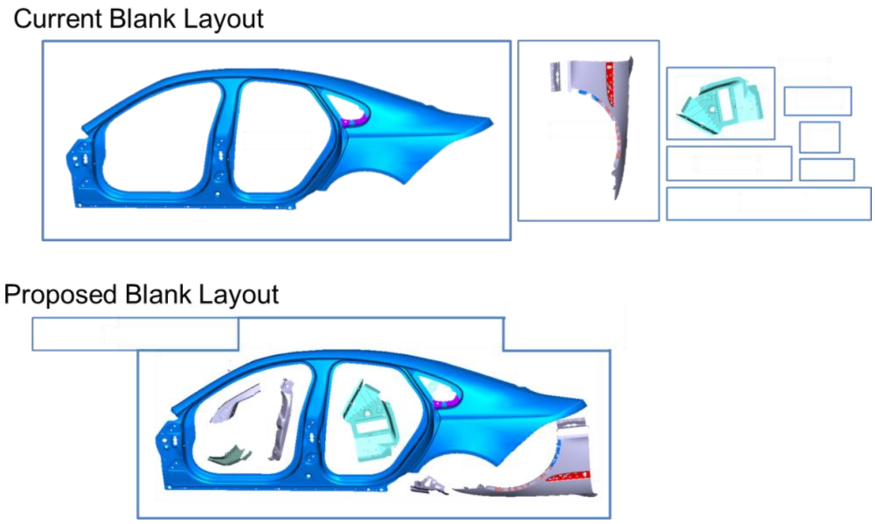



**Figure 3.19 Results from case study 3, improving material utilisation through increasing nesting options.**

Stamping scrap from the body side addendum surface is reduced through nesting the front fender in the wheel arch liner as both of these parts have a large draw depth. Other parts are made from material in the door apertures, either as a separate blank or stamped in the same process. Nesting multiple components would reduce the material requirement of these components by 33%. This would save approximately 20kg of material per car.

Nesting multiple parts around the body side during forming has reduced the material requirement and has increased production capacity through producing multiple parts together. However, the cost of this saving is high. The stamping design process is more complex increasing the risk of production failures. In addition the flexibility of production volume and material selection is reduced. For this case study example, 82 body sides would be scrapped each year due to differences in service requirements between the fender and the body side. The eight parts considered are currently made from seven different coils. Limiting material selection to one material may reduce the functionality of these parts. From this case study, these yield improvements strategies are evaluated as:

- **Nest multiple different blanks:** Nesting multiple different blanks together reduces blanking scrap. It is a successful scrap reduction strategy in the textiles industry. However, opportunities in the automotive industry are limited as very few parts are made from the same material. This material saving strategy is therefore not a priority for implementation in the automotive industry at this time. However, nesting multiple different blanks could be achieved further up the supply chain by the material supplier; this would require a significant change in industry process to eliminate the intermediate coil product.
- **Nest multiple different components:** Nesting multiple different components together during forming can reduce the material requirement, but increases the risk of product failure due to added complexity in drawing. Implementation of this strategy is limited by the number of components which have the same material and production volumes. Nesting in stamping is not recommended for further research.

### Case Study 4: Component Design

Case Study 4 evaluates the potential to '*combine parts to reduce material overlap*' and '*design parts to nest'* to improve the material utilisation of the XF body side reinforcement. The current process forms four components from separate blanks, shown in figure 3.20. In the proposed process four parts are combined to be stamped as one large component, either as one large blank or four smaller blanks which are laser welded into one, also shown in figure 3.20. Combining the body side reinforcement parts reduces the material requirement by 16%. Designing separate blanks to nest perfectly and welding to form one blank, reduces the material requirement by 61%.

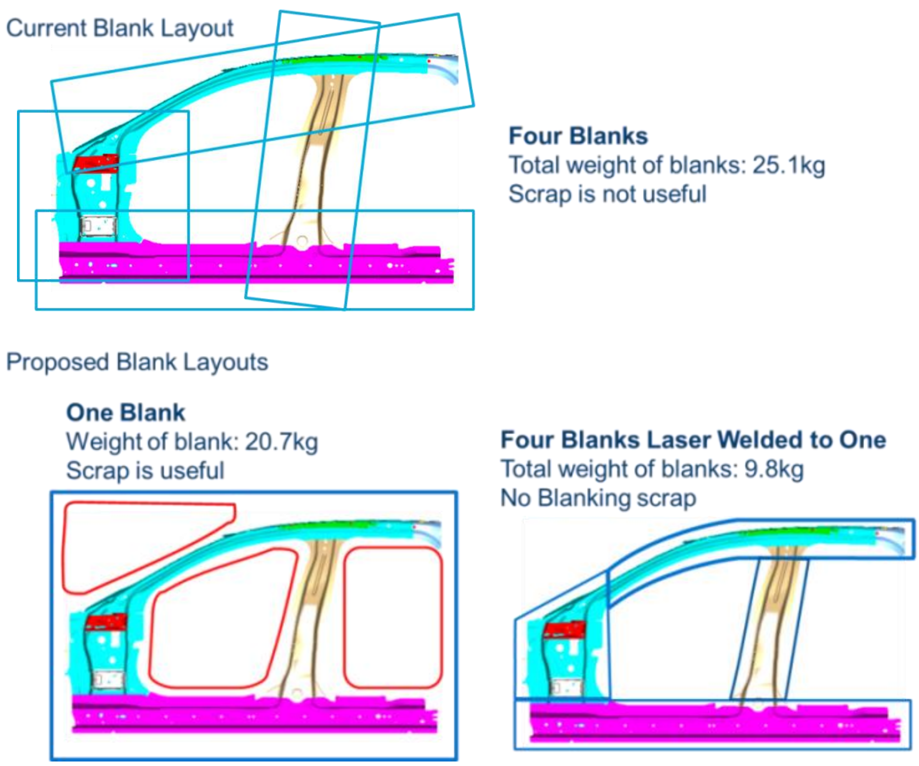



**Figure 3.20 Results from case study 4, improving material utilisation through component design.**

Combining the components selected in this case study reduces the material requirement in production. Additional benefits of reducing assembly and production costs, increasing component stiffness and reducing the total part weight are also realised through eliminating joints. Forming the four components separately requires four sets of stamping tools. Using one large blank reduces the number of tools required, saving investment costs and tool material. However, forming the part as one large component reduces the flexibility in material selection which may negativity affect the functionality of the part. This is overcome through the use of tailored welded blanks which can combine multiple materials in one blank. The additional cost of laser welding the blanks is reclaimed through a substantial reduction in material requirement since the blanks are designed to nest perfectly on the coil. From this case study, the potential of these yield improvements strategies are evaluated as:

- **Combine parts to reduce material overlap:** This strategy could reduce the total blank holder and addendum surface required to form a part. Implementation may be limited due to the material selection strategy. Simplification of material selection, or the use or tailored welded blanks should be considered to increase the opportunity to combine parts. This strategy should be implemented whenever combining parts reduces the material requirement without compromising on the functionality of the part.
- **Design parts to nest:** Designing parts to nest can generate significant material savings, but can increase the complexity and time required to develop a part. The high number of coil types used to manufacture this vehicle prevents nesting multiple parts together. Future limitation of coil selection in part design could enable yield improvements through this strategy. Where material selection cannot be rationalised, nesting could be improved by designing tailored welded blanks. The use of tailored welded blanks also adds an additional manufacturing process of welding, increasing production costs. However, where economically viable it should be implemented as it increases flexibility in material selection and can dramatically reduce material demand. Increased production costs could be offset with material savings to enable implementation of this strategy.

### Summary of yield improvement case studies study

Material savings for each case study have been estimated and identify substantial material saving opportunities, summarised in figure 3. 21.

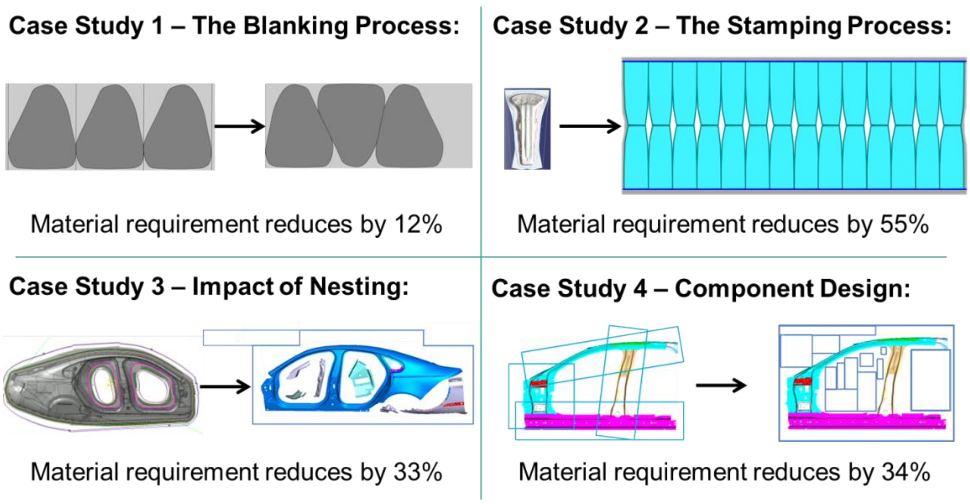



Figure 3.21 - Summary of case study findings undertaken to evaluate proposed yield improvement strategies.

The blanking, stamping and product design processes can be modified to reduce the material required to manufacture a part. However, these changes have been shown to add additional costs to the process in the form of: additional financial investment; a reduction in production flexibility; a potential limitation of part quality; process reliability; and material selection strategy. Additional benefits from reducing the material requirement are also identified.  These include the potential to improve part performance, formability and increase in production capacity. The evaluation of proposed yield improvement strategies is summarised in figure 3.22.

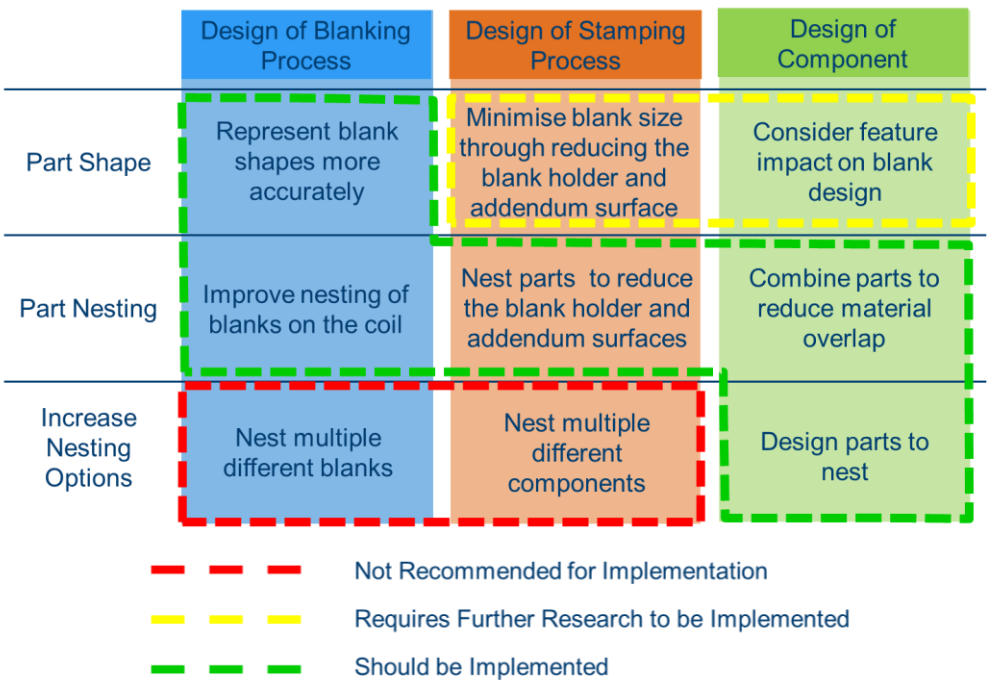



Figure 3.22 - Evaluation summary for yield improvement strategies.

## 3.4 Conclusions: The opportunity

Results from the process and component studies show that some yield losses are inevitable with existing cutting and forming technology. However, variations in yield losses identified in the industry study indicate an opportunity for most organisations to improve material utilisation. The four hypotheses proposed at the start of this chapter are now considered in turn to conclude the findings of this research.

### Are existing assumptions, of 60% material utilisation and 10% improvement opportunity, good estimates for manufacturing automotive sheet metal components?

Previous values for automotive material utilisation and the improvement opportunity have been shown to be estimates. This chapter has improved on these previous estimates for material utilisation through considering a larger evidence base. Through an industry study of 46 vehicles, it has been calculated that the average material utilisation of a passenger vehicle is 56% and there is a potential to improve the average material efficiency by at least 14%, demonstrated by the variability between vehicle models. Further innovation into material efficiency could increase this saving opportunity.

### Can the saving opportunity for material efficiency be quantified in terms of financial and environmental savings?

The annual global cost of automotive sheet metal yield losses has been quantified as £15 billion, and 43 million tonnes of $CO_2$. Benchmarking the automotive industry identified a best practice material utilisation of 70%. Improving the industry average material efficiency to 70% would reduce the embodied emissions and material costs of the sheet metal car structure by 26% and 24% respectively. This could provide a global annual saving opportunity of 25 million tonnes of $CO_2$, and £8 billion.

### Are the suggestions of improving material utilisation through the design of the nest on the coil and the gripping area in forming valid?

A detailed evaluation of every sheet metal component in a case study vehicle revealed that yield losses occur when a blank is nested inefficiently on the coil, simplified to a regular shape, or increased in size due to the design of the part, blank holder and addendum surfaces. A study of business processes identified that yield losses are increased to meet part design and manufacturing requirements. Suggestions to improve nesting and gripping are therefore valid strategies to improve the material utilisation of automotive sheet metal components. However, these two strategies do not capture all of the opportunity for material efficiency.

### Are there any other strategies which could improve the material utilisation of sheet metal component?

In addition to the design of the nest and the gripping area, this investigation has shown that material savings could be made through consideration of material utilisation during part design and manufacturing process selection decision making. Results from the industry, vehicle and business process investigations were analysed to propose and evaluate nine strategies for sheet metal scrap reduction. Five of these strategies could be implemented immediately and two further strategies could be implemented with additional research. Two of the nine strategies were considered to be unsuitable for implementation at this time.

Suggestions have made to enable immediate and long term implementation of yield improvement strategies. A motivated company can implement the yield improvement strategies identified in figure 3.22 if they consider material utilisation earlier, generate specific targets and allow process improvements. Enabling actions to implement yield improvement strategies include:

- Introducing and ensuring implementation of process guidelines, with specific material utilisation targets for all stages of the design process.

- Increasing cross-functional collaboration and training in Design-for-Manufacture could improve organisational capability to design components for maximum material utilisation.
- Evaluating the costs and benefits of yield improvement could increase the motivation for change and raise the priority of material utilisation compared with other performance criteria.
- Reducing reliance on surrogate data could facilitate continuous improvement and process innovation in the design and manufacture of material efficient parts.
- Long term improvements could be achieved through researching enabling technologies such as improved laser blanking, tailor welded blanks and advances in stamping technology.

Chapter 4 will now consider these strategies further through a detail case study, in order to quantify the opportunity and potential implementation barriers. Later in this thesis; chapter 5 will consider the specific targets required to support implementation of material efficiency, and Chapter 6 will address the lack of evidence-based guidelines for the design of component geometry with improved material utilisation.

# Chapter 4 Realising the Potential

Material efficiency is a method of reducing industrial $CO_2$ emissions by meeting service requirements with less material, (Allwood et al. 2010). This strategy can provide savings with no knock-on effect for the consumer. Engert & Baumgartner (2016) identified a gap between sustainability strategies and their implementation in an industrial setting. This chapter aims to bridge this gap, working in partnership with an automotive manufacturer, the study explores how much of the potential saving opportunity identified in chapter 3 can be realised in practice and identifies the barriers to industrial implementation. This gritty implementation knowledge is crucial in the context of urgent aspirations to reduce industrial $C0_2$ emissions. This chapter presents a case study to investigate the following hypotheses:

- To what extent can the material efficiency opportunity identified in chapter 3 be realised in an industrial setting?
- Are implementation barriers significant in improving the material utilisation of sheet metal component?
- Can an intervention be made to reduce these implementation barriers and enable improved material efficiency in the automotive industry?

Section 4.1 introduces the case study methodology. Section 4.2 gives detailed results and examples of the optimisation activities. A summary of the results is analysed in section 4.3 and the findings are then evaluated in section 4.4 to establish whether any intervention can be made to improve the extent in which material efficiency strategies are realised in an industrial setting.

## 4.1 Methodology: A case study to improve material efficiency in automotive sheet metal components

The literature review in section 2 demonstrates that many material efficiency strategies can reduce sheet metal yield losses for automotive components, but in practice implementation barriers exist which prevent saving opportunities from being fully realised. This chapter presents a case study developed in partnership with an automotive manufacturer as a means to demonstrate the realistic saving opportunity from these material efficiency strategies and recommend actions to overcome any implementation barriers identified.

The partner company formed a cross-functional team and invested approximately 300 man-hours of engineering time into a trial process led by the author. As a result, the findings of the case study accurately reflect the challenges of implementing material efficiency strategies in an industrial setting. The component engineers involved followed a multi-step optimisation process to identify opportunities for material utilisation improvement. These savings were recorded, and if an opportunity could not be implemented, the barrier was identified. All product development decisions were undertaken by the professional engineers developing these components and were made in conjunction with the existing product development cycle of the automotive manufacturer.

Figure 4.1 shows the steps undertaken to set up, gain permission for, and implement the case study. These steps were essential to ensure the opportunities and barriers identified were a true reflection of decision making in an industrial setting. This flow chart was developed specifically for the partner automotive manufacturer in this material utilisation case study, but could be applied to other material efficiency case studies. More broadly, the individual activities shown in figure 4.1 are transferable to other sustainability focused exercises, such as those described by Lewis et al. (2001) in their guide for considering the environment during product design across multiple industries. The steps displayed with a double box are specific to this case study and are discussed in more detail in this chapter.

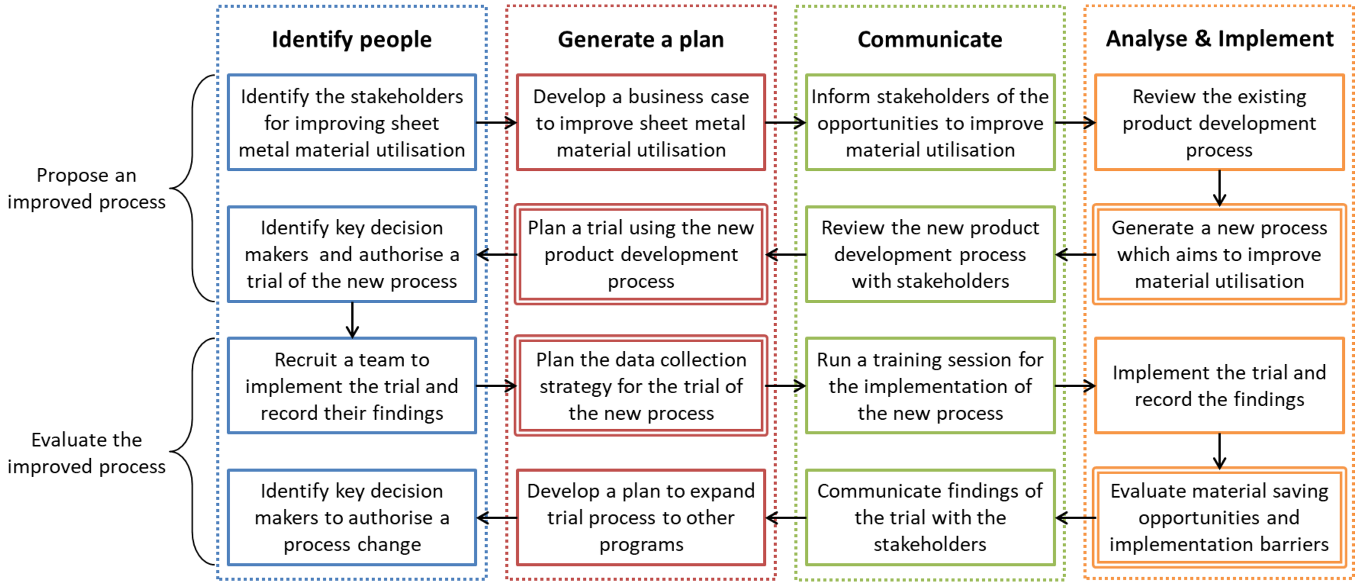



**Figure 4.1** **Flow chart of the steps taken to implement an industrial trial for improving material utilisation in practice.**

This section now provides further detail on the proposed product development process developed to improve material utilisation, the parts selected for the process trial and the data collection strategy used to gather results from the case study.

### 4.1.1 Proposed material utilisation improvement process

The cross-functional team involved in the study was provided with a new structured design process for improved material utilisation. The new process was designed to ensure the team considered all available strategies to improve sheet metal material utilisation in their decision making.

These activities consider the design of the 'blank nesting' and 'gripping area' described by Milford et al. (2011), as well as the new material efficiency strategies which were identified in chapter 3. This new design process was generated by breaking down the nine material utilisation improvement strategies detailed in chapter 3 into individual activities which could improve the material utilisation of a component throughout the product development cycle. Sixteen activities were required to consider all material utilisation improvement strategies. This material utilisation improvement process is described in table 4.1.

**Table 4.1 Summary of material utilisation improvement process proposed in this study**

| Activity | Description | Area |
|---|---|---|
| 1. Benchmark parts | Compare the material utilisation for the same part on different vehicles. Identify how differences in the geometry and manufacturing process affect material utilisation. Use this information to set component level targets and inform future decision making. | Component geometry |
| 2. Design Joints between components | Evaluate whether the location and method of joining to neighbouring components can be changed to improve material utilisation. | Component geometry |
| 3. Adapt geometry for process selection | Consider if the component geometry can be modified to allow the part to be manufactured using a simpler process, e.g. formed rather than drawn. | Component geometry |
| 4. Adapt geometry for addendum design | Features such as large flat areas and rapid changes of section are difficult to form so require a large addendum surface. Evaluate if the geometry can be changed to improve material utilisation. | Component geometry |
| 5. Adapt geometry for blank profile | Evaluate if features of the part periphery, such as flanges and tabs, can be modified to enable tighter nesting on the coil. | Component geometry |
| 6. Design part radii for formability | Tight radii can be difficult to form so require additional material in the addendum surface. Evaluate where radii can be softened to reduce the material required in manufacturing. | Component geometry |
| 7. Select the simplest appropriate manufacturing process | Select the simplest appropriate manufacturing process, as a general rule the more simple the process the better the material utilisation. | Stamping |
| 8. Design impressions (number & spacing) | Evaluate whether changing the number of components (impressions) manufactured from each blank can improve the material utilisation. Where multiple impressions are drawn position the parts to minimise the size of the blank. | Stamping |
| 9. Design addendum surface | Evaluate whether the design of the addendum surface can be modified to reduce the size of the blank. | Stamping |
| 10. Position draw beads and trim lines | Minimise the spacing between the component's trim edge and draw bead. Ensure the formed blank edge finishes at the draw bead. | Stamping |
| 11. Define a developed blank shape | Design the blank shape specifically for the component rather than a generic trapezoidal or rectangular blank. Developed blanks require less addendum material and can be nested more tightly on the coil. | Blanking |
| 12. Allow non-conventional manufacturing process | Automotive manufacturers use design rules to minimise the risk of part failure. In some scenarios material can be saved if these rules are not followed, as long as the part is independently evaluated as being safe to form. For example, forming the component's flange on blank holder rather than the punch reduces the addendum surface required. | Stamping |
| 13. Nest blanks flexibly on the coil | Consider complex blank layouts which can be nested more tightly on the coil to reduce blanking scrap. | Blanking |
| 14. Reduce blank size during tool try outs | Forming simulations have an error margin compared to the physical forming process. Blanks are designed with additional material to account for this error. This additional material can be minimised during the tool try-out stage of production. | Blanking and Stamping |
| 15. Total savings identified | Consider the interaction between activities 2-14 to identify the greatest available material saving opportunity. | Combined |
| 16. Total savings implemented | Feedback the material used in the final production component to record the saving opportunity which was able to be implemented. | Combined |

The first activity is a benchmarking exercise. Activities 2-6 consider the design of the component geometry, activities 7-14 consider the manufacturing process and activities 15 and 16 evaluate the total saving opportunity identified and implemented. Each activity is based on decision points which affect material utilisation over the product development cycle. A detailed example of each activity can be found in section 4.2. The case study process was implemented over a 6 month period alongside the existing product development process. The only exception was activity 14 which could not take place until the tools were manufactured. Since this would not happen for another year, surrogate data from another vehicle is used to estimate the saving opportunity for this activity. The activities are evaluated independently so the savings can be compared.

Improving material utilisation with the proposed process requires an iterative approach to product design and manufacturing engineering with feedback loops between multiple business areas. The activities described in table 4.1 were managed through weekly cross-functional workshops coordinated by a process engineer and supported by product, manufacturing, cost and sustainability engineers. Additional focus meetings took place on an ad-hoc basis when required. The material saving opportunity was quantified by the team for each product development activity and assessed to decide whether a change should be implemented.

The components selected for this process trial are now described.

### 4.1.2 Parts selected to trial the proposed process

The vehicle selected to trial the proposed product development process is an existing production vehicle. Key parameters of the case study vehicle are:

- Annual production volume ~ 200000 vehicles
- Powertrain system: combustion engine or battery technology
- Sheet metal weight ~ 300kg
- Sheet metal material mix aluminium vs steel ~ 50:50

The vehicle was selected for this study as is was undergoing a model year refresh. As shown in figure 4.2, a model year refresh sits below the model variant design in the hierarchy of product development. This means that during a model year refresh some, but not all, of the sheet metal components are modified to upgrade the vehicle design. For the vehicle selected, some of the sheet metal components required modification and re-tooling in order to the move from a combustion engine to battery powertrain technology. It is possible to compare the material utilisation of these modified components to the original components. Selecting these components for the case study trial enables the improvement opportunity from the proposed product design process to be measured.

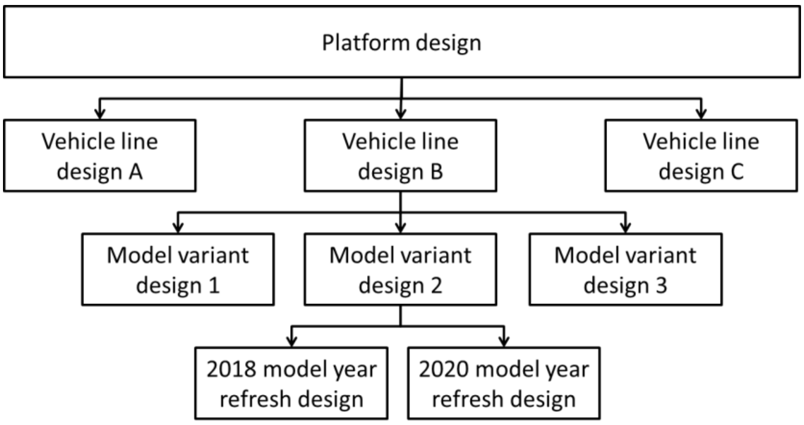



**Figure 4.2 Structure of product design activities in the automotive industry.**

Ten components were selected for the trial. The material required to manufacture these ten components accounts for 12% of the sheet metal required to manufacture the whole vehicle. The saving opportunities identified for these components are extrapolated to estimate the potential saving opportunity if the whole vehicle was considered. These ten components are produced from five blanks as the left hand and right hand components are manufactured together. To simplify the analysis the left and right hand components are evaluated together as one ‘part’. The case study parts include both steel and aluminium components and have initial material utilisation values ranging from 32% to 60%. The case study will reduce these yield losses, shown in orange and blue in figure 4.3.

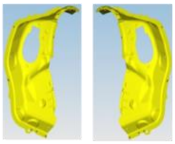
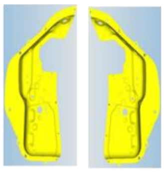
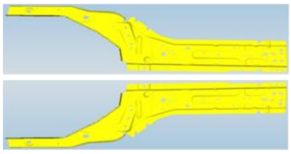
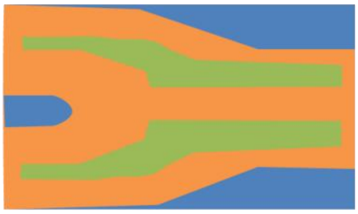
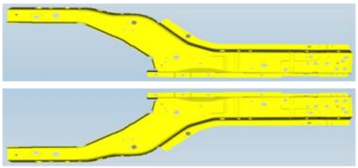
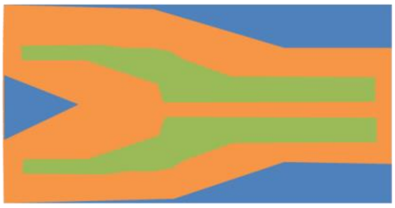
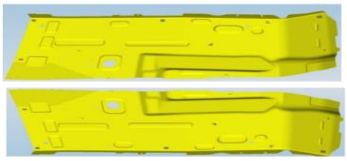
| Part No. | (a) CAD view | (b) Blank view |
|---|---|---|
| 1. |  |  |
| 2. |  |  |
| 3. |  |  |
| 4. |  |  |
| 5. |  |  |

**Figure 4.3 Parts investigated in the case study. (a) CAD of the final component, (b) a diagram showing how much blanking scrap (blue) and stamping scrap (orange) is generated to make the final component (green) from the sheet metal blank.**

The methodology for data collection to process results from the proposed product design process trial is now outlined.

### 4.1.3 Data collection and evaluation of the savings opportunity

In order to evaluate the new product design process, a consistent data collection strategy was developed. At each point in the improvement process, the team both identified material utilisation improvement opportunities for the five parts and calculated the expected savings, as follows.

The material utilisation improvement is recorded as a percentage point change as described in equations 4.1, 4.2 and 4.3. Percentage point change is the industry recognised performance measure for material utilisation improvement; it enables the comparison of savings gained for components which have different part and coil masses. For example, if an optimisation activity improved the material utilisation from 50% to 55% the increase in Material Utilisation (MU) is recorded as $5\%_{pts}$.

$$MU_{initial} = \frac{\text{Initial part mass}}{\text{Initial coil mass}} \times 100 \quad (4.1)$$

$$MU_{new} = \frac{\text{New part mass}}{\text{New coil mass}} \times 100 \quad (4.2)$$

$$MU_{increase} = MU_{new} - MU_{initial} \quad (4.3)$$

The changes proposed during each activity were costed. The implemented saving opportunity was calculated by comparing the starting material utilisation value with the implemented value, detailed in the final manufacturing process sheet for each part. Savings are also reported as a material demand change in kilograms, and a cost change measured in both GBP and kilograms of $CO_2$e. Material savings are reported for the production of one vehicle, assuming production volumes of 200,000 vehicles per year and an even mix of steel and aluminium sheet metal. Financial savings are estimated from the reduction in material demand including the loss of revenue from reduced scrap metal recycling, additional processing costs and additional investment costs depreciated over two years. Environmental savings are estimated from the reduction in material demand including the effect of recycling scrap. The change in environmental impact of the manufacturing process is considered to be negligible compared to change in material demand so is not included in the analysis, (Cooper et al. 2017). The exact values for material and processing costs vary between components and organisations so an approximate figure of the correct order of magnitude is used for the analysis, as detailed in table 4.2. These values were estimated using cost and environmental profiles from the automotive manufacture partner in this study.

**Table 4.2 Values used for saving calculations.**

| Description | Value |
|---|---|
| Financial cost of aluminium scrap per tonne* | £2100 |
| Financial cost of steel scrap per tonne* | £500 |
| Environmental cost of aluminium per tonne* | 0.94 kg of $CO_2e$ |
| Environmental cost of steel per tonne* | 1.5 kg of $CO_2e$ |
| Additional drawing tool cost | £200,000 |
| Additional forming tool | £20,000 |
| Additional press process cost per part | £1.50 |
| Additional laser welding process per part | £1 |
| Additional process cost to laser cut a blank | £1 |
| Material utilisation improvement for activity 14 | 2.66% |

*assuming all production yield losses are recycled

This analysis only considers savings which are a direct result of material demand reduction. Indirect savings will also be generated, for example a reduction in material demand will reduce the number of coil deliveries required generating further financial and environmental savings.

In addition to the numerical data, the challenges associated with implementing each activity were recorded, as well as whether the proposed change was implemented on the vehicle. Implementation barriers were listed as they were recognised throughout the case study. Where an improvement was not implemented the potential saving in percentage points is allocated to the appropriate barrier. Where more than one barrier existed the missed saving opportunity is allocated in whole to every appropriate barrier. This method of allocation is used since all barriers must be removed to successfully implement a material utilisation improvement. Information was gathered through observing project meetings and reviewing process sheets which outline the details of component manufacturing process. Section 4.2 now reports the results as raw data and gives detailed example of each activity. The results are then collated and analysed in section 4.3 to determine the industry potential for material efficiency strategies and the significance of implementation barriers

## 4.2 Results: Implementation of material efficiency strategies in the design and manufacture of automotive sheet metal components

The results from the industrial trial of a product design process for improved material utilisation are detailed in section 4.2.1. To support these results, an example of each activity is given in section 4.2.2

### 4.2.1 Opportunities and implementation barriers

Tables 4.3 and 4.4 summarise the average material utilisation saving opportunity and the implementation barriers identified by the automotive manufacturer during the trial of a new product design process. It can be seen that the most rewarding activities are designing the component geometry for process selection, selecting the simplest manufacturing process, designing the joints between components, and defining a shaped blank. The most significant implementation barrier is the lack of development time or resource, followed by the lack of equipment and lack of confidence in new technology.

Table 4.3 Material utilisation breakdown for optimisation activities.

| Process Step | | Average MU% $_{pts}$ Saving |
|---|---|---|
| 1. | Benchmark parts | 16 |
| 2. | Design joints between components | 13 |
| 3. | Adapt geometry for process selection | 16 |
| 4. | Adapt geometry for addendum design | 1 |
| 5. | Adapt geometry for blank profile | 0.1 |
| 6. | Design part radii for formability | <0.1 |
| 7. | Select simplest manufacturing process | 16 |
| 8. | Design impressions (number & spacing) | 1 |
| 9. | Design addendum surface | 1 |
| 10. | Position draw beads and trim lines | 5 |
| 11. | Define a developed blank shape | 10 |
| 12. | Allow non-conventional manufacturing process | 4 |
| 13. | Nest blanks flexibly on the coil | 2 |
| 14. | Reduce blank size during tool try outs | 3 |
| 15. | Total savings identified | 24 |
| 16. | Total savings implemented | 3 |

**Table 4.4 Average cost for implementation barriers.**

| Implementation Barrier | | Importance |
|---|---|---|
| 1 | Lack of development time/resource | 38% |
| 2 | Lack of equipment (soft and hard) | 20% |
| 3 | Lack of confidence in new technology | 16% |
| 4 | Risk of failure in production | 8% |
| 5 | Risk to dimensional stability of the part | 7% |
| 6 | Other component performance requirements | 5% |
| 7 | Increased assembly complexity | 3% |
| 8 | Neighbouring components and carryover content | 2% |
| 9 | Increased investment cost | 1% |
| 10 | Insufficient payback | 0.1% |
| 11. | Witness marks on the part | <0.1% |
| 12 | Increased processing cost | <0.1% |
| 13 | Lack of communication between departments | Not Assessable |
| 14 | Requires a change in business processes | Not Assessable |

Tables 4.4 to 4.9 now present the material utilisation saving opportunities for each part identified using the process described in section 4.1.

Table 4.5 Material Utilisation Opportunities Identified for Part 1.

| Optimisation Activity | $MU_{increase}$ $\%_{pts}$ | Saving (kg) | Saving (£) | Saving (CO2e) | Extent of implementation | Implementation challenges |
|---|---|---|---|---|---|---|
| 1. Benchmark parts | 10 | - | - | - | Variance information used to set benchmark material utilisation | |
| 2. Design joints between components | 18 | 2.36 | 3.03 | 2.22 | Not implemented | Increased assembly complexity |
| 3. Adapt geometry for process selection | 18 | 2.36 | 3.03 | 2.22 | Not implemented | Risk to dimensional stability of the part |
| 4. Adapt geometry for addendum design | No opportunity identified | | | | | |
| 5. Adapt geometry for blank profile | No opportunity identified | | | | | |
| 6. Design part radii for formability | No opportunity identified | | | | | |
| 7. Select simplest manufacturing process | 18 | 2.36 | 3.03 | 2.22 | Not implemented | Risk to dimensional stability of the part |
| 8. Design impressions (number & spacing) | 2 | 0.35 | 0.73 | 0.33 | Not implemented | Lack of development time/resource |
| 9. Design addendum surface | 1 | 0.15 | 0.31 | 0.14 | Fully implemented | - |
| 10. Position draw beads and trim lines | 3 | 0.52 | 1.08 | 0.48 | Not implemented | Risk of failure in production |
| 11. Define a developed blank shape | 0 | 0.00 | -1.00 | 0.00 | Implemented for formability not MU | - |
| 12. Allow non-conventional manufacturing process | 0 | 0.00 | 0.00 | 0.00 | Already Implemented for formability | - |
| 13. Nest blanks flexibly on the coil | No opportunity identified | | | | | |
| 14. Reduce blank size during tool try outs | 3 | 0.40 | 0.84 | 0.38 | Planned implementation | - |
| 15. Total savings identified | 29 | 3.38 | 3.71 | 3.18 | - | - |
| 16. Total savings implemented | 3 | 0.55 | 0.16 | 0.52 | - | - |

Table 4.6 Material Utilisation Opportunities Identified for Part 2.

| Optimisation Activity | $MU_{increase}$ $\%_{pts}$ | Saving (kg) | Saving (£) | Saving (CO2e) | Extent of implementation | Implementation challenges |
|---|---|---|---|---|---|---|
| 1. Benchmark parts | 21 | - | - | - | Variance information used to set benchmark material utilisation | |
| 2. Design joints between components | No opportunity identified | | | | | |
| 3. Adapt geometry for process selection | No opportunity identified | | | | | |
| 4. Adapt geometry for addendum design | 0.3 | 0.16 | 0.08 | 0.23 | Not implemented | Package constraints from neighbouring components |
| 5. Adapt geometry for blank profile | 0.3 | 0.18 | 0.09 | 0.27 | Fully implemented | - |
| 6. Design part radii for formability | 0.1 | 0.08 | 0.04 | 0.12 | Not implemented | Saving is not worth the change |
| 7. Select simplest manufacturing process | No opportunity identified | | | | | |
| 8. Design impressions (number & spacing) | No opportunity identified | | | | | |
| 9. Design addendum surface | 1 | 0.58 | 0.29 | 0.87 | Fully implemented | - |
| 10. Position draw beads and trim lines | 1 | 0.47 | 0.23 | 0.70 | Not implemented | Risk of failure in production |
| 11. Define a developed blank shape | No opportunity identified | | | | | |
| 12. Allow non-conventional manufacturing process | 0 | 0.00 | 0.00 | 0.00 | Already implemented for formability not MU | - |
| 13. Nest blanks flexibly on the coil | No opportunity identified | | | | | |
| 14. Reduce blank size during tool try outs | 3 | 1.56 | 0.78 | 2.34 | Planned implementation | - |
| 15. Total savings identified | 5 | 2.69 | 1.35 | 4.04 | - | - |
| 16. Total savings implemented | 4 | 1.99 | 0.99 | 2.98 | - | - |

**Table 4.7 Material Utilisation Opportunities Identified for Part 3.**

| Optimisation Activity | $MU_{increase}$ $\%_{pts}$ | Saving (kg) | Saving (£) | Saving (CO2e) | Extent of implementation | Implementation challenges |
|---|---|---|---|---|---|---|
| 1. Benchmark parts | 18 | - | - | - | Variance information used to set benchmark material utilisation | |
| 2. Design joints between components | 10 | 6.25 | 10.16 | 5.87 | Not implemented | Lack of development time/resource |
| 3. Adapt geometry for process selection | 13 | 7.05 | 11.83 | 6.62 | considered for future programmes | Lack of confidence in new technology e.g. TWB |
| 4. Adapt geometry for addendum design | No opportunity identified | | | | | |
| 5. Adapt geometry for blank profile | No opportunity identified | | | | | |
| 6. Design part radii for formability | No opportunity identified | | | | | |
| 7. Select simplest manufacturing process | 13 | 7.05 | 11.83 | 6.62 | considered for future programmes | Lack of confidence in new technology e.g. TWB |
| 8. Design impressions (number & spacing) | 1 | 0.53 | 1.11 | 0.50 | Fully implemented | - |
| 9. Design addendum surface | 2 | 0.73 | 1.53 | 0.69 | Fully implemented | - |
| 10. Position draw beads and trim lines | 7 | 2.91 | 6.08 | 2.74 | Not implemented | Risk of failure in production |
| 11. Define a developed blank shape | 21 | 6.27 | 13.10 | 5.89 | Not implemented | Lack of equipment (soft and hard) |
| 12. Allow non-conventional manufacturing process | 9 | 1.34 | 2.81 | 1.26 | Not implemented | Risk to dimensional stability of the part |
| 13. Nest blanks flexibly on the coil | 4 | 1.86 | 3.90 | 1.75 | Not implemented | Lack of equipment (soft and hard) |
| 14. Reduce blank size during tool try outs | 3 | 1.20 | 2.51 | 1.13 | Planned implementation | |
| 15. Total savings identified | 34 | 8.69 | 18.17 | 8.17 | - | - |
| 16. Total savings implemented | 4 | 1.93 | 4.03 | 1.81 | - | - |

Table 4.8 Material Utilisation Opportunities Identified for Part 4.

| Optimisation Activity | $MU_{increase}$ $\%_{pts}$ | Saving (kg) | Saving (£) | Saving (CO2e) | Extent of implementation | Implementation challenges |
|---|---|---|---|---|---|---|
| 1. Benchmark parts | 21 | - | - | - | Variance information used to set benchmark material utilisation | |
| 2. Design joints between components | 8 | 5.43 | 8.45 | 5.10 | Not implemented | Lack of development time/resource |
| 3. Adapt geometry for process selection | 12 | 6.23 | 10.12 | 5.86 | considered for future programmes | Lack of confidence in new technology e.g. TWB |
| 4. Adapt geometry for addendum design | No opportunity identified | | | | | |
| 5. Adapt geometry for blank profile | No opportunity identified | | | | | |
| 6. Design part radii for formability | No opportunity identified | | | | | |
| 7. Select simplest manufacturing process | 12 | 6.23 | 10.12 | 5.86 | considered for future programmes | Lack of confidence in new technology e.g. TWB |
| 8. Design impressions (number & spacing) | 0.7 | 0.28 | 0.59 | 0.27 | Fully implemented | - |
| 9. Design addendum surface | 0.5 | 0.48 | 0.99 | 0.45 | Fully implemented | - |
| 10. Position draw beads and trim lines | 9 | 2.91 | 6.08 | 2.74 | Not implemented | Risk of failure in production |
| 11. Define a developed blank shape | 26 | 6.72 | 13.64 | 6.31 | Not implemented | Lack of equipment (soft and hard) |
| 12. Allow non-conventional manufacturing process | 10 | 1.34 | 2.81 | 1.26 | Not implemented | Risk to dimensional stability of the part |
| 13. Nest blanks flexibly on the coil | 5 | 1.86 | 3.90 | 1.75 | Not implemented | Lack of equipment (soft and hard) |
| 14. Reduce blank size during tool try outs | 3 | 1.03 | 2.14 | 0.96 | Planned implementation | |
| 15. Total savings identified | 40 | 8.63 | 18.04 | 8.11 | - | - |
| 16. Total savings implemented | 4 | 1.50 | 3.14 | 1.41 | - | - |

**Table 4.9 Material Utilisation Opportunities Identified for Part 5.**

| Optimisation Activity | $MU_{increase}$ $\%_{pts}$ | Saving (kg) | Saving (£) | Saving (CO2e) | Extent of implementation | Implementation challenges |
|---|---|---|---|---|---|---|
| 1. Benchmark parts | 27 | - | - | - | Variance information used to set benchmark material utilisation | |
| 2. Design Joints between components | 17 | 1.51 | 3.16 | 1.42 | Not implemented | Other component requirements |
| 3. Adapt geometry for process selection | 9 | 1.12 | 3.24 | 1.05 | Not implemented | Package constraints from neighbouring components |
| 4. Adapt geometry for addendum design | 4 | 0.53 | 1.11 | n/a | Not implemented | Other component requirements |
| 5. Adapt geometry for blank profile | No opportunity identified | | | | | |
| 6. Design part radii for formability | No opportunity identified | | | | | |
| 7. Select simplest manufacturing process | 9 | 1.12 | 3.24 | 1.05 | Not implemented | Package constraints from neighbouring components |
| 8. Design impressions (number & spacing) | 6 | 0.72 | 3.57 | 0.68 | Not implemented | Increased investment cost |
| 9. Design addendum surface | 0.3 | 0.04 | 0.07 | 0.03 | Fully implemented | - |
| 10. Position draw beads and trim lines | 8 | 0.94 | 1.96 | 0.88 | Not implemented | Risk to dimensional stability of the part |
| 11. Define a developed blank shape | No opportunity identified | | | | | |
| 12. Allow non-conventional manufacturing process | No opportunity identified | | | | | |
| 13. Nest blanks flexibly on the coil | No opportunity identified | | | | | |
| 14. Reduce blank size during tool try outs | 3 | 1.48 | 3.10 | 1.40 | Planned implementation | - |
| 15. Total savings identified | 12 | 1.39 | 3.90 | 1.48 | - | - |
| 16. Total savings implemented | 3 | 0.38 | 0.80 | 0.56 | - | - |

An example is now given for each activity to illustrate how the material efficiency opportunities reported in tables 4.5 to 4.9 were generated.

### 4.2.2 Material utilisation improvement activity examples

This section provides an example of the material utilisation improvement activities 1-14 as described in section 4.1.

**Activity 1: Benchmark parts**

On average there is a 16%$_{pts}$ material utilisation variance to manufacture the same case study components between different vehicle models. The most extreme difference is observed for Part 5 which has a material utilisation variance of 27%$_{pts}$, as shown in table 4.10.

Table 4.10 Results of benchmarking exercise for Part 5.

| | **Vehicle 1** | **Vehicle 2** | **Vehicle 3** | **Vehicle 4** |
|---|---|---|---|---|
| **Material** | Aluminium | Steel | Steel | Aluminium |
| **Raw material weight (kg)** | 3.8 | 17.4 | 12.7 | 4.5 |
| **Part weight (kg)** | 2.5 | 8.0 | 6.0 | 3.3 |
| **Material Utilisation (%)** | 65 | 46 | 47 | 73 |

Vehicle 4 has the highest material utilisation. This is enabled by a shallow part design which can be formed rather than drawn, and a straight edge profile which can be efficiently nested on the blank. This design is not possible for the case study vehicle as limited ground clearance means that a deeper drawn part is required to avoid contact with neighbouring components. The best material utilisation for vehicle with a deep drawn floor pan is vehicle 1, an appropriate benchmark value was therefore considered to be 65%.

**Activity 2: Design Joints between components**

Redesigning the interface between the tunnel and the pan floor (part 5) to a straight edge reduces the blanking scrap compared to a tapered joint, as shown in figure 4.4. For part 5 this design change improves material utilisation by 5%$_{pts}$.

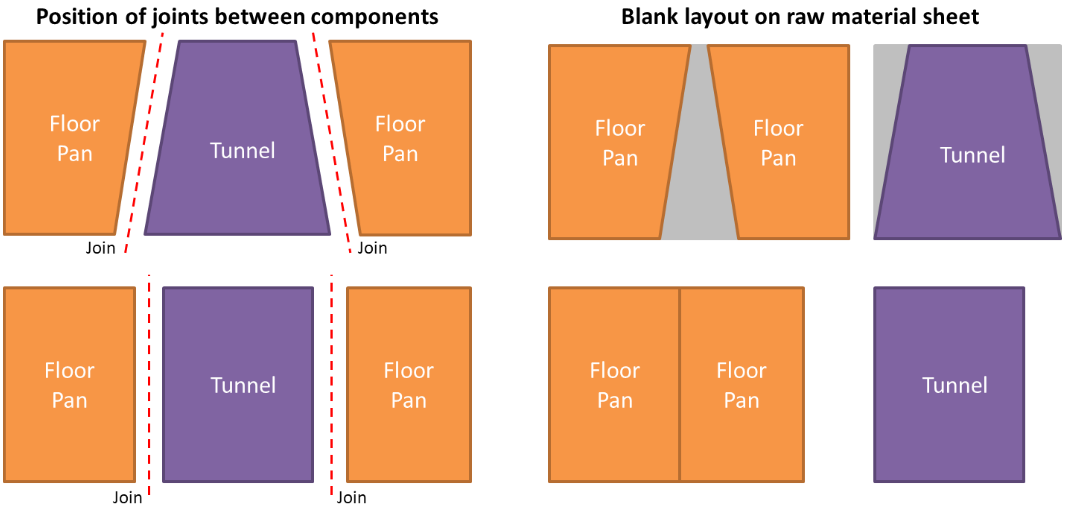



**Figure 4.4** **Straightening the joints within the assembly reduces blanking scrap (grey) to improve the material utilisation by 5%pts.**

Alternatively the components in the assembly could be combined and manufactured as one part, as shown in figure 4.5. This would reduce stamping scrap to increase the material utilisation of the assembly by $17\%_{pts}$.

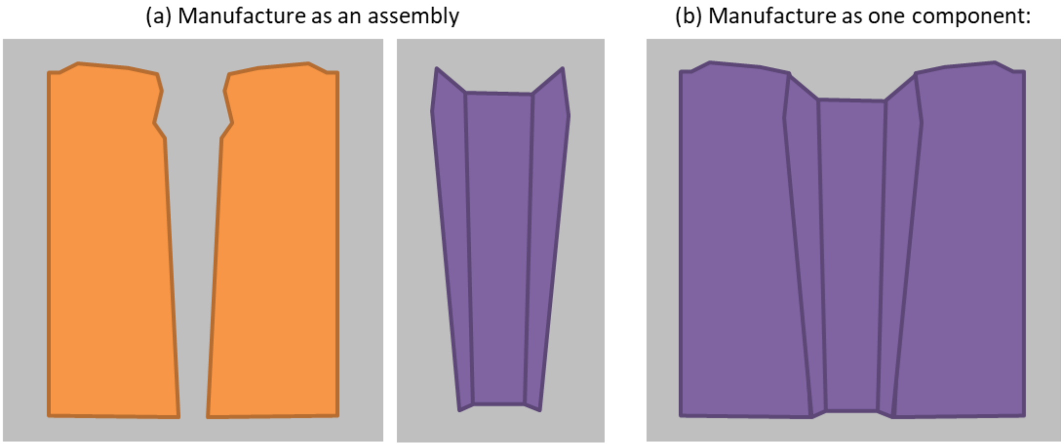



**Figure 4.5** **Representation of the stamping scrap (grey) generated in manufacturing individual components for an assembly (a), compared to one combined part (b). Combining the assembly improved the material utilisation by 17%pts.**

These changes could not be implemented for the case study vehicle as the tunnel was not being re-tooled for the model year refresh, therefore the joining strategy could not be changed. This change could be implemented in future programmes when the joining strategy is being reviewed early in the product development cycle.

**Activity 3: Adapt geometry for process selection**

Splitting and laser welding the blanks for both parts 3 and 4 improves the material utilisation of part 3 by 12%$_{pts}$, as shown in figure 4.6.The component geometry requires modification to implement this saving opportunity, in order to maintain the structural performance of the component.

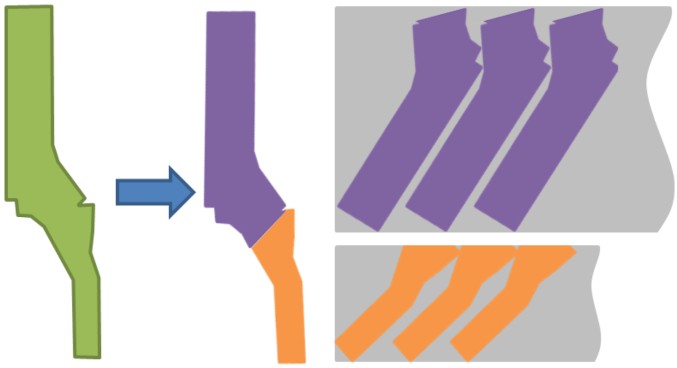
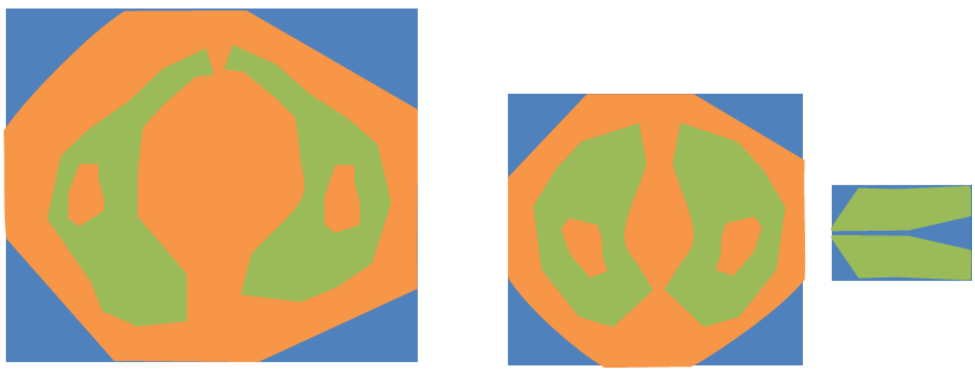


Figure 4.6 Splitting the blank reduces blanking scrap to improve the material utilisation by 12%pts.

This change was not implemented as additional testing was required to confirm the structural properties of the laser welded joint, the program did not have the time to undertake this test work. It was acknowledged that this change could be implemented in future programmes if this design change was considered earlier in the product development cycle.

**Activity 4: Adapt geometry for addendum design**

Part 1 is a complex deep drawn component requiring a large addendum surface. If this component is split into two, the lower section can be crash formed reducing the size of the addendum surface as shown in figure 4.7. This change improves material utilisation by 18%$_{pts}$.



(a) Component geometry with large addendum surface

(b) Component geometry with reduced addendum surface

Figure 4.7 Designing the geometry to reduce the addendum surface improves the material utilisation by 18%pts.

The change drives additional manufacturing processing costs, additional tools and increased complexity in the assembly plant. This change was not accepted for implementation due to lack of development time available to design the component in this new way.

**Activity 5: Adapt geometry for blank profile**

Modifying the tab design of part 2 reduces the blank pitch by 10mm, as shown in figure. 4.8. This change improves the material utilisation by 0.3%$_{pts}$ and has been implemented.

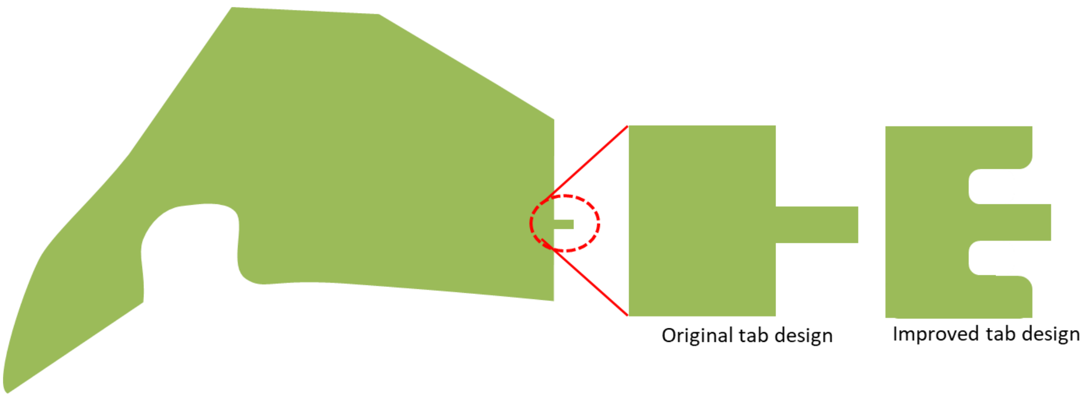



Figure 4.8 Redesigning the tab of part 2 reduces the pitch by 10mm.

**Activity 6: Design part radii for formability**

The 10mm radius highlighted with a red dotted line in figure 4.9 is not constraint by neighbouring components. This radius can be opened up to 20mm, making the part easier to draw and reduce the size of the addendum surface required. This change improves the material utilisation by 0.1%$_{pts}$.

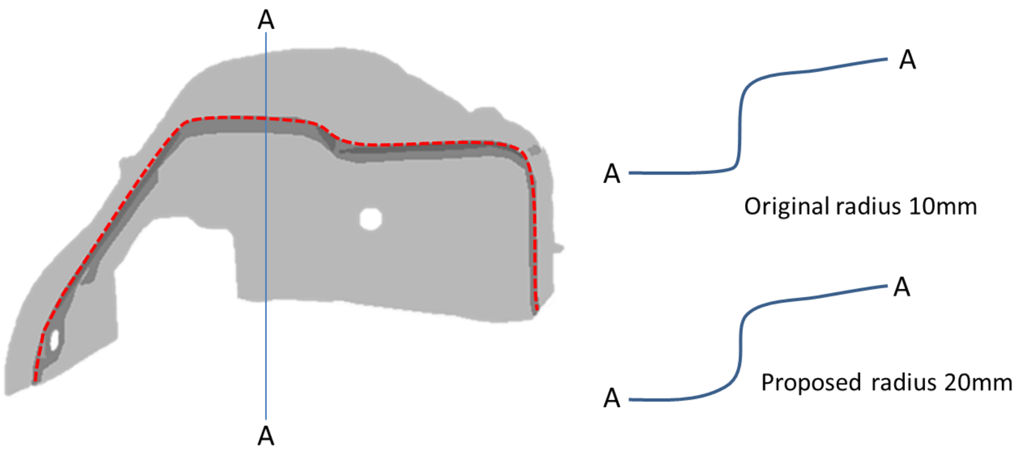



Figure 4.9 Opening the radius reduced the requirement for draw beads from a double bead to a single bead.

### Activity 7: Select the simplest appropriate manufacturing process

Each of the parts were considered for alternative manufacturing methods which require less material than deep drawing,  for example, roll forming, crash form and control forming. No saving opportunities were identified as all components in the study require deep drawing to be manufactured. Savings could be generated through appropriate process selection after a geometry change. These savings are captured in activities 2 and 3.

### Activity 8: Design the number of impressions & minimise spacing between parts

Increasing the number of impressions in part 5 from two to four parts per hit improves material utilisation by $6\%_{pts}$, this is shown in figure 4.10

(a) Two impressions per stamping

(b) Four impressions per stamping

Figure 4.10 Increasing the number of impressions formed in one hit improves material utilisation by 6%pts.

Implementing this change may reduce the dimensional stability of the components, as the replicated parts may not be identical to the originals, and required an increase in tool size. Increasing the number of parts per hit provided a material saving and increases the manufacturing rate. This change was not implemented due to change in budget requirements to increase investment costs of larger tools.

### Activity 9: Design the addendum surface

The shape of the addendum surface and blank holder area for part 3 can be modified to make the blank profile smaller by 2%, as shown in figure 4.11.This change has been implemented.

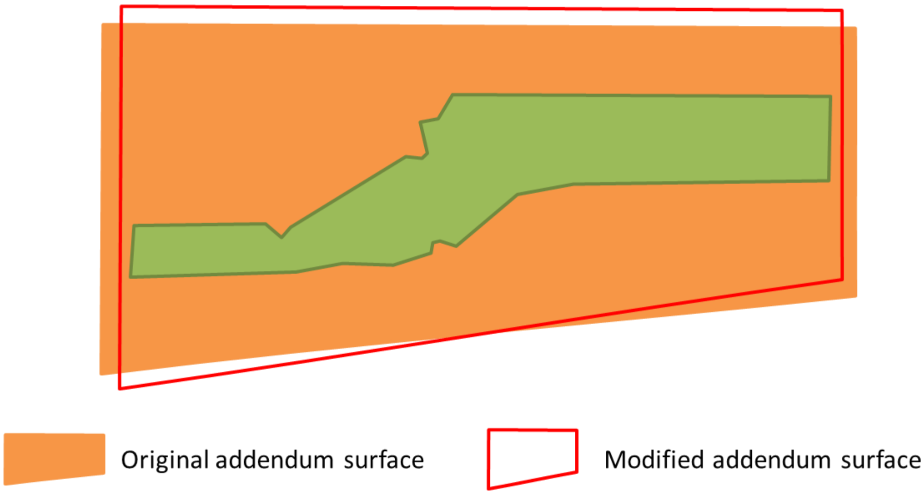



**Figure 4.11** **The blank profile is shown in orange and the part is shown in green. Modifying the addendum surface creates a smaller blank profile (not to scale).**

### Activity 10: Design the position of draw beads and trim lines

The position of draw beads for part 4 can be optimised to improve material utilisation as shown in figure 4.12.The blank edge of the formed part finishes 40mm from the draw bead. Material which finishes outside of the draw bead provides no benefit so this distance can be reduced. In addition the draw bead is 40mm from punch at closest point. This distance could be reduced to 18mm. This reduces the pitch and width of the blank improving material utilisation by 9%$_{pts}$.

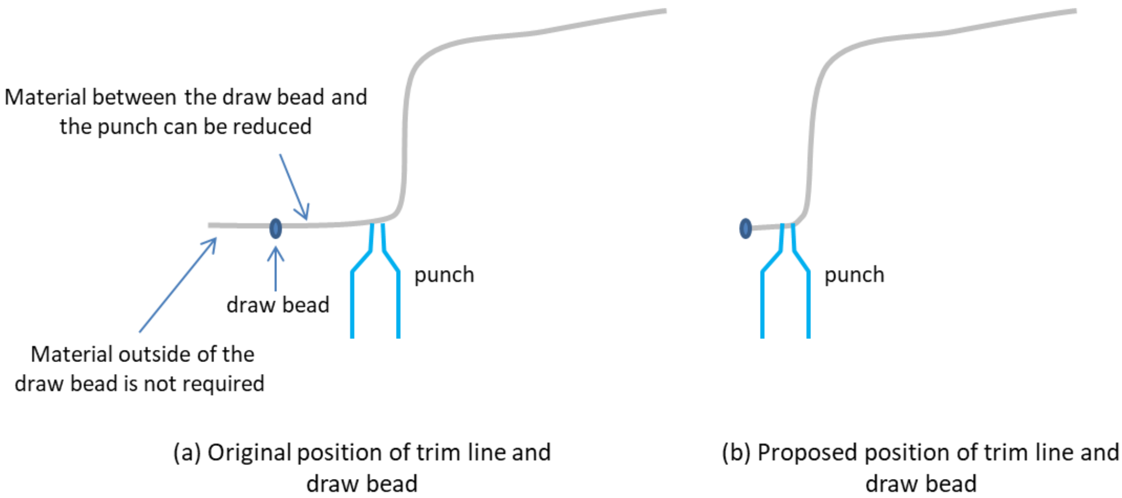



**Figure 4.12** **Modifying the position of the draw bead and trim line improves the material utilisation of part 4 by 9%pts.**

**Activity 11: Define a developed blank shape**

Designing the shape of the blank reduces the requirement for addendum surface and allows for closer nesting on the coil. This improves material utilisation. When the blank for part 4 is designed to be formed as a double unattached part with a shaped blank, material utilisation improves by 26%$_{pts}$, as shown in figure 4.13.This change was not implemented due to technology limitations restricted by size of blank on the blanking line.

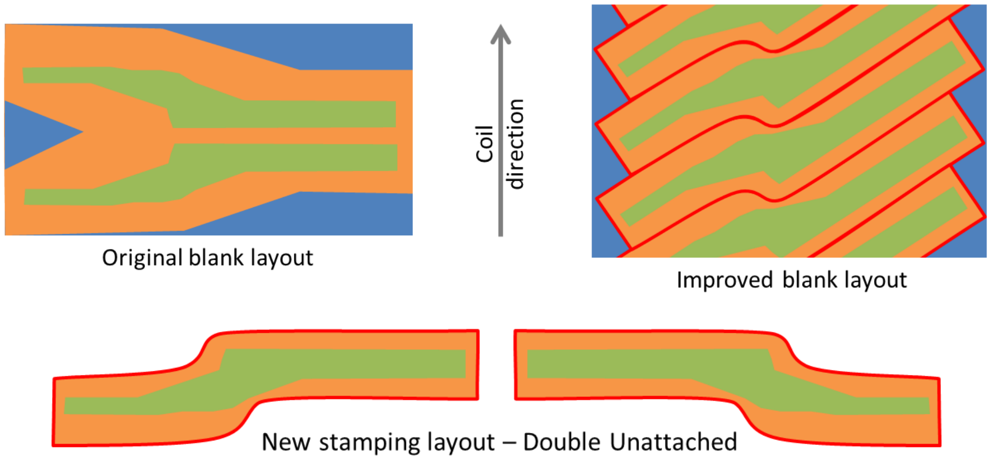



Figure 4.13 A shaped blank improves the material utilisation by 26%$_{pts}$ compared to a rectangular blank.

**Activity 12: Allow non-conventional process design**

Forming the flange on the blank holder rather than on the punch reduces the draw depth and trimming allowance, as shown in figure 4.14. A reduction in draw depth has an additional benefit of being easier to draw so requires a smaller addendum surface. The approximate saving for part 1 is 15%$_{pts}$, this is already implemented in the benchmark component due to formability challenges when forming on the punch.

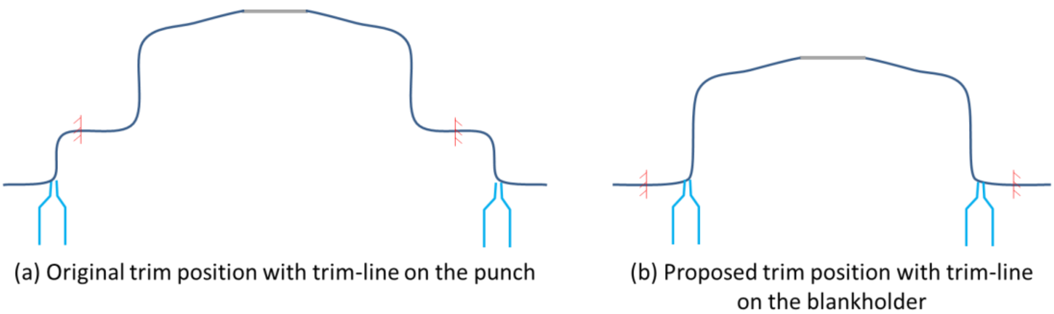
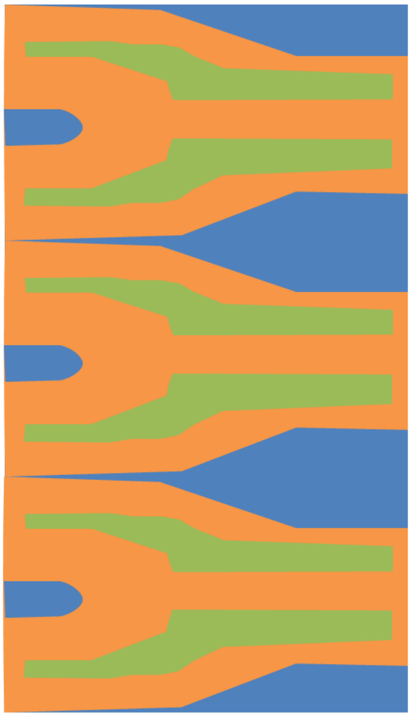


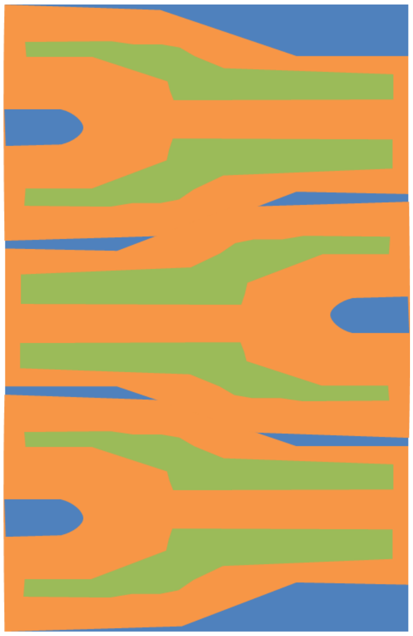

Figure 4.14 Forming the component flange on the blank holder rather than the punch improves the material utilisation of part 1 by 15%pts.

**Activity 13: Nest the blanks flexibly on the coil**

Alternating the blank orientation of part 3 improves the material utilisation by 4%, as shown in figure 4.15.This requires more space for two stacking robots at the end of the blanking line. This equipment constraint meant that this change could not be implemented.



Original blank layout



Improved blank layout

**Figure 4.15** **Alternating the blank orientation improves the material utilisation by 4%pts.**

**Activity 14: Reduce blank size during tool try outs**

The blank size is overestimated to allow for uncertainties in the forming simulation software. This additional material can be removed during the tool try-out process. Since the tools for the case study components have not yet been manufactured, the analysis uses surrogate data from 40 components which had a material utilisation improvement opportunity of 2.6 $\%_{pts}$.

These results are now analysed to reveal the extent in which material efficiency strategies are able to be implemented in an industrial setting using the proposed product design process.

## 4.3 Analysis: Structuring implementation case study results

To reveal why the full potential of material efficiency strategies has not yet been realised in the automotive industry, the trial of a new product design process for improved material utilisation was carried out over the period November 2017 – April 2018. The trial aimed to investigate the opportunities and barriers the automotive industry faces for improving the material utilisation of components. This analysis presents the results for the total and implemented saving opportunities for each of the five parts as a table. The results are extrapolated to consider the whole vehicle and then presented as a graphical summary. Structuring the results in this way displays the interaction between different activities and enables identification of the most beneficial interventions to implementing material efficiency in an industrial setting.

### 4.3.1 The total saving opportunity

Table 4.11 shows the total saving opportunity identified and implemented for each of the parts described in section 4.1.2. Results are given in terms of percentage point change, material demand reduction in kilograms, financial saving in GBP and environmental saving in kilograms of $CO_2e$. On average, the case study identified a significant average saving opportunity of 24%pts, but only 3%pts were able to be implemented.

**Table 4.11** Case study results, the total saving opportunity for each part and the average opportunity for one component.

| Evaluated savings per car | | MU ($\%_{pts}$) | Material (kg) | Financial (£) | Environmental (kg $CO_2e$) |
|---|---|---|---|---|---|
| **Part 1.** | Savings Identified | 29 | 3.38 | 3.71 | 3.18 |
| | Savings implemented | 3 | 0.55 | 0.16 | 0.52 |
| **Part 2.** | Savings Identified | 5 | 2.69 | 1.35 | 4.04 |
| | Savings implemented | 4 | 1.99 | 0.99 | 2.98 |
| **Part 3.** | Savings Identified | 34 | 8.69 | 18.17 | 8.17 |
| | Savings implemented | 4 | 1.93 | 4.03 | 1.81 |
| **Part 4.** | Savings Identified | 40 | 8.63 | 18.04 | 8.11 |
| | Savings implemented | 4 | 1.50 | 3.14 | 1.41 |
| **Part 5.** | Savings Identified | 12 | 1.39 | 3.90 | 1.48 |
| | Savings implemented | 3 | 0.38 | 0.80 | 0.56 |
| **Part average** | Savings Identified | 24 | 4.96 | 9.03 | 5.00 |
| | Savings implemented | 3 | 1.27 | 1.82 | 1.46 |

The part average material utilisation improvement opportunity of 24% is calculated as the average of the percentage point improvement for the five parts. In order to extrapolate the saving potential to estimate the annual saving opportunity, a weighted part average is calculated from the sum of the part weights divided by the sum of the coil weights. The weighted part average improvement opportunity for the case study components is calculated as 20%. This value is less than the average part improvement as the percentage point saving opportunity is less for the larger parts. The annual weighted saving opportunity for the five case study parts is shown in table 4.12. The saving opportunity realised is substantial considering only 12% of sheet metal parts were optimised. These figures would be much greater if the trial was scaled up to consider all 300+ sheet metal components, this opportunity is also shown in table 4.12.

Table 4.12 Case study results, summed for all case study components and the annual saving opportunity.

| Evaluated savings per year | | MU ($\%_{pts}$) | Material | Financial | Environmental |
|---|---|---|---|---|---|
| Weighted average saving from case study parts. | Savings Identified | 20 | 25kg | £45 | 25kg of $CO_2e$ |
| | Savings implemented | 3 | 6kg | £9 | 7kg $CO_2e$ |
| Annual weighted average saving from case study parts. | Savings Identified | 20 | 5kt | £9million | 5kt $CO_2e$ |
| | Savings implemented | 3 | 1kt | £2million | 2kt $CO_2e$ |
| Weighted average saving extrapolated to all parts. | Savings Identified | 20 | 209kg | £375 | 208kg $CO_2e$ |
| | Savings implemented | 3 | 49kg | £75 | 58kg $CO_2e$ |
| Annual weighted average saving extrapolated to all parts. | Savings Identified | 20 | 42kt | £75million | 42kt $CO_2e$ |
| | Savings implemented | 3 | 10kt | £15million | 12kt $CO_2e$ |

These material saving opportunities are now analysed by activity and represented in a graphical format.

### 4.3.2 Breakdown of saving opportunity by optimisation activity

Table 4.3 summarised the material utilisation saving opportunity for each activity averaged across the five components. The interaction of these saving opportunities and the timing in which they are required to be implemented provides context to interpret which activities provide the most potential. This interaction and timing is shown in figure 4.16, where the width of the line is proportional to the size of the saving opportunity identified.

The activities are positioned left to right along a product development timeline to demonstrate when they should be undertaken. Activities are connected on a line when some of the saving opportunity calculated from one activity is dependent on a previous activity being undertaken. Some activities cannot be implemented simultaneously as they eliminate the same material. For example, material requirement can either be reduced by designing a shaped blank or the same material could be eliminated by nesting a regular blank more efficiently. The savings from these activities are connected by a diamond to demonstrate that a decision is required to determine which activity to implement. The saving opportunities which can be combined to generate the maximum savings of $24\%_{pts}$ are shown in blue. The green lines represent material saving opportunities which were implemented. Opportunities which could not be implemented due to implementation barriers are shown with orange lines. The list to the right of figure 4.16 weights the relative importance of these implementation barriers.

The largest saving opportunities occur in the early phases of both part and manufacturing design strategy identified from activities 2 and 11, designing the joints and blank shape. However, it can be seen from figure 4.16 that implementation was not possible for these opportunities. Saving opportunities which were able to be implemented came from activities which took place later in the product development cycle when the detail of the design is considered. These results are now explored further in the discussion, to establish whether intervention is possible in order to realise the full potential of material efficiency opportunities.

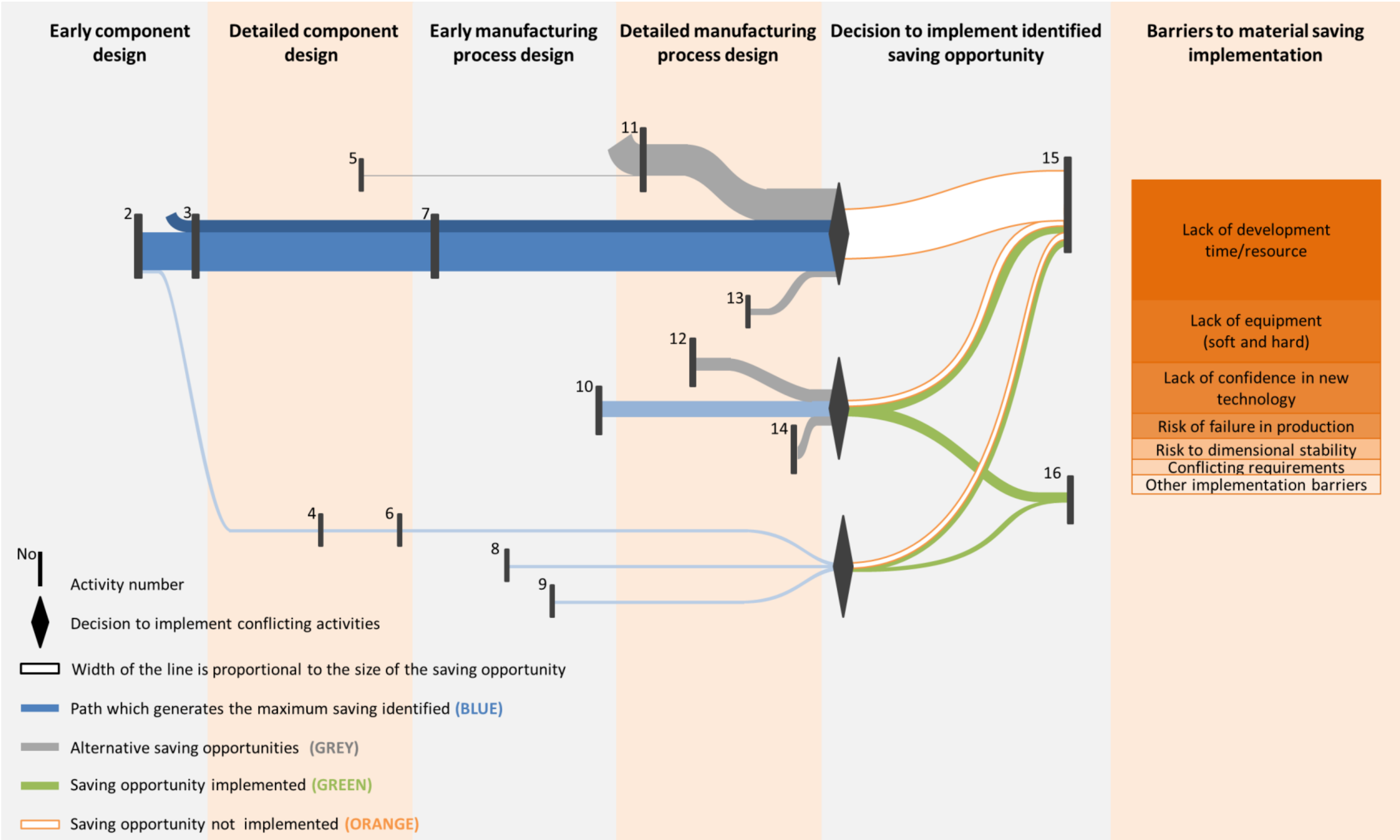



Figure 4.16 Interaction diagram showing the saving opportunity identified for each activity, the combination of activities which generates the maximum saving opportunity identified (blue), the saving opportunities implemented (green) and the saving opportunities which could not be implemented due to implementation barriers (orange). The width of the line is proportional to the size of the saving opportunity identified.

## 4.4 Evaluation: Realising the technical potential of material efficiency strategies in automotive sheet metal components

The trial process identified annual material utilisation savings of £9 million and 5kt of $CO_2$ from the five selected parts. The extent in which these results capture the full material efficiency opportunity for automotive sheet metal components is first considered. Since not all of the saving opportunities identified were able to be implemented on the vehicle, the barriers to implementation are next discussed. With this data, sourced directly from a car manufacturer, it is possible to make evidence based recommendations for future activities to increase the extent in which material efficiency strategies are realised in the automotive industry. Finally, more general observations are provided on using case studies to support material efficiency strategies.

### 4.4.1 To what extent was the proposed process able to capture the material efficiency opportunity?

In this case study, the material utilisation improvement opportunity was calculated by applying a trial process to five components and extrapolating the results to the whole vehicle i.e. a bottom up approach. Chapter 3 evaluated the material utilisation of other vehicles to identify the gap between the material utilisation of this vehicle and the industry best practice. This top down approach provided an estimate of the material utilisation improvement opportunity for the same vehicle. Figure 4.17 compares the two approaches.

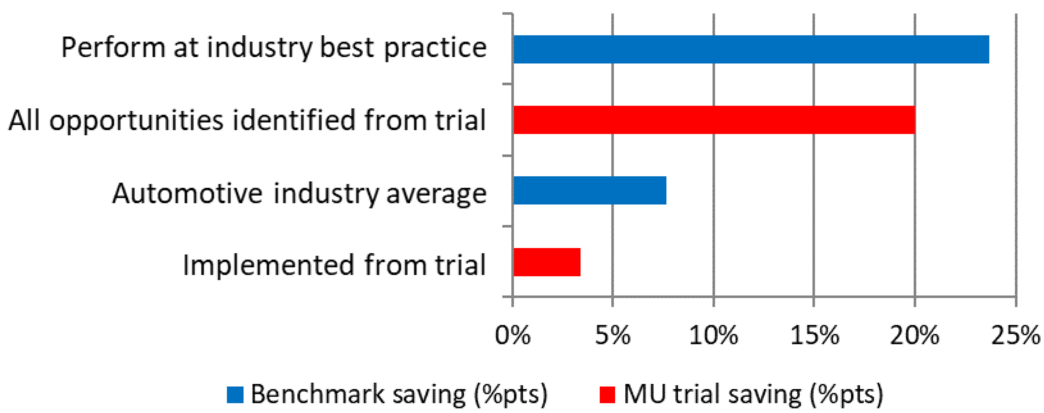



Figure 4.17 Bar chart showing material utilisation improvement opportunities from this trial (red) compared with other benchmark research in chapter 3 (blue).

As shown in figure 4.17, the maximum saving opportunity estimated by this case study using a bottom-up approach is very close to the value generated from the top-down approach in chapter 3. The proximity of the two approaches suggests that it is possible to achieve the best practice material utilisation value through applying the trial process, therefore the case study activities are an effective method of identifying improvement opportunities. This result also indicates that the scale of the material efficiency opportunity identified in chapter 3 is realistically achievable in an industrial setting. However, the actual saving implemented is significantly smaller, suggesting that whilst the saving opportunities are achievable, barriers must currently exist which prevent the full potential from being realised. The material utilisation opportunities and implementation barriers shown in figure 4.16 are now discussed to make recommendations on when and how material utilisation should be considered to overcome these barriers.

### 4.4.2 Why are the barriers to implementation so high?

The implemented saving opportunity is significantly lower than the total identified opportunity suggesting the implementation barriers are significant. A large contributor to this difference is because the activity with the greatest opportunity, activity 2, takes place during the strategy design phase when resources are not focused on material utilisation. Since material utilisation is usually considered to be a manufacturing engineering metric, resources are invested later during the product development process. The greatest opportunity to improve material utilisation occurs from modifying how components are joined and manufactured. These decisions are made early in the product development process. Material utilisation should therefore be considered from the start of a program, not just in the design of the manufacturing process. This links with the most significant implementation barrier identified, which is lack of product development time. To overcome this barrier, resources and training to improve material utilisation should be reprioritised from the end of the product development cycle to the start, as illustrated in figure 4.18. This would enable design for material utilisation at the early stages of product development.

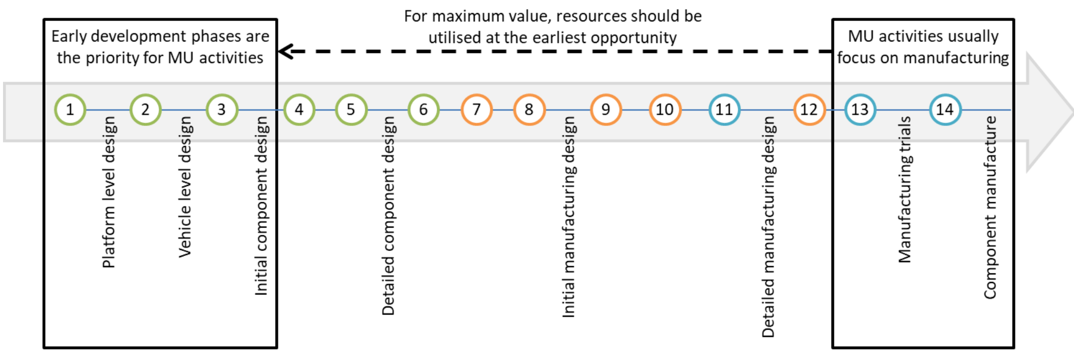



**Figure 4.18** **Material utilisation activities are mapped onto a product development timeline, coloured to represent the focus of the activity. Component design activities are shown in green, stamping is orange and blanking is blue.**

The next largest opportunity is activity 11, designing a shaped blank. This activity generated the largest opportunity for the material efficiency in the manufacturing engineering, but implementation was not possible. Material utilisation is a performance metric at this stage in the product development process, therefore resources are made available to implement efficiency improvements. The barrier to implementing this activity is the second most significant barrier—lack of equipment. Manufacturing shaped blanks requires investment into flexible blanking equipment, for example multiple unloading robots and laser blanking lines. This investment is required much earlier in the product development cycle during the early component design. The results show that cost was not a significant barrier to investing in new equipment as most material utilisation opportunities provided a significant financial saving. Investment was not made due to a lack of awareness of best practice processes. For example, investment in new blanking equipment requires guidance to move away from designing simple rectangular and trapezoidal blanks to complex shapes and nesting patterns.

Activities 2 and 11 generate the most significant opportunities. The savings recorded for activities 4–9 are much lower than expected. These activities were not part of the existing business process therefore it might be that the project team did not have the skills and experience to identify all of the saving opportunities in these areas. It is possible that the material saving opportunity is even greater for these activities. Best practice guidance and skill development is required to increase the confidence in using new technology, such as tailor welded blanking, to improve material efficiency.

The results complement previous studies on material efficiency in that the barriers identified in this case study are also recognised in previous research, discussed in chapter 2. However, the relative importance of the barriers differs between this case study, which focuses on implementing sheet metal material efficiency, and previous studies, which take a more general approach to material and energy efficiency. For example, in this case study development time and equipment were identified as the most significant barriers whereas financial investment and information availability were found to be the most critical barriers in the automotive sector analysis by Veshagh & Li (2015) and the multi sector analysis by Trianni & Cagno (2012).

### 4.4.3 How can the case study be implemented on a wider scale?

The case study evaluated five components which were being updated for a model year refresh. Since only some of the components are updated during a model year refresh, it is not possible to improve the material utilisation of all of the sheet metal parts in the vehicle. Therefore, the opportunity for material utilisation improvement identified in table 4.11 is only possible if the intervention is made at platform engineering level when it is possible to optimise all sheet metal components. This is illustrated in figure 4.19.

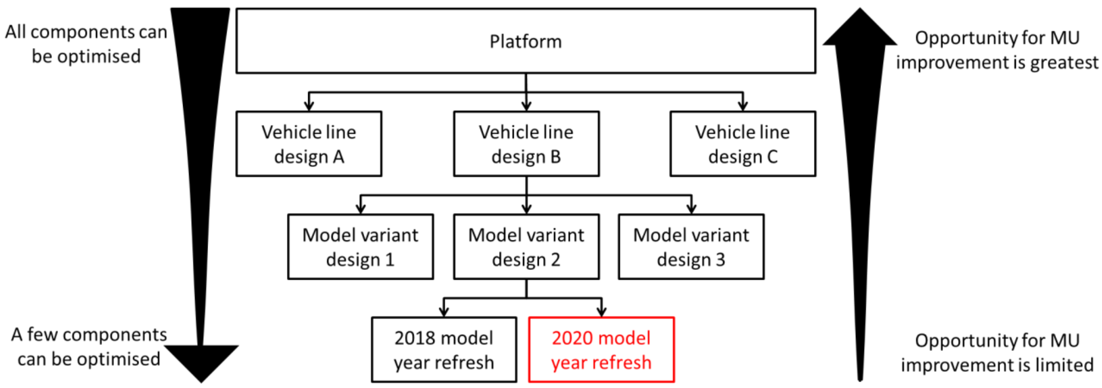



Figure 4.19 The earlier the intervention the greater the opportunity for material utilisation improvement.

Vehicle manufacturing platforms are only redesigned every 10-20 years, so the timing of implementing material efficiency initiatives is critical to exploit the whole of the saving opportunity.

The saving opportunity is sensitive to the material mix of steel and aluminium. From the numbers detailed in table 4.2, it can be determined that the financial saving opportunity would be greater if more aluminium is used as aluminium is more expensive than steel. However, the $CO_2$ saving would be greater if more steel was used. If the process is expanded to other vehicles, to consider industry wide savings, the size of the saving opportunity would be dependent on material selection.

In order to identify which area of the business should be responsible for implementing material efficiency, figure 4.20(a) groups the saving opportunities identified by business area. This pie chart confirms that improving material utilisation is not just a manufacturing activity and should be considered by multiple business areas throughout the development cycle. To extend the case study to all components, the collaborative environment illustrated in the Venn diagram in figure 4.20(b) would have to be embedded to the normal business process.  This collaborative environment was essential to identify realistic saving opportunities.

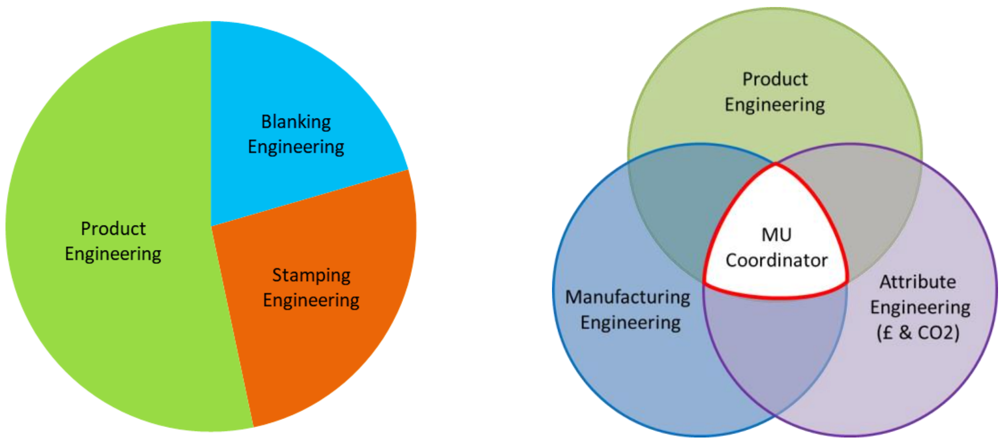



**Figure 4.20** **Implementation of material utilisation required collaboration between multiple business areas, this is illustrated through (a) a pie chart showing the split of material utilisation improvement opportunity by the business activity and (b) a Venn diagram of how different team worked together to identify and implement savings.**

It is likely that the barriers of communication and business change would exist if the trial process was implemented on all programs, but this could not be quantified as this case study created a project team which encouraged communication between departments and was able to operate away from the standard business process.

On the whole, the trial of a material efficient product design process was considered a success by the industry partner. Implementation of the trial process motivated and informed the automotive manufacturer to increase their focus on material efficiency during the early stages of the product design process, and subsequently implement process change to achieve material utilisation improvement on a wider scale. Since material utilisation should be considered by multiple stakeholders throughout the product development cycle it is recommended that material efficiency is championed on senior level and a team installed to coordinate material utilisation activities across the organisation. To support the implementation of material utilisation improvement activities into 'business-as-usual' processes, the process flow chart in figure 4.21 was generated and presented to senior stakeholders at the automotive partner.

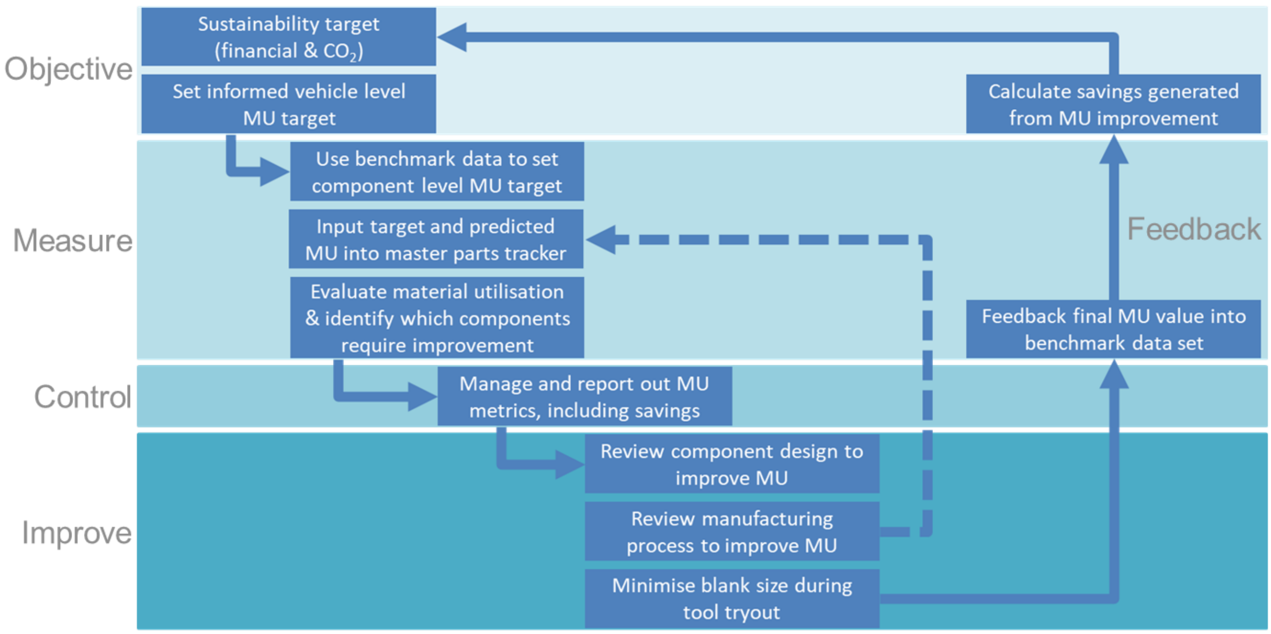



Figure 4.21 An example structure which could be used to implement savings across the business

The findings of this implementation case study are now concluded to summarise the extent in which material efficiency strategies can be realised in an industrial setting.

## 4.5 Conclusions: Realising the potential

To investigate the extent in which material efficiency opportunities can be realised in an industrial setting, this chapter developed a case study to design and manufacture five sheet metal automotive components and observe the opportunities and barriers for sheet metal material utilisation improvement. The case study demonstrates that it is possible to use less sheet metal to manufacture automotive components without technological or strategic innovation, but significant implementation barriers exist. The case study was undertaken by an automotive manufacture, so the results accurately reflect decision making in an industrial setting. The three hypotheses proposed at the start of this chapter are now considered in turn to conclude the findings of this research.

### To what extent can the material efficiency opportunity identified in chapter 3 be realised in an industrial setting?

A practical case study was set up with an automotive manufacturer to investigate whether the automotive industry could realise the full potential of the material efficiency opportunities identified in chapter 3. The trial identified that of the possible 24%pts increase in material utilisation available for this vehicle (from improvement to the best practice material utilisation value identified in chapter 3), 20%pts were identified using the proposed design process. The proposed design prosed is therefore considered to be an effective method of realising the potential of material efficiency in an industrial setting. The greatest saving opportunities were found early in the product development cycle, before the production method is determined by component geometry. Through following the proposed design process, a motivated organisation could significantly improve the material utilisation of sheet metal parts, saving money and reducing the embodied $CO_2e$ of the components. However, whilst the engineers in this case study were able to identify improvement opportunities, the decision to implement changes was not always taken. In these cases, the justification for not implementing the change was recorded as an implementation barrier.

### Are implementation barriers significant in improving the material utilisation of sheet metal component?

The case study found that implementation barriers are significant to improving the material utilisation of sheet metal components in an industrial setting. Of the 20% improvement opportunity identified, only 3%pts were actually implemented on the production vehicle. Whilst this generated significant savings of £2 million and 2 kilotonnes of $CO_2$ annually, overcoming the implementation barriers would enable the full potential of material efficiency to be realised. The case study identified availability of resources and technology as the most significant barriers to implementing material efficiency strategies in an industrial setting.

### Can an intervention be made to reduce these implementation barriers and enable improved material efficiency in the automotive industry?

Through an evaluation of the case study results, it is proposed that it is possible for the automotive industry to overcome these barriers through focusing resources on the upfront design for material utilisation and flexible blanking. To ensure material utilisation is considered throughout the product development cycle, not just during manufacturing, material utilisation performance metrics should be applied early in the product design process and high in the vehicle platform hierarchy. Communication barriers were not able to be directly measured in this study, but the evaluation demonstrates that they could be significant due to the large numbers of stakeholders required to improve material utilisation. To overcome potential communication barriers it is recommended that material efficiency is championed on senior level and a team installed to coordinate material utilisation activities across the automotive manufacturer.

This chapter demonstrates that it is advantageous to use a practical case study to demonstrate how improvements could be made in order to overcome implementation barriers and improve material efficiency in an industrial setting. This approach should be considered for other aspects of material demand reduction.

During the interaction with industry to research Chapters 3 and 4 the question of how material efficiency fits into the circular economy was repeatedly asked. There is a common perception within the automotive industry that material efficiency is not important since sheet metal, particularly aluminium, is readily recyclable. As a response to this question, Chapter 5 will now consider material efficiency within the context of the circular economy.

# Chapter 5 Material Efficiency in the Circular Economy

Since the first use of the phrase ‘Circular Economy’ by Kenneth Boulding in 1966, the concept of retaining resources in a bounding cycle of use has become the aim of many environmentally focused initiatives. This chapter explores how material efficiency can be achieved within the circular economy to investigate the following hypotheses:

- Can material efficiency be implemented alongside recycling, to support the automotive industry’s ambition of achieving a circular economy?
- The circular economy is considered to be more important than material efficiency in the production of automotive sheet metal automotive components. Does the evidence support this order of priority?
- Can existing performance metrics be used to measure and promote the implementation of both material demand reduction and recycling in the manufacture of automotive sheet metal components?

The interaction between circular economy and material efficiency strategies is now introduced. Human demand on resources is increasing. Even if resources are successfully bound in a circular economy, the circle is continuously increasing in size. Material efficiency aims to reduce the rate of this growth in material demand. In circular economy terms, material efficiency is aiming to shrink the circle; this is shown in figure 5.1.

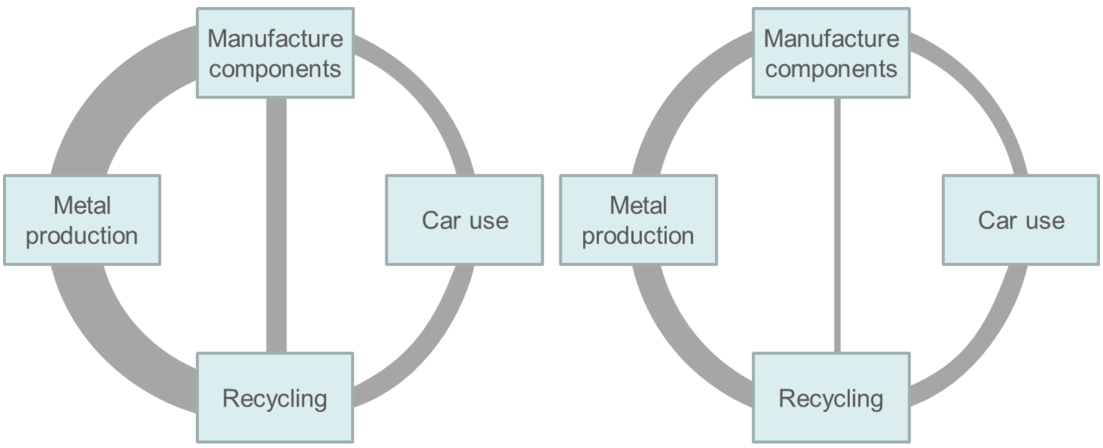



**Figure 5.1 Simplified diagram of the circular economy for automotive sheet metal, where the width of the flow represents the mass of material. Left is an example of the ideal circular economy, right portrays this circular economy with improved material efficiency.**

Allwood (2014) discussed how the focus on the circular economy distracts attention from the need for material demand reduction.
For this thesis the complex issue of the circular economy is simplified to recycling. Recycling and material efficiency are not mutually exclusive. It should be possible for automotive manufacturers to implement both strategies to reduce their demand for sheet metal. However, the process interviews in Chapter 3 revealed a perception that the environmental and economical savings from closed-loop recycling are so great that yield losses are not always considered to be important within these organisations. A strong belief in the circular economy has created a culture in which designers are motivated to produce more scrap to increase recycling rates. Addressing this observation is critical to the success of implementing material efficiency strategies.

In this chapter, existing approaches to both material efficiency and recycling are described. These targets are then reviewed in the context of other material efficiency and circular economy metrics. Finally, an automotive example is given to demonstrate the importance of selecting appropriate metrics when setting targets for circular economy and material efficiency initiatives.

## 5.1 Definitions of material efficiency and recycling

This section outlines the strategies for recycling and material efficiency in turn and considers the extent in which the two strategies have been implemented in the automotive industry. To illustrate the flow of sheet metal in the production of automotive components, a diagram of scrap generation and recycling streams is shown in figure 5.2.

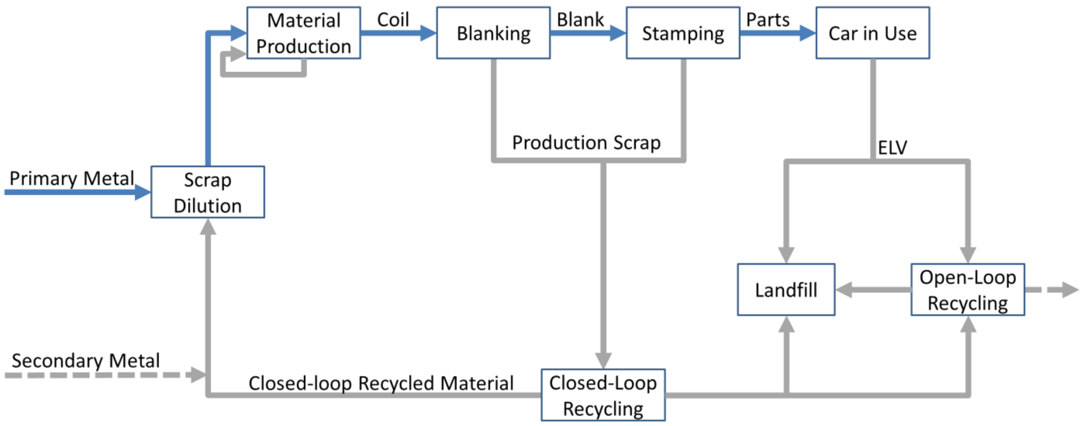



Figure 5.2 Recycling streams for the production and use of sheet metal automotive components.

### 5.1.1 How is sheet metal recycling defined?

Bartl (2014) categorise recycling processes by the type of change being made, they state:

- **Product recycling** is where the product is reused for a different purpose than it was originally manufactured for, without making any chemical or physical changes. The example given by Bartl is using tyres or glass bottles as building material.
- **Material recycling** is described as being the process in which the physical form is changed e.g. by melting, but the chemical composition of the material remains the same.
- **Feedstock recycling** is described as being a process in which the physical as well as the chemical constitution of a material is reprocessed into its original constituents, e.g. de-polymerization in the recycling of plastics.
- **Closed-loop recycling** occurs when the recycled material is not changed and can therefore be used to manufacture the same component. In closed-loop recycling the use of secondary material directly displaces the use of primary material.

- **Open-loop recycling** occurs when the material is recycled into another product system so has a change in its inherent properties. This is often referred to as down-cycling or up-cycling depending on whether the new material has a greater or lesser value than the original material.

In addition to the categorisation of recycling by the material properties, the source of scrap material is important. Graedel et al. (2011) categorise metal recycling processes by the material source as follows.

- **Home scrap** is described as the scrap material generated during material production which can be directly reinserted in the process that generated it. Home scrap recycling is generally economically beneficial and easy to accomplish. It is usually excluded from recycling statistics.
- **New scrap** is generated in the manufacturing process, but requires further processing, usually in a different facility, to be recycled. New scrap is also referred to as **production scrap**, **post-industrial scrap, manufacturing scrap** and **fabrication scrap**.
- **Old scrap** refers to scrap which originates from a product which has been used and has reached the end of its functioning life. Old scrap is also referred to as **End of Life scrap (EOL)** or **post-consumer scrap**. The recycling of old scrap usually requires more effort than new scrap as the material mix is harder to control.

Recycling of automotive sheet metal tends to refer to closed-loop recycling of production scrap. Sheet metal home scrap is not owned by the automotive manufacturers so is not included in recycling statistics. The automotive industry tends to consider the scrap generated from transforming the coil into a component when discussing sheet metal recycling. End of life recycling does occur as discussed by Andersson et al. (2017) in their comprehensive review of Swedish end-of-life-vehicle (ELV) recycling. However, ELV recycling is currently open-loop and the material is downgraded so cannot be used to manufacture automotive sheet metal component. For this evaluation of material efficiency in the circular economy, automotive recycling refers to closed-loop production scrap.

### 5.1.2 How is material efficiency defined?

As described in the literature review, material efficiency strategies are process innovations which aim to provide the same service with less material. Allwood et al (2013) outline six approaches in which this could be achieved, these are:

- **Light-weight design** aims to reduce the material used to achieve a function by optimising the design for material reduction rather than cost reduction. In the automotive industry light weight design could be achieved through optimising each component or more simply by designing smaller cars as described in Serrenho et al. (2017)
- **Longer life products**, replacing a passenger vehicle every 20 years rather than every 10 years, as described in Serrenho & Allwood (2016), would reduce the demand for new vehicles, which in turn would reduce the demand of sheet metal.
- **More intense use** of vehicles, for example if household members shared one car rather than two, this would reduce the demand for new vehicles. This would in turn reduce the demand of sheet metal as described by Serrenho & Allwood (2016).
- **Re-using components** could be achieved when a product is scrapped due to the failure of only a few components within the product. In this scenario the remaining parts could be re-used. An example given by Allwood et al (2013) is in steel-framed buildings, where steel does not degrade in use, and building replacement is typically driven by changed user requirements or planning policies. The potential in the refurbishment of old sheet metal components for new vehicles has yet not been studied.
- **Diverting manufacturing scrap** could use the yield losses of blanking process to manufacture another smaller component. As described in chapter 3 there is a limited opportunity to implement this strategy due to the complex shapes and material selection requirements of automotive components.
- **Reducing Yield losses** is the focus of this thesis. As described in section 1, sheet metal is transformed into automotive components through a series

of cutting and shaping operations, known as blanking and forming. Minimising the production yield losses which occur during these operations would reduce the demand for raw material.

In the automotive industry, material efficiency tends to refer to material demand reduction achieved through reducing yield losses. In this evaluation of material efficiency in the circular economy, automotive material efficiency is considered to be the sole result of yield improvement during the production of components. It is assumed that no other material efficiency strategies have been implemented.

### 5.1.3 Implementing closed-loop recycling and material demand reduction

Although the waste hierarchy favours scrap prevention strategies to recycling strategies, implementation of closed-loop recycling has been more widespread than material demand reduction, (Ewijk & Stegemann 2016). For example, in 2014 the Jaguar Land Rover-led research project 'REALCAR' established 11 closed-loop press shops with aluminium supplier Novelis enabling the Jaguar XE to use a closed-loop recycled aluminium alloy, (Jaguar Land Rover 2016). In contrast, successful implementation of material demand reduction has not yet been reported by the automotive industry, (Bartl 2014). Through a bibliometric analysis on 6967 articles in the field of sustainable management of metals on a global level between 1993 and 2017 Aznar-Sánchez et al. (2018) identified improving recycling and reusing metal as a major theme, however reducing material demand through material efficiency was not identified as a major theme. Similar scenarios exist for other materials. Haupt et al. (2016) consider the interaction of recycling and material efficiency in plastics and Ewijk et al. (2017) do the same for paper. Both studies identify the importance of material efficiency, but observe an industrial focus on reporting recycling rates over material efficiency.

Bartl (2014) suggest the lack of success on material demand reduction could be due to the difficulty in measuring waste prevention compared to the ease in which recycling can be measured. These metrics are now considered.

## 5.2 Setting performance metrics

Performance metrics are used to measure and promote a desired behaviour in industry. This section considers the performance metrics used to measure recycling and material efficiency through yield improvement for sheet metal within the automotive industry. Metrics are identified from published research and the interviews conducted for chapter 3 of this thesis. These metrics are then reviewed to consider their effectiveness for promoting both material demand reduction and closed-loop recycling.

### Metrics for recycling

In their review of recycling rates for different metals Graedel et al. (2011) state that metal recycling can be measured with the following three metrics:

- The **Collection Rate** measures the proportion of metal which is collected to be recycled compared to the metal which is discarded into landfill.
- The **Recycling Process Efficiency,** also called the recovery rate, measures the yield of the recycling process. This is the metal which leaves the recycling process as a proportion of the mass of metal which is collected to be recycled.
- **End-of-Life (EOL) Recycling Rate** measures useful output of the recycling process. This material can be a pure metal or an alloy, but must be functional i.e. not a 'tramp element'.

Graedel et al. (2011) also identifies metrics which are used to measure the performance of recycling in metal production, these are:

- The **Recycling Input Rate,** which measures the fraction of scrap metal, from a specific source, in the total input materials in metal production.
- **Recycled Content** sometimes referred to as **recycling rate** is usually equivalent to the Recycling Input Rate, unless material from another source is used to manufacture the product.
- The **Old Scrap Ratio** measures the proportion of scrap material which enters the recycling flow to be made into new products.

In their analysis of recycling indicators for metals, Espinoza & Soulier (2018) extend the work of Graedel et al. to consider the metrics:

- **End-of-life (EOL) collection rate** measures the efficiency with which end-of-life metal is collected. This metric is similar to the collection rate, but only considers end-of-life scrap as a source for recycling.
- **End-of-life (EOL) processing rate** measures the efficiency of the end-of-life scrap recycling. This metric is similar to the recycling process efficiency metric, but only considers end-of-life material.
- **Overall recycling efficiency rate** measures the useful output of the recycling process for all sources of scrap. This metric is similar to the metric EOL Recycling Rate except that it considers all sources of secondary material, old and new scrap.

The industry interaction for chapters 3 and 4 revealed that recycled content is the favoured metric for reporting recycling in the automotive industry, due to its simplicity to calculate and ease to communicate to the public.

### Metrics for material efficiency through yield improvement

The automotive industry measure the material efficiency of a production process using the metric material utilisation (MU). Through the interviews described in chapter 3, it was revealed that material utilisation had a different meaning depending on who was measuring it. These are described as:

- **Vehicle MU** is the sheet metal weight of the vehicle compared to the total sheet metal weight required to manufacture it. This metric considers both blanking and stamping scrap.
- **Component MU** is the sheet metal weight of the component compared to the sheet metal weight of the blank required to manufacture it. This metric only considers stamping scrap, blanking scrap is excluded. This metric is often used when the manufacture purchases the sheet metal as a blank rather than a coil.
- **Design MU** is considered to be the material utilisation in which the component designer can influence. It is generated from unfolding the component to estimate the size and shape of the minimum blank required

to form it. This shape is nested in a rectangle to give weight of material required to cut the blank. This metric produces an estimated value for blanking scrap, but does not consider stamping scrap.

- **Process MU** is the sheet metal weight of the component compared to the total sheet metal weight required to manufacture it. This metric considers both blanking and stamping scrap.

The material utilisation metric which aligns with the calculations in this thesis is the process MU. In this document the term 'material utilisation' has always referred to the process MU in order to consider both blanking and stamping scrap. A reduction in yield losses is communicated as a percentage point change in material utilisation. This metric enables the comparison of savings gained for components which have different part and coil masses. For example, if an optimisation activity improved the material utilisation from 50% to 55% the increase in material utilisation is recorded as $5\%_{pts}$.

### Creating a structure for sheet metal use and recycling metrics

These metrics are now structured to allow comparison between different measurements of material use, scrap generation and recycling. Figure 5.3 annotates the flow of sheet metal scrap with the performance metrics identified in this section.

Structuring all identified metrics in this way highlights the complexity of measuring and communicating material efficiency and recycling performance in a consistent and meaningful manner. Of the performance metrics shown in figure 5.3, recycled content is the most commonly used metric for recycling in the automotive industry. Recycled content metrics used in the automotive industry do not usually distinguish between production scrap and end of life scrap. The inclusion of production scrap in this calculation means that recycled content has very little relation to environmental performance. This can generate misleading communications on the environmental performance of vehicles. This has been recognised by the European Aluminium Association who recommend the communication of on end-of-life recycling rates rather than recycled content, (European Aluminium 2016). Process material utilisation is the most useful metric for yield loss reduction since it considers both blanking and stamping scrap.

The effectiveness and interaction of these metrics are now considered further by varying the yield losses and recycled content of a case study vehicle.

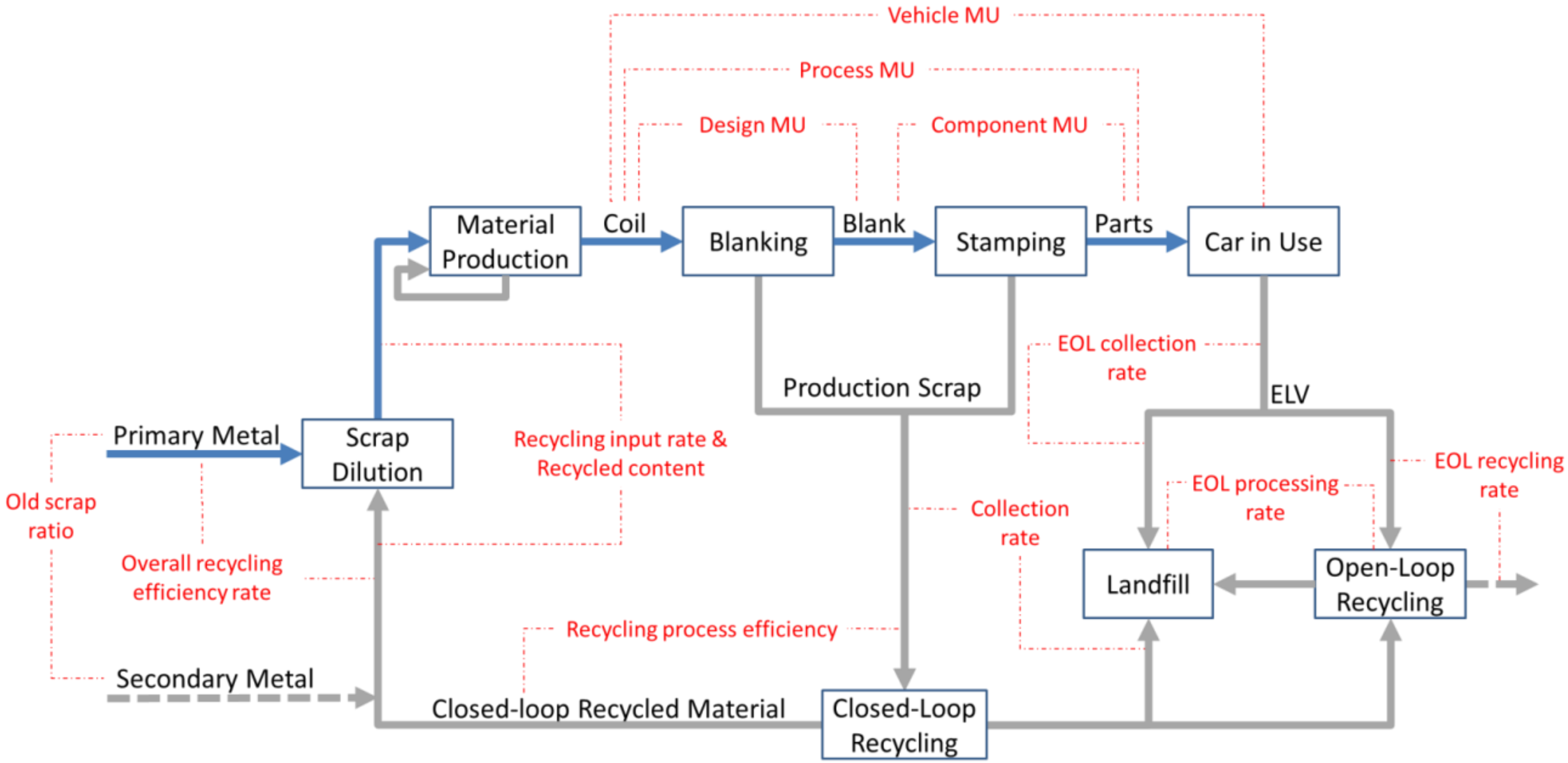



**Figure 5.3** Performance metrics for sheet metal recycling and material utilisation in the production of automotive components, the performance metric is connected to the flows measured with red lines.

## 5.3 An automotive example of material efficiency in the circular economy

It has been shown by Allwood et al. (2010) that both material demand reduction and closed-loop production scrap recycling can reduce the embodied emissions of a vehicle. However, a more efficient production process generates less scrap, so the opportunity for closed loop production scrap recycling reduces when material utilisation improves. The percentage of recycled content is an important performance metric for the automotive industry (Daaboul et al. 2017), therefore understanding this interaction is essential to the success of implementing both closed-loop recycling and material demand reduction strategies.

This chapter now evaluates a case study vehicle to explore the benefits of implementing both material demand reduction and closed-loop production scrap recycling. The methodology and assumptions are defined in section 5.3.1. The effect of material demand reduction on the mass of recycled material is explored and the saving opportunity for each strategy is quantified. With this information, the suitability of 'recycled content' as a performance metric is evaluated in Section 5.3.2. The implications of these findings for the automotive industry are discussed in Section 5.3.3 and recommendations for motivated automotive manufacturers to achieve material efficiency within the context of the circular economy are proposed in Section 5.4.

### 5.3.1 Methodology

Yield losses occur in every stage of producing automotive sheet metal components, particularly in blanking and stamping. The current approach by the automotive industry to manage this scrap is to reduce the embodied $CO_2e$ of vehicles through closed-loop recycling. Closed-loop production scrap recycling is an output focused strategy, in which recovered production scrap is converted back into metal coil which increases the recycled content of the vehicle, as shown in figure 5.4. In contrast, material demand reduction through material efficiency is input focused. This strategy reduces metal coil demand through improving material utilisation, without differentiating between primary and secondary material sources, also shown in figure 5.4.

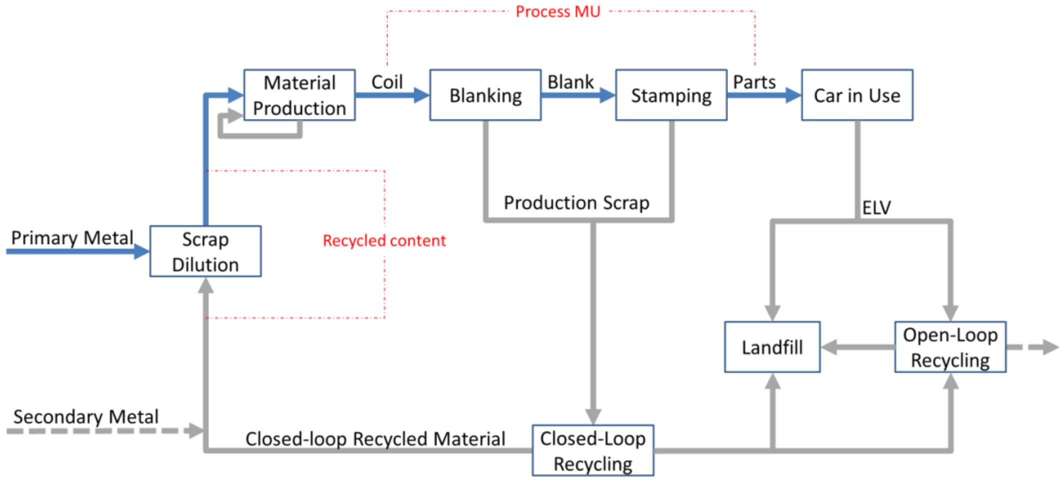



**Figure 5.4 Diagram showing the flow of material in the production of automotive components. Closed-loop recycling maximises the value of material outputs using the metric 'recycled content', whereas material demand reduction minimises material inputs using the performance metric 'process MU'.**

The case study vehicle has an aluminium intensive body shell containing 300kg of sheet aluminium components. For the worst case production process, it is assumed that material utilisation is 35% and all production scrap is open loop recycled. The production process is modified to investigate the effect of implementing both material demand reduction and closed-loop recycling to include all production scrap. The values for the best and worst case material utilisation are as per the results presented in chapter 3.

Financial and $CO_2e$ savings are estimated, using the values in table 5.1. Carbon savings are calculated using the End-of-Life approach, which credits the production of recyclable material as recommended by Atherton (2007). In their lifecycle analysis of sheet metal stamping, Cooper et al. (2017) found that the operational cost of stamping is insignificant compared to the material cost. Therefore the environmental costs used in this study reflect the environmental cost of the raw material. For simplicity, implementation costs are not included, it is assumed that no material losses occur in closed-loop recycling and no post-consumer scrap is used. The effect of these assumptions is discussed in Section 5.3.3. The results are analysed to determine the effectiveness of recycled content as a sustainable manufacturing metric.

**Table 5.1 Information sources for carbon and financial saving calculations.**

| Measure | Value | Source |
|---|---|---|
| Material utilisation for worst, average and best case production scenarios | 35%, 56%, 70% | Chapter 3 |
| Financial cost of coiled automotive sheet aluminium | \$3600/t of Al | Chapter 3 |
| Financial value of closed-loop recycled aluminium production scrap | \$1725/t of Al | Chapter 3 |
| Financial value of open-loop recycled aluminium production scrap | \$960/t of Al | Chapter 3 |
| $CO_2e$ cost for producing primary aluminium coil | 9.8 t/t of Al | Assessed with GaBi analysis software |
| $CO_2e$ value of closed-loop recycled aluminium production scrap | 8.9 t/t of Al | Assessed with GaBi analysis software |
| $CO_2e$ value of open-loop recycled aluminium production scrap | 7.9 t/t of Al | Assessed with GaBi analysis software |

### 5.3.2 Results

The following results show the interaction between material demand reduction and closed-loop production scrap recycling in the production of sheet aluminium components for the case study vehicle. The analysis quantifies material flow, environmental and financial savings, and evaluates the use of recycled content as a performance metric. Figures 5.5, 5.6, 5.7 and 5.8 are material flow Sankey diagrams for the sheet aluminium required to produce one vehicle, where the width of the line represents the mass of material. Compared to the average production process (figure 5.5), the primary material requirement per car reduces when all production scrap is closed-loop recycled (figure 5.6) and, to a lesser extent, when material demand reduction is implemented (figure 5.7). The recycled content only increases when closed-loop recycling is implemented. Figure 5.8 shows the quantity of this recycled material when both strategies are implemented together. Figure 5.9 gives the recycled content for different levels of closed-loop recycling. It can be seen that implementing closed-loop recycling of production scrap increases the recycled content, arrow (a), but when material demand is reduced the recycled content reduces, arrow (b).

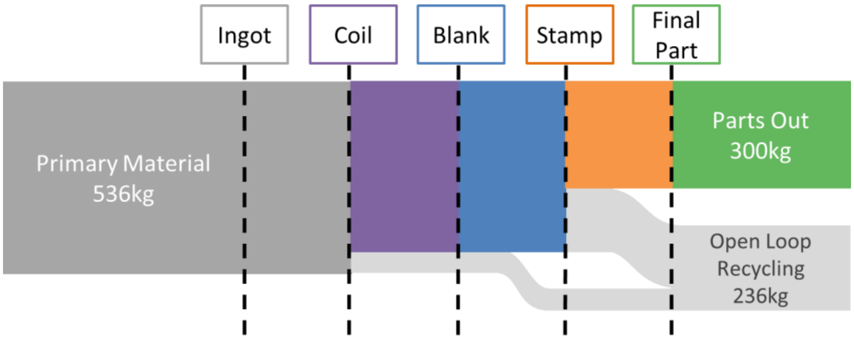



**Figure 5.5 Material flow for the average production process with no closed-loop recycling.**

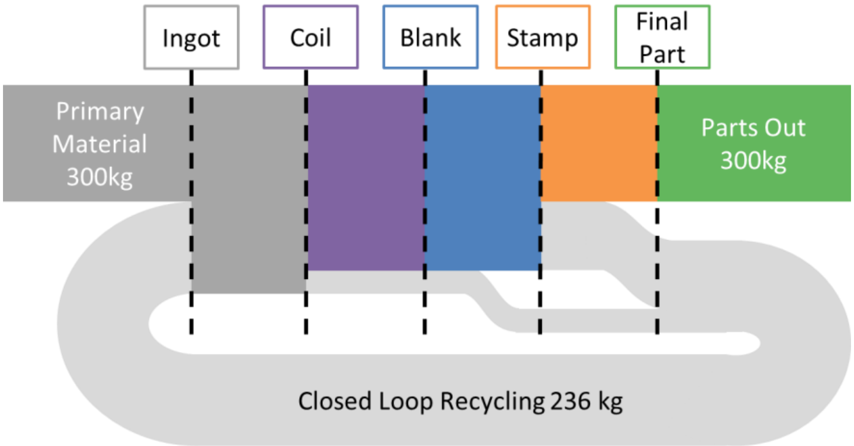



**Figure 5.6 Material flow for the average production process with 100% closed-loop production scrap recycling.**

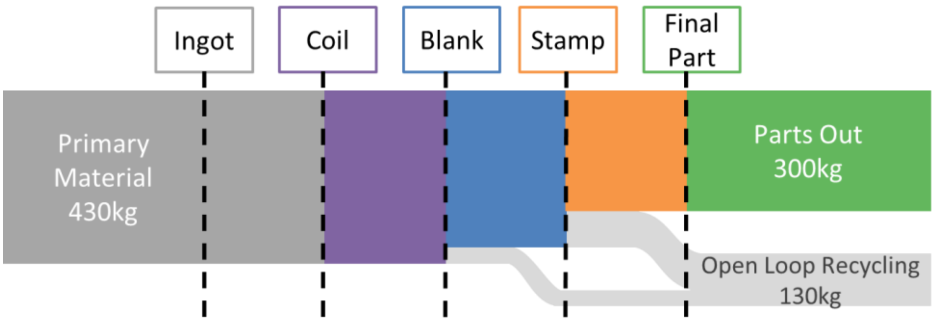



**Figure 5.7 Material flow with material demand reduction to achieve 70% material utilisation.**

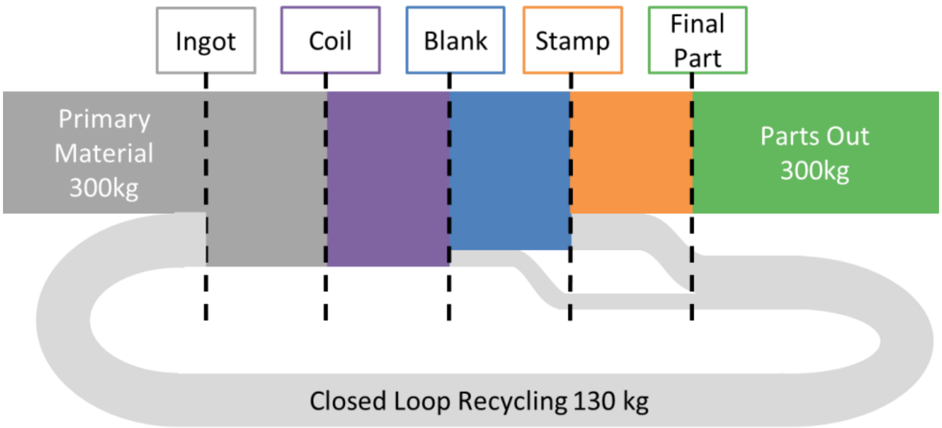



Figure 5.8 Material flow with material demand reduction and closed-loop recycling.

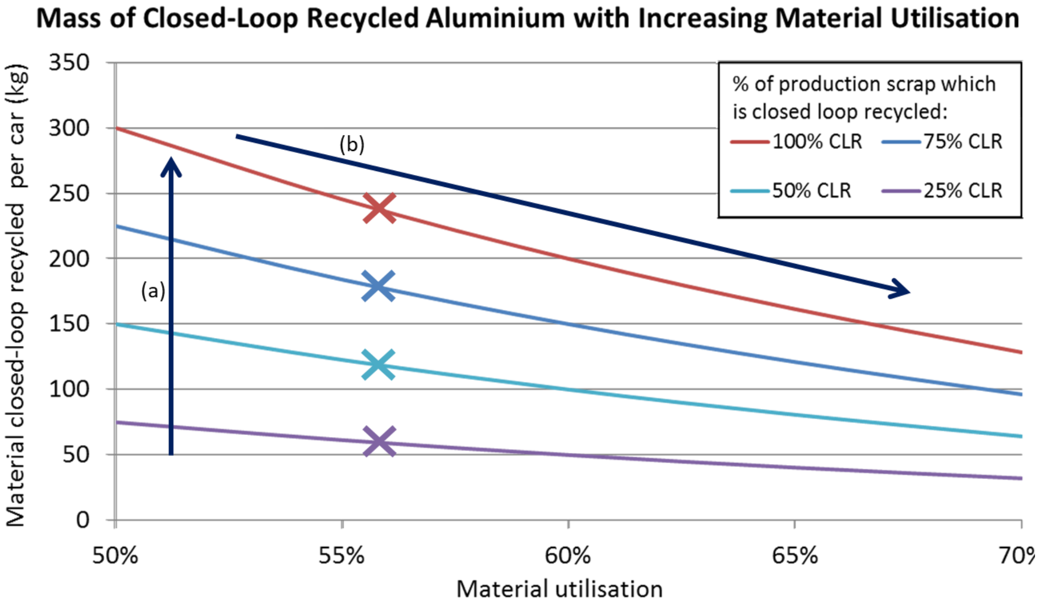



Figure 5.9 Graph showing the change in recycled material for closed-loop production scrap recycling, arrow (a) and material demand reduction, arrow (b). Crosses are marked to indicate the production scrap material which is recycled for the industry average material utilisation value identified in chapter 3 at different closed loop recycling (CLR) rates.

Reducing production scrap is often considered a low priority as recycled production scrap is perceived to have a low environmental and financial cost. The validity of this perception is now evaluated. Figure 5.10 and figure 5.11 evaluate the interaction between the two strategies in terms of $CO_2e$ and financial savings per car. Savings are calculated using the values in table 5.1 for the case study vehicle. The graphs show that the benefits of material demand reduction significantly outweigh the reduction in recycled content. Implementing only material demand reduction (point a) gives greater $CO_2e$ savings than only implementing closed-loop production scrap recycling (point b). The greatest $CO_2e$ saving is achieved when both strategies are implemented together (point c). Financial savings are much greater for material demand reduction (point d) than for closed-loop production scrap recycling (point e), but again the greatest saving occurs when both strategies are implemented together (point f). The graphs show that when all production scrap is closed-loop recycled, increasing material utilisation from the industry average to best practice gives net savings of over $200 and 100kg of $CO_2e$ per car. Based on these saving opportunities, material demand reduction should be considered as a greater priority than closed-loop production scrap recycling.

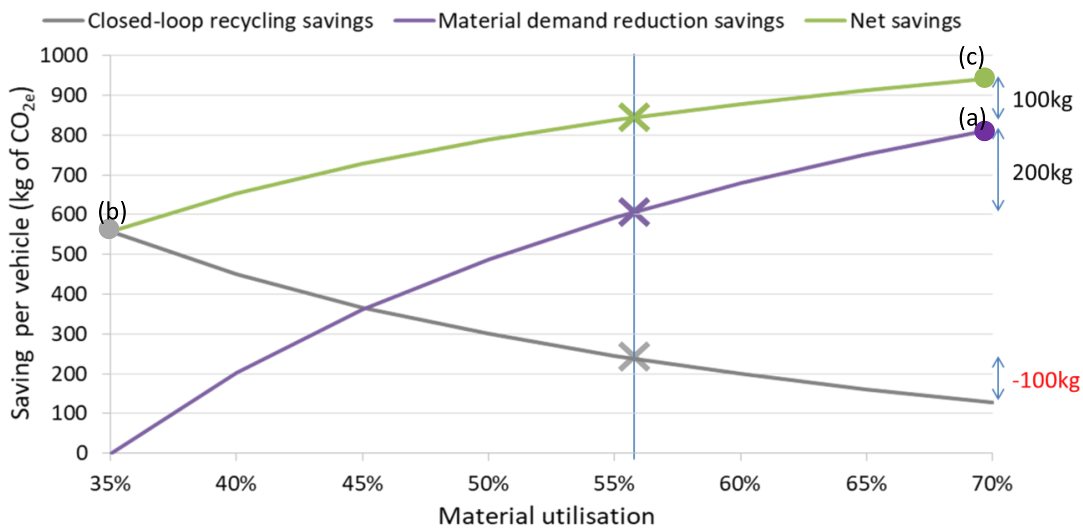



**Figure 5.10** **Graphs showing the breakdown and net savings for implementing material demand reduction, when all production scrap is closed-loop recycled.**

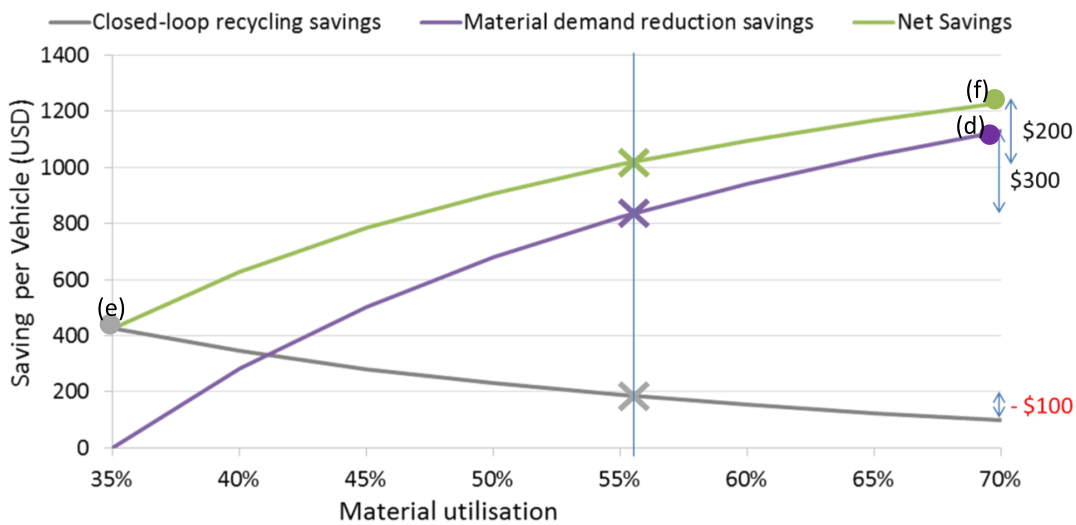



**Figure 5.11** **Graphs showing the breakdown and net savings for implementing material demand reduction, when all production scrap is closed-loop recycled.**

In order to promote closed-loop production scrap recycling the automotive industry has introduced ‘recycled content’ performance metrics, meaning a reduction of available production scrap can be viewed negatively. Figure 5.9 showed that material demand reduction reduces the availability of production scrap, and it is shown in figure 5.12 that the cost of aluminium reduces even though the recycled content is less. For example, when all production yield losses are closed loop recycled the case study vehicle, made with a recycled content of 50%, contributes 12% more embodied emissions than when the same car is manufactured with an improved material efficiency but only 30% recycled material. In this scenario, reducing recycled content is favourable, since avoiding scrap generates greater savings than recycling it. Measuring recycled content can therefore be ineffective, as it does not promote or capture the savings gained from material demand reduction.

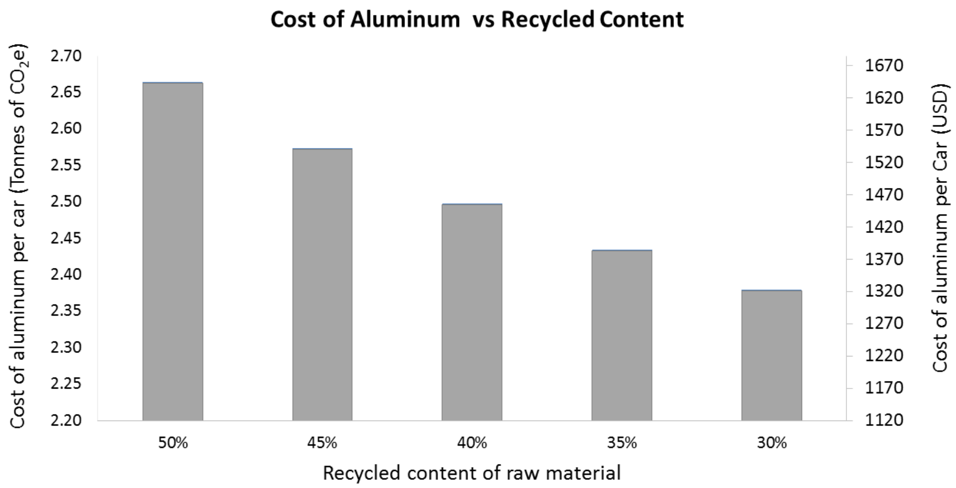



**Figure 5.12 Graph showing the environmental and financial cost of aluminium as material demand reduction is implemented. Counterintuitively, the cost reduces as the recycled content reduces.**

This study has shown that material demand reduction, achieved through improving material utilisation, reduces the potential for closed-loop production scrap recycling, but generates greater $CO_2$e and financial savings. It has been demonstrated that recycled content performance metrics are not effective at promoting both material demand reduction and closed-loop recycling. The impacts of these findings for the automotive industry are now discussed.

### 5.3.3 Discussion of case study results

The automotive industry is becoming increasingly aware of the environmental impact of their products. Strategies to reduce environmental impact while saving money are considered 'win-win' opportunities that provide compelling business cases. This chapter demonstrates that both material demand reduction and closed-loop recycling of post-industrial scrap should be included in the automotive industries approach to sustainable manufacture. The observation that material demand reduction delivers greater savings than closed-loop production scrap recycling can inform manufacturers to increase the priority of this strategy. The discussion considers how this can be motivated through effective target setting, and outlines the technical and financial requirements.

#### Target setting:

Existing automotive targets have been based on the volume of recycled material or percentage of recycled content. These metrics do not capture savings from material utilisation and could perversely encourage the generation of scrap material to meet recycling metrics. This is illustrated in figure 5.13. Which, using the data from figure 5.12, gives an example of material flows for the production of 100 vehicles.

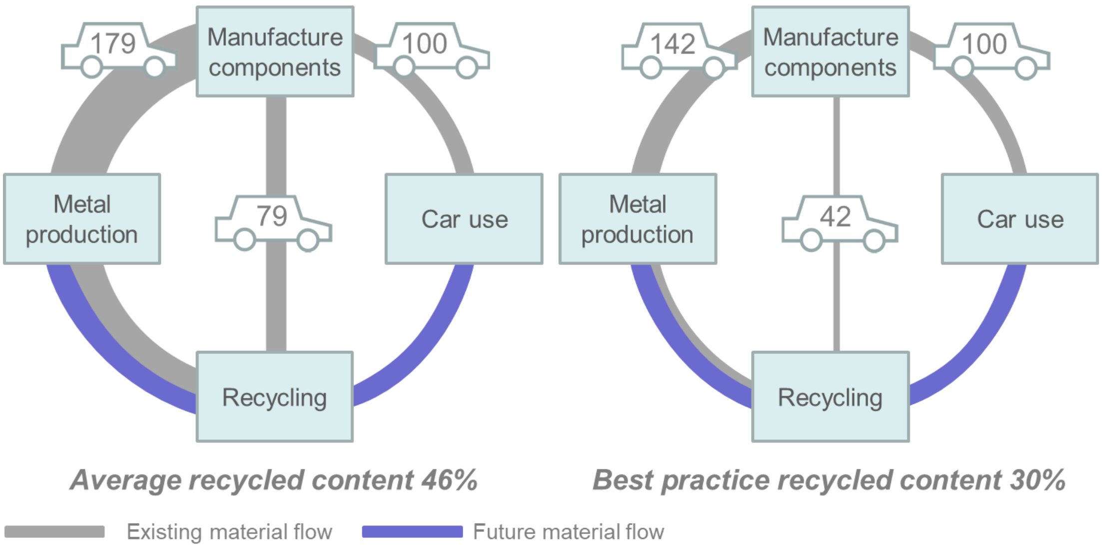



Figure 5.13 – Illustration of the findings in this case study. Improving automotive sheet metal utilisation to current best practice reduces the demand for raw material. This reduces the embodied $CO_2$ emissions by 12%, but it shrinks the circular economy measure of recycled content.

More mature metrics are required to promote the savings available from improving material utilisation, as detailed in equations 5.1 & 5.2.

$$\text{Material Utilisation \%} = (\Sigma \text{ part weight} / \Sigma \text{ coil weight}) \times 100 \quad (5.1)$$

$$\text{Production Scrap Recycled \%} = (\Sigma \text{ recycled weight} / \Sigma \text{ scrap weight}) \times 100 \quad (5.2)$$

Existing performance metrics do not recognize post-consumer or end-of-life (EOL) scrap recycling. Setting mature material utilisation and recycling targets enables the future inclusion of performance metrics which promote the use of post-consumer scrap, such as the metric in equation 5.3.

$$\text{EOL Scrap Recycled \%} = (\Sigma \text{ EOL recycled weight} / \Sigma \text{ part weight}) \times 100 \quad (5.3)$$

### Technical and financial requirements:

Improved material utilisation needs to be embedded in the product development process of vehicle design. This presents challenges due to the large number of stakeholders and requirements in the product development cycle. In contrast to closed-loop recycling strategies, there is no published best practice framework on how organizations should implement material demand reduction. Without a guideline, implementation practices are not optimised and vary between organisations. Implementation of closed-loop recycling needs to build on the consideration in the product development process (e.g. new alloy or component design) before amending the value chain design. Due to simple infrastructure constraints, implementation of both strategies is easier in new purpose-built facilities and becomes increasingly challenging when retrofitting existing facilities. It should also be noted that many automotive supply chains include stamping at multiple internal and external locations. Therefore implementation involves multiple locations and complex logistics.

Cost of implementation for either strategy is not included in this analysis and should be considered in future research. The cost of implementation closed-loop production scrap recycling is dominated by infrastructure investment. In contrast material demand reduction costs are dominated by training and implementing process change in the product development cycle. In addition to the total cost of implementation, budgets are separated across different areas of a business and supply chain. Benefits should be shared across stakeholders to prevent local optimization at the expense of the whole system. Other, less tangible benefits exist which can be very attractive to companies. These include a reduction in the amount of virgin material that is required to be sourced, logistical, financial and environmental benefits from reduce scrap transportation.

Findings from this example are now considered, together with the structure of material flow metrics presented in figure 5.3, to conclude on how material efficiency strategies can be implemented within a circular economy.

## 5.4 Conclusions: Material efficiency in the Circular Economy

The automotive industry has scope to reduce the environmental and financial cost of sheet metal used in the production of vehicles. To maximise savings, sustainable manufacturing strategies should implement both material demand reduction and closed-loop production scrap recycling. The three hypotheses proposed at the start of this chapter are now considered in turn to conclude the findings of this chapter.

Can material efficiency be implemented alongside recycling, to support the automotive industry's ambition of achieving a circular economy?

This chapter has investigated material efficiency in the context of the circular economy. Environmentally aware automotive manufacturers recycle aluminium production scrap in closed-loop systems to generate environmental and financial savings. If material demand is reduced, through improving the material utilisation of the production process, the opportunity for closed loop recycling reduces since a more efficient production process generates less scrap. This interaction means that, with existing performance metrics, material efficiency does not support the automotive industries ambition of achieving a circular economy.

The circular economy is considered to be more important than material efficiency in the production of automotive sheet metal automotive components. Does the evidence support this order of priority?

This chapter has shown that, whilst material efficiency does not increase the circularity of sheet metal flows with the automotive industry, it generates greater environmental savings than recycling, so material demand reduction should be considered a greater priority than the circular economy for meeting climate change goals. That said, it has been shown that the greatest savings are achieved when both strategies are implemented together. This finding informs the automotive industry that material efficiency can and should be implemented along side recycling.

### Can existing performance metrics be used to measure and promote the implementation of both material demand reduction and recycling in the manufacture of automotive sheet metal components?

It has been shown that many different metrics can be used to measure the performance of material efficiency and recycling in the automotive industry. The most prominent metrics are recycled content and process material utilisation. To investigate these metrics further, the interaction between material demand reduction through yield improvement and closed loop recycling is explored for an aluminium intensive case-study vehicle. It is shown that a 'recycled content' target does not capture these saving opportunities. With new performance metrics, implementation of material efficiency strategies would support the automotive industries aim of achieving a circular economy. Recommendations for a motivated company are:

- Set material utilisation targets and introduce process improvements across the product development cycle to reduce post-industrial scrap.
- Replace recycled content targets with recycling process efficiency targets for production scrap to both promote material utilisation and closed-loop recycling.
- Introduce post-consumer recycled aluminium into the supply chain and set process efficiency targets for end-of-life production scrap.

This chapter has reviewed the interaction between closed-loop recycling and material demand reduction for a specific case of automotive sheet aluminium, however the conclusions are also relevant to encourage sustainable design and manufacture of other materials, industries and production processes.

Chapter 6 will now consider how design for material efficiency could be enabled through the development of geometry based process formability guidelines.

# Chapter 6 Design for Material Efficiency

Chapters 3 and 4 identified a significant opportunity to improve the material efficiency of sheet metal components through considering material utilisation during the design of the component geometry and manufacturing process selection. To demonstrate this opportunity, figures 6.1 and 6.2 present the material efficiency of the sheet metal components reviewed in the vehicle analysis in chapter 3 by the forming process used to manufacture them. The graphs show that on average, drawing without a blank holder was 12% more material efficient than drawing with a blank holder. This is a logical result as the addendum surface would be smaller if no blank holder is required.

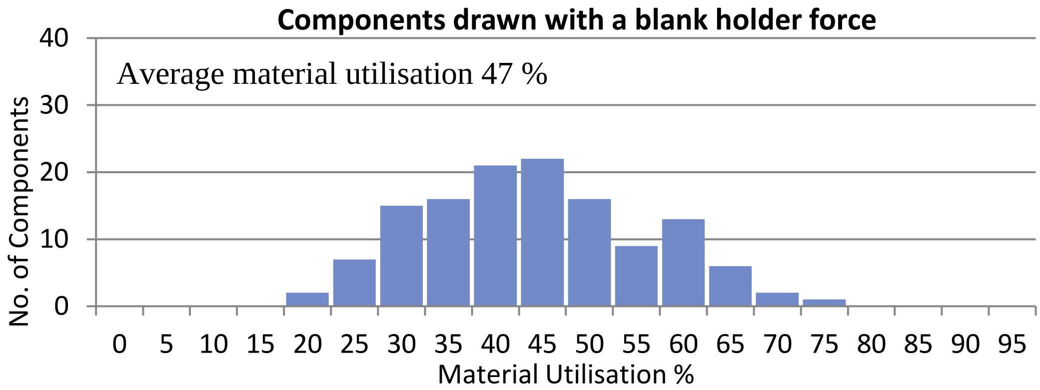



**Figure 6.1** Distribution of material utilisation values for components drawn with a blank holder force in the vehicle reviewed in chapter 3.

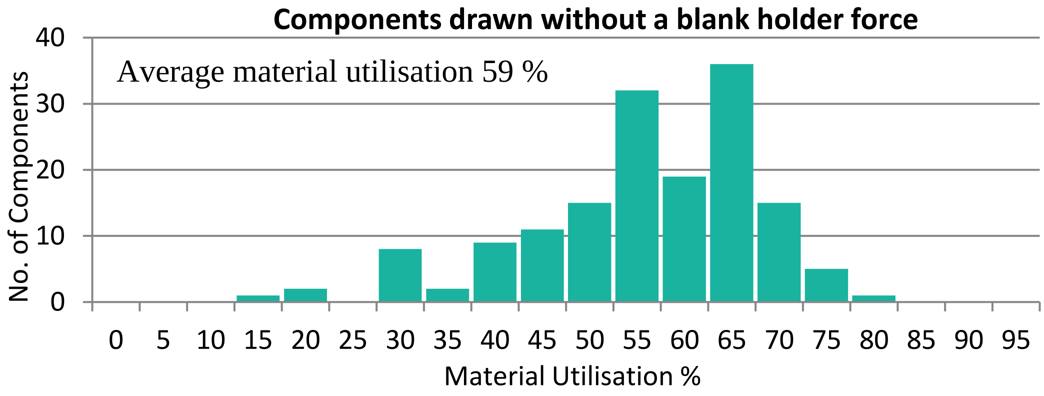



**Figure 6.2** Distribution of material utilisation values for components drawn without a blank holder force in the vehicle reviewed in chapter 3.

Similarly components which can be drawn with a blank holder but without draw beads would be more material efficient than components which require draw beads to be manufactured.

It should be possible to reduce the amount of scrap generated in sheet metal forming by designing components within geometric forming guideline for material efficient manufacturing processes. Existing methods of predicting failure which could be used early in the product development cycle were reviewed in chapter 2. This review demonstrated that there is insufficient information currently available to develop a formability guideline from component geometry. This chapter investigates the extent in which such a guideline could be created and will address the following hypotheses:

- Can sheet metal component geometry be designed to select a forming process which improves the material utilisation?
- To what extent can the maximum draw depth be predicted from component geometry in sheet metal forming with and without a blank holder?
- Can these findings be extended to support the implementation of design for material efficient manufacture in an industrial environment?

Section 6.1 details the methodology of the component geometry, experiments and finite element model developed for the study. The results of the physical experiments are presented in section 6.2. These results are then extended using a validated finite element model to evaluate more component geometries. The results are analysed in section 6.3 to establish whether a trend exists and to what extend the failure draw depth can be predicted from the corner, die and punch radius.

## 6.1 Methodology: Physical and experimental trials to establish geometry based forming limits

This chapter aims to provide formability guidance during the early stages of sheet metal component design. The processes considered in this chapter are deep drawing both with and without a blank holder. Formability is investigated through physical trials and the results are extended using validated Finite Element Analysis (FEA) simulations. This methodology details the component geometry studied, experimental setup, failure criteria, FEA model parameters, preliminary experiments undertaken and the experiment design.

### 6.1.1 Defining the component geometry

Sheet metal components are complex shapes. To generate forming limits, the complex shape is broken down into shrink and stretch corners with a flange. The corner geometry can be described by the die radius, punch radius, corner radius and draw depth as shown in figure 6.3. A shrink corner is created when material is drawn into a radius which is smaller than the starting blank radius. A stretch corner is created when material is drawn into a larger radius than the starting blank radius. This study will consider the maximum draw depth for shrink corners with different radii. The same approach could be applied to the stretch corner.

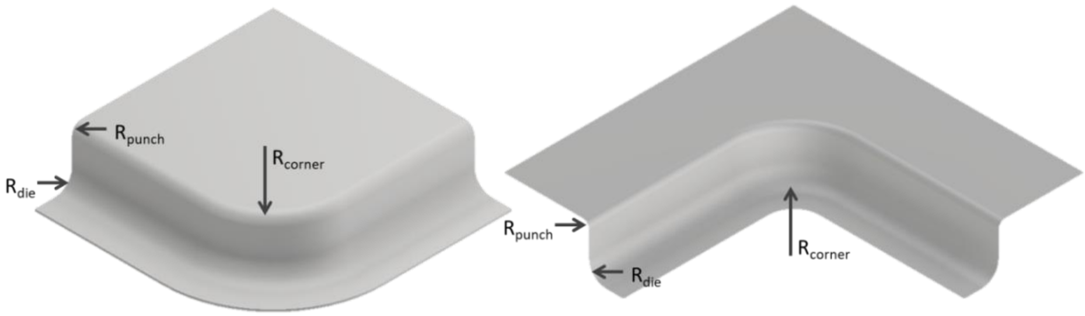



Figure 6.3 Shrink corner (left) and stretch corners (right).

The shrink corner is formed from a shaped blank of sheet metal. To eliminate the effect of the blank shape on the failure draw depth, the unfolded blank width and blank corner radius is calculated for all corner geometries. The blank width is calculated using equation 6.1, as shown in figure 6.4:

$W_b = OA + AB + BC + CD + DE$

$W_b = (w_p - r_p) + (\pi r_p/2) + (d - r_p - r_d) + (\pi r_d/2) + w_f$

$$W_b = w_p + ((\pi/2)-2)\, r_p) + ((\pi/2)-1)\, r_d) + d + w_f \qquad (6.1)$$

Where:
Blank half width = $w_b$; Flange width = $w_f$; Punch half width = $w_p$; Punch radius = $r_p$; Die radius = $r_d$ and Draw depth = d

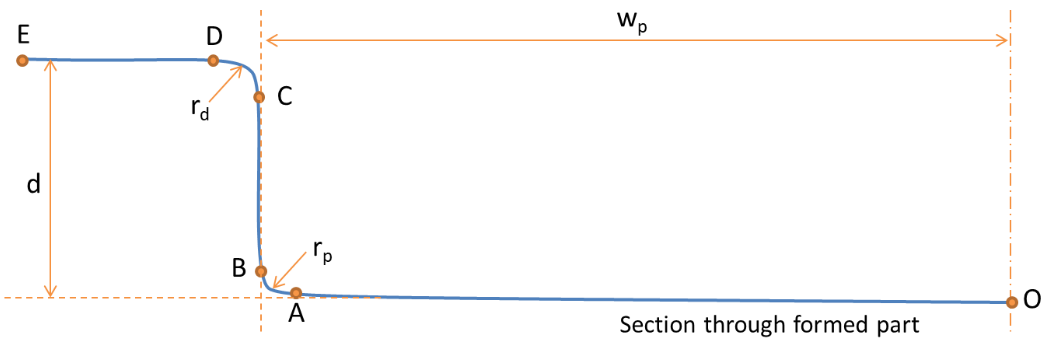



Figure 6.4 Calculation of blank width assuming no thinning.

The blank corner radius is calculated using equation 6.2 as shown in figure 6.5.

$r_b = r_c + AE$

$r_b = r_c + (W_b - OA)$

$r_b = r_c + W_b - (W_p - r_p)$

$$r_b = r_c + r_p + W_b - W_p \qquad (6.2)$$

Where:

Blank half width = $w_b$; Punch half width = $w_p$; Punch radius = $r_p$; Blank radius = $r_b$ and Part corner radius = $r_c$.

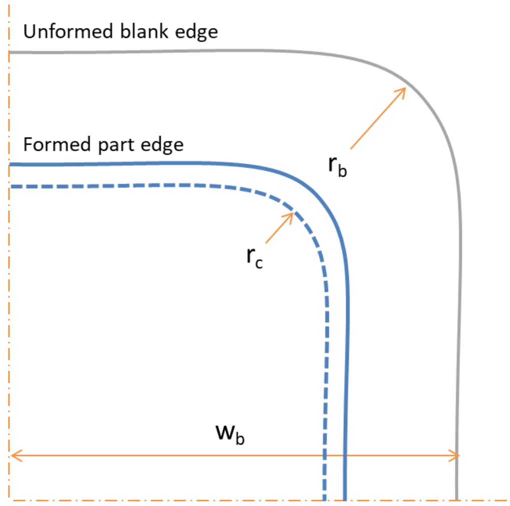



Figure 6.5 Calculation of blank corner radius

### 6.1.2 Experiment setup

Drawing multiple component geometries, both with and without a blank holder force, would typically require a new set of press tools for each experiment. This study investigates many component geometries so would require a large number of press tools. To avoid this expense the experiment is designed to produce multiple shrink corner geometries from one configurable tool. The press tool should be reconfigurable to perform both forming processes, drawing with and without a blank holder, and form multiple corner radii, die radii and draw depths. This section outlines how this is achieved through the design of the formed component, the press tool design and the blank preparation and measurement procedure.

#### Design of the formed component

In order to analyse the failure depth of multiple shrink corner geometries a component shape with multiple different corners is designed to be drawn in a press. The component is drawn on a square punch with different radii on each corner, as shown in figure 6.6. This will enable multiple results to be generated from each component. The punch width is large enough to ensure the corners do not interact, as each corner is being analysed independently. To ensure there is no interaction between corners the size of the punch is determined by preliminary experiments as detailed in section 6.1.4.

Figure 6.6 Component designed to be formed with different corner geometries.

In order to scale the experiment down to a laboratory environment, the component size is reduced using cut outs. The cut outs are positioned in the blank so the punch corners can be closer together without interacting, as shown in figure 6.7. This cut out also provides a location feature to position the blank in the press. The design of the press tool is now outlined.

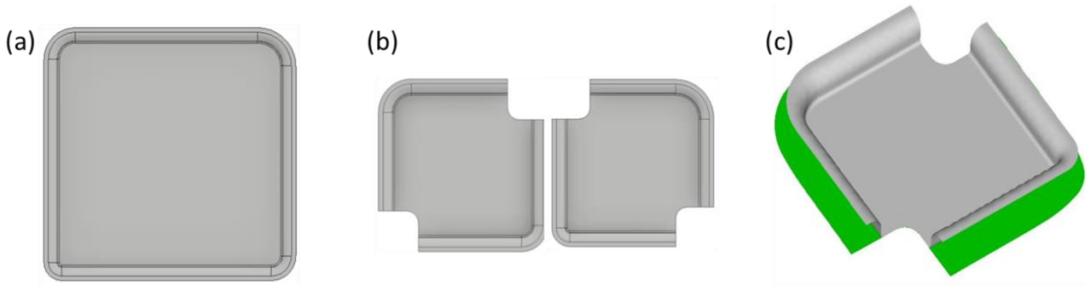



Figure 6.7 Using a cut out to reduce the component size and locate the blank. (a) The starting component design which can form four corners per tool stroke, (b) two smaller components with cut outs which can each form two corners per tool stroke, (c) the blank with cut outs (green) shown with the formed component.

## Press tool design

The press tools are designed to be configurable to draw multiple geometries both with and without a blank holder force applied. The tool design to achieve this is shown in figure 6.8. The set up for drawing with and without a blank holder are shown in figure 6.9 and 6.10 respectively. Images of the tool are shown in figure 6.11.

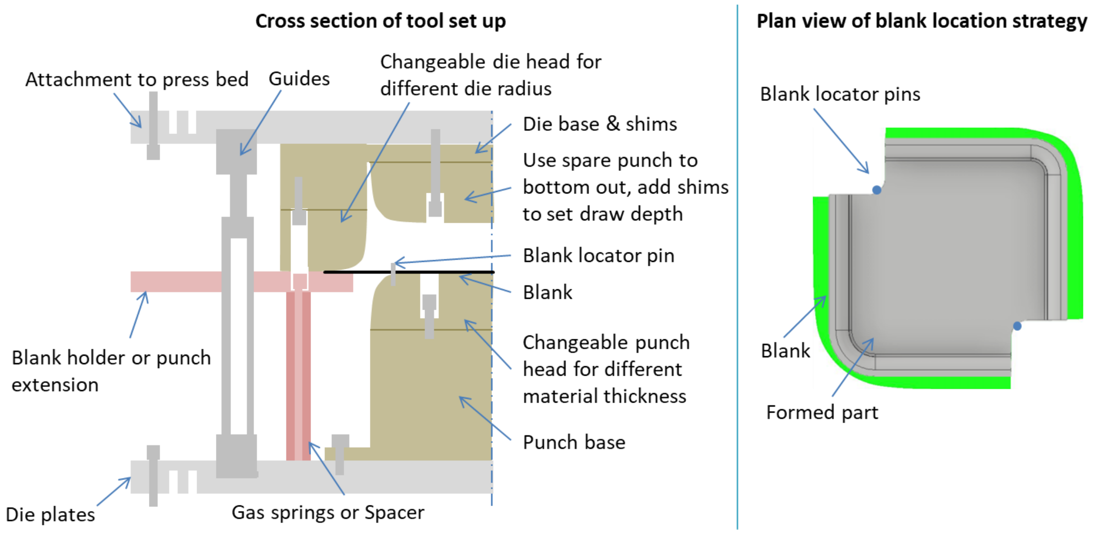



Figure 6.8 Illustration of configurable tool set up.

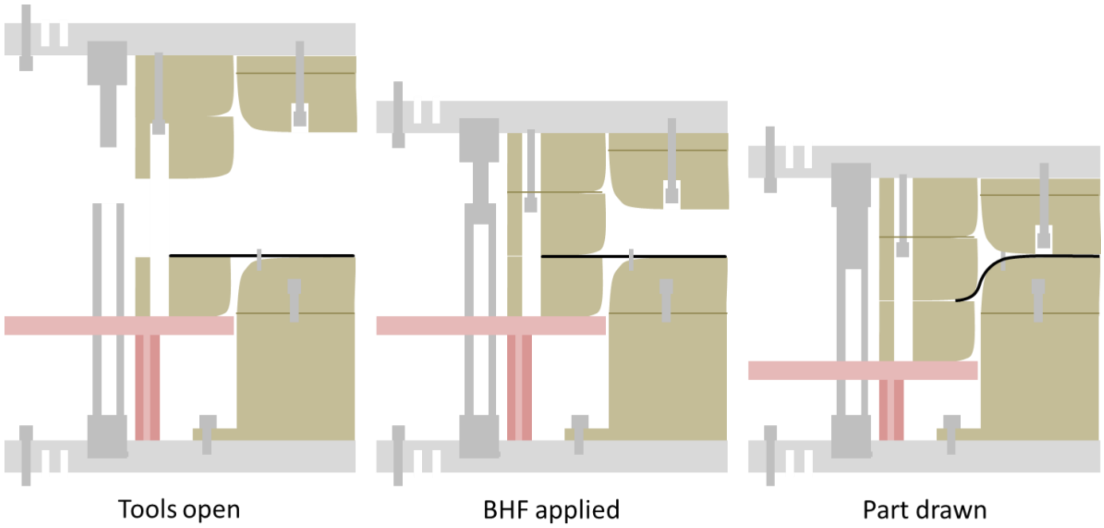



Figure 6.9 Illustration of tool set up for drawing with a blank holder.

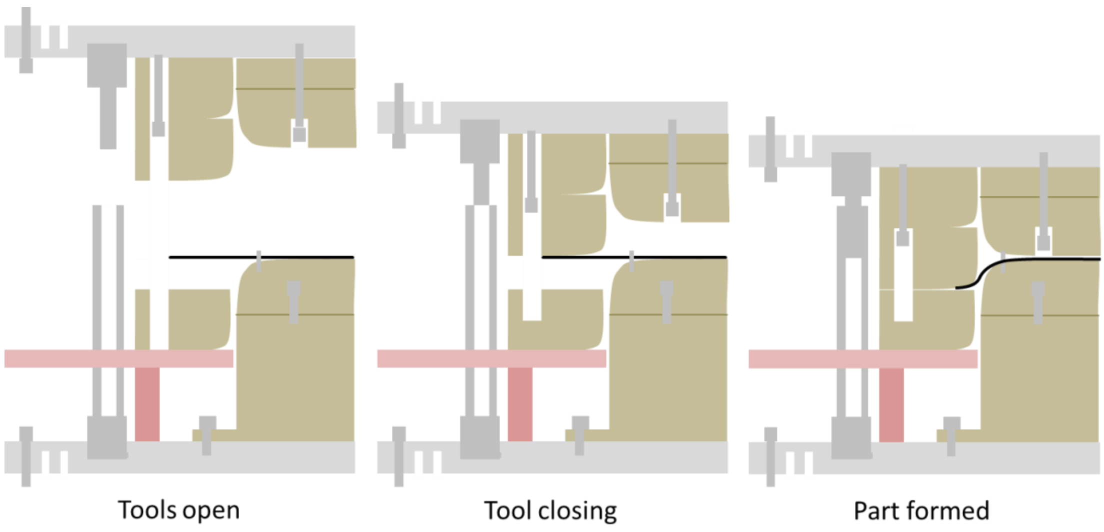



Figure 6.10 Illustration of tool set up for drawing without a blank holder.

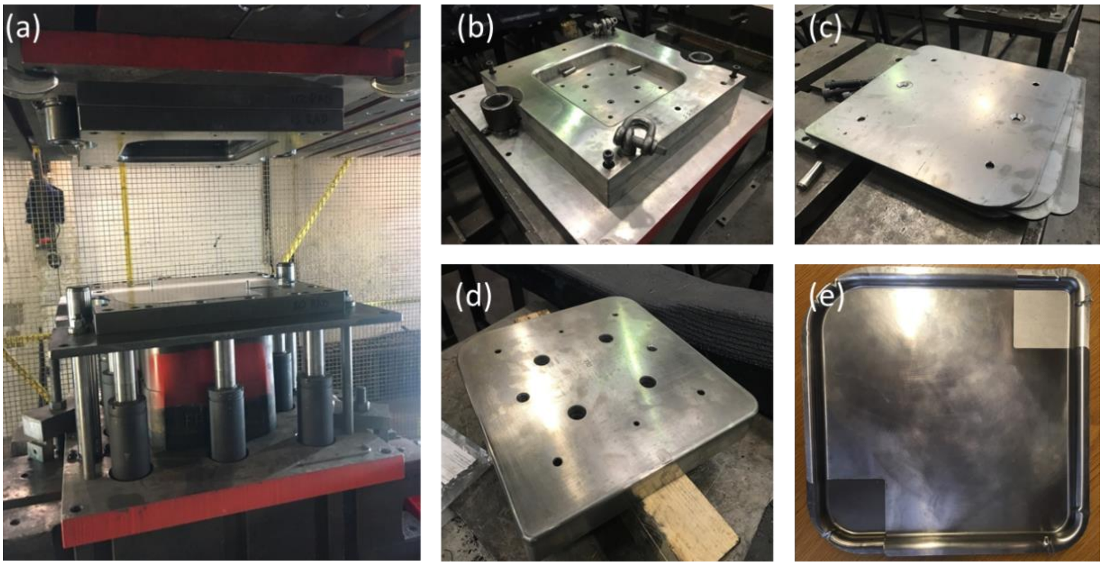



Figure 6.11 Photos of the physical experiments. (a) the tool in the press, (b) the die, (c) shims to set the draw depth, (d) the punch head, (e) two parts formed with cut outs in different locations.

A hydraulic single action press with position control is used, with custom tooling, to perform the laboratory studies. To achieve the effect of a blank holder, fixed gas springs are used; however, the applied blank holder force consequently varied with draw depth. A fixed tooling displacement is used to set the non-blank holder position. The blank holder force is provided by fixed gas springs so varies with the draw depth as described in table 6.1.

Table 6.1 Bank holder force for physical experiments.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Draw depth (mm) | 5 | 10 | 15 | 20 | 25 | 30 | 35 |
| Blank holder force (kN) | 95 | 99 | 103 | 107 | 110 | 114 | 118 |

To reduce the variability of the results, the manufacturing process parameters such as tool clearance and lubricant are kept constant. The tool clearance is 10% of the material thickness and the lubricant used is a thin, oil based, liquid lubricant applied manually with a roller over each blank. The blank preparation and measurement procedure are now described.

### Blank preparation and measurement

The sheet metal used for the experiments and simulations is aluminium alloy 5251 H22. The starting material thickness for an automotive aluminium sheet metal component is between 1.1mm and 1.5mm. The experiments have been scaled down by a half to fit a laboratory press shop. Therefore the material thickness investigated is half of the industry standard. The material properties are described in table 6.2. The blanks are drawn on the diagonal so the anisotropic effect of the rolling direction is eliminated. The blanks are cut from flat rolled sheet using a water jet cutter, cleaned, dried and manually deburrred. Oil based lubricant is applied by hand using a roller before the blank is potitioned in the press.

**Table 6.2 Material properties for physical experiments which identify the failure depth during the forming of shrink corners, with and without a blank holder force.**

| Material | Aluminium 5252 |
|---|---|
| Temper | H22 |
| Material thickness | 0.55mm & 0.75mm |
| Young's modulus (E) | 70 GPa |
| Poisson's ratio (v) | 0.3 |
| Density (ρ) | 2700 Kg/$m^3$ |
| Yield Stress ($\sigma_0$) | 165 MPa |

This study considers drawing failure by thinning and wrinkling which are measured as engineering strains. Table 2.2 from the literature review demonstrates that many different failure strains have been applied when identifying the maximum draw depth of square cups. The failure criteria selected for this study are based on the drawing recommendations of the automotive research partner. A thinning failure is recorded if the material thickness reduces by more than 20% and a wrinkling failure is recorded when wrinkles are visible. To better define the onset of visible wrinkles, wrinkling is predicted by the thickening strain. The maximum allowable thickening strain for each forming process is determined with a set of preliminary experiments as described in section 6.1.4.

Material thickness is measured using spring calipers, taking the average value of three measurements for each point, the sensitivity of this equipment is 0.005mm. The maximum, minimum and nominal material thicknesses are measured in the location identified in preliminary experiment B. Since the nominal thickness varies slightly between blanks the pass/fail criteria is calculated independently for every blank based on the nominal thickness for that blank. Each experiment is repeated three times and the decision to pass or fail the geometry is based on the average measurements from the three experiment repeats. Practical considerations limited the range of component radii that could be studied experimentally; and therefore the design space was extended using FEA. The setup of this model is now described.

### 6.1.3 Finite Element Analysis setup

Finite Element Analysis (FEA) simulations are used to extend the physical experiments to consider a greater number of geometric variables as described in section 6.1.5. The FE model is validated with the practical experiments detailed in section 6.2. This section outlines the setup of the finite element model.

The FE model was set up using Abaqus/Standard and was generated from a parametrised python script. This enabled the component geometry described in section 6.1.1 to be quickly adapted. The model was generated for one corner with symmetry conditions applied at the boundary to represent a square cup. The FE setup is shown in figure 6.12 for both scenarios, forming with and without a blank holder force.

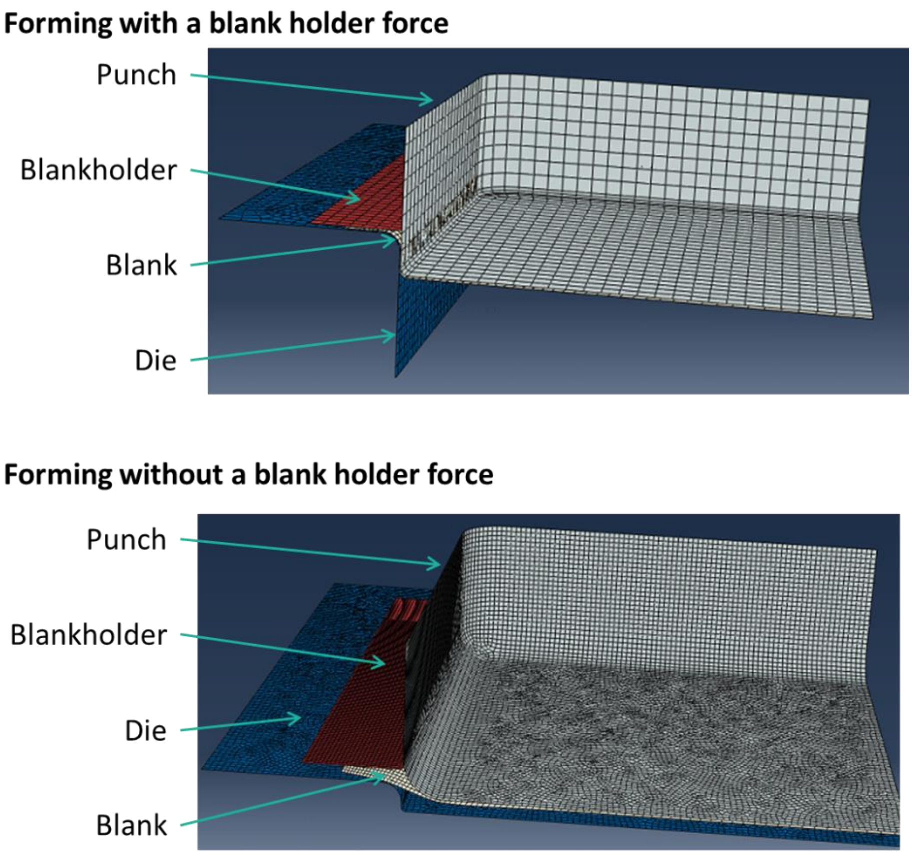



Figure 6.12 Simulation set up for forming with and without a blank holder force.

The simulation set-up for forming without a blank holder still uses a blank holder part, but this part moves with the punch during forming. The blank holder then acts as an extension to the punch and forms the flange at the end of the stroke. This simulation matches the set-up of the physical experiments. It can be seen in figure 6.12 that the mesh is more refined for forming without a blank holder force. This reduced mesh size was required in order for the simulations to converge.

The FE settings used are described in table 6.3. The friction coefficient is set to represent the oil based lubricant used in the physical experiments, as described in Zein & Shazly (2013).

Table 6.3 Abaqus model setup.

| | | |
|---|---|---|
| **Friction coefficient** | 0.1 | |
| **Interaction properties** | Exponential overclosure | |
| **Exponential overclosure curve** | **Pressure** | **Clearance** |
| | 300 | 0mm |
| | 0 | 0.75mm |
| **Material thickness** | 0.55mm & 0.75mm | |
| **Young's modulus (E)** | 70 GPa | |
| **Poisson's ratio (ν)** | 0.3 | |
| **Density (ρ)** | 2700 Kg/m$^3$ | |
| **Yield Stress ($\sigma_0$)** | 165 MPa | |
| **Element type** | Structured, Quad | |
| **Element size** | 1mm-2mm | |
| **Contact control** | Standard contact control | |
| **Contact type** | Automatic stabilisation | |
| **Parts considered rigid** | Blank holder, die, punch | |
| **Abaqus version** | Abaqus/CAE 6.14-1 | |

The average nominal thickness for the 0.75mm material is measured as 0.735mm and the average nominal thickness for the 0.55mm material is 0.535mm. This variation is within the allowable tolerance from the manufacture and is a common variation in industry. To allow comparison between the experiments and the FE model, the values of 0.735mm and 0.535mm are used as the starting thicknesses for the simulations. The FE failure criteria are calculated from these nominal thicknesses.

As identified in the literature review, the blank holder force impacts the failure draw depth. At the maximum draw depth, splitting and wrinkling failure occur simultaneously. If only one failure criterion is met, the blank holder force could possibly be modified to increase the draw depth. To eliminate this variable in the FE model, multiple blank holder forces are simulated for each shrink corner geometry.

Preliminary experiments and FE studies were conducted to inform the experiment design. The findings from these investigations are now discussed.

### 6.1.4 Preliminary investigations

Three preliminary investigations were undertaken using FE simulations and experiments made during a tool try-out. Firstly the material flow during forming is studied to determine the required punch width which allows each corner to be drawn independently to the others. Secondly the material thickness is investigated to establish the location of the maximum and minimum material thicknesses, as well as the thickening strain in which wrinkling starts to occur for both forming processes. Finally the blank corner radius is varied to evaluate the optimum radius to produce a constant flange around the perimeter of the corner. The results to these preliminary investigations are now presented.

#### Preliminary study A: Designing the punch width

Each corner of the punch should be sufficiently far from another corner so material is able to flow without being affected by the neighbouring corner. Suschy (2006) state that the width of a square cup should be at least 5 times the corner radii to provide sufficient material for forming. Based on this rule the punch width should be at least 275mm. This assumption was checked using a one-step solver simulation, FTI Forming Suite 2018. The corners were drawn for punch widths of 150mm, 300mm and 500mm as shown in figure 6.13. The one step results showed that a punch width of 500mm was required to eliminate the interaction between corners. This is demonstrated by the presence of a region which has not been drawn into the corner along each side of the square cup, shown in grey. The punch width is further reduced to 300mm using the blank cut outs which were shown in figure 6.7.

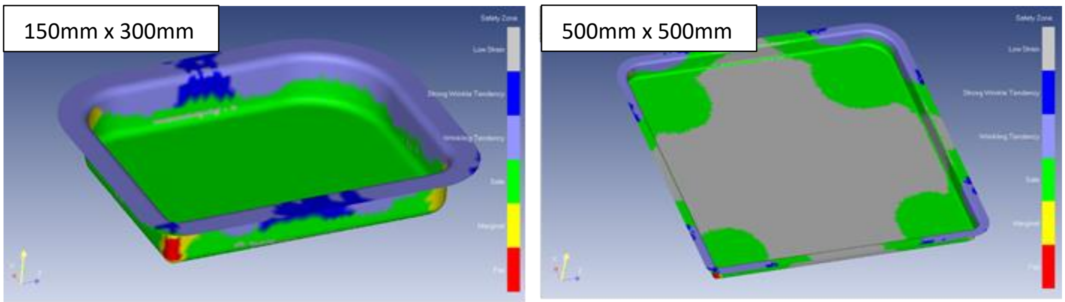
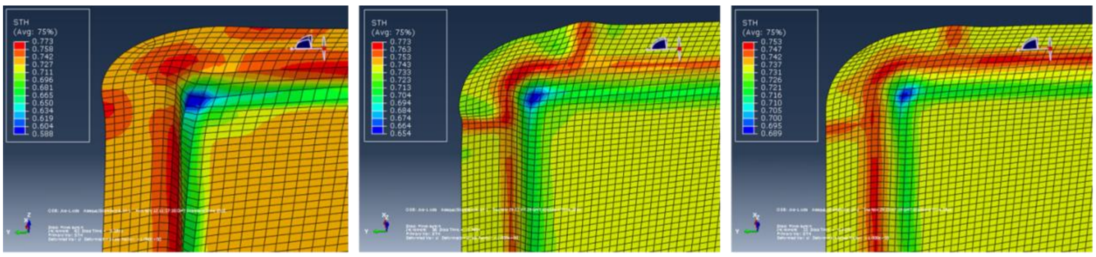



**Figure 6.13** **Simulation of forming corners with different punch widths. A blank width of 500mm is required to ensure corners do not interact during forming.**

## Preliminary study B: Thickening strain failure criteria

For this investigation the onset of wrinkling is predicted from the thickening strain. The literature review identified that Kumwenda & Zhoude (2015) and Kim et al. (2009) set different thickening strain limits to predict wrinkling during sheet metal forming. In order to set appropriate failure criteria for each process, these thickening strain limits were investigated using the FE model and validated by measuring the parts produced in the tool try out. Figure 6.14 shows that wrinkles did not occur for a thickening strain of 5% when a blank holder is applied, so a failure criterion of 5% strain can be applied to this process. In contrast, wrinkling can be observed for the same geometry when there is no blank holder force applied at 5% thickening, but not at 2.5% thickening. Therefore a failure limit of 2.5% thickening strain is more appropriate for the process of drawing without a blank holder.



5% thickening strain with a blank holder | 5% thickening strain without a blank holder | 2.5% thickening strain without a blank holder

**Figure 6.14** **Selecting the wrinkling failure criteria for drawing with and without a blank holder. The colour map represents material thickness, Red areas are the thickest and blue are the thinnest.**

The components produced during the tool try out were measured to identify the location in which the maximum, minimum and nominal thicknesses should be measured; these areas are shown in figure 6.15. Each measurement from the tool try out study was taken 10 times to estimate the variability of the measuring process as ±0.01mm. When combined with the sensitivity of the calipers, the total error for measuring the material thickness is therefore ±0.02mm. The nominal thicknesses for the two materials being investigated were measured as 0.535mm and 0.735mm.

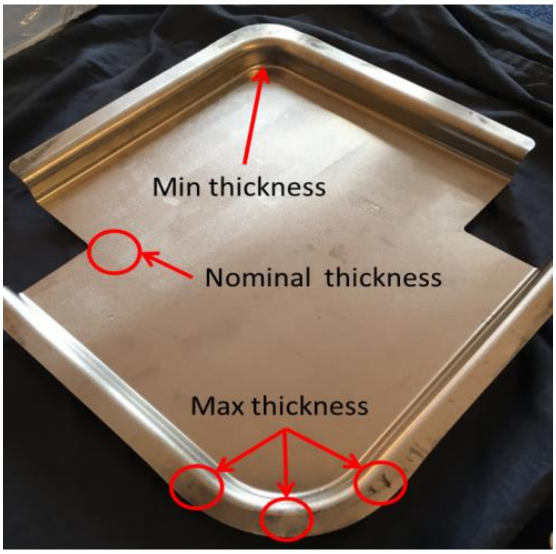



**Figure 6.15 Measurement locations identified on a component produced during the tool try out.**

The simulations and experiments conducted to investigate material thickness showed that less material is drawn into the centre of the corner than the edge component, increasing the size of the flange at the corner. To eliminate this excess material the blank corner radius should be adjusted to allow for different rates of material flow. The size of this offset is now calculated in the final preliminary experiment.

### Preliminary study C: designing the size of the blank corner radius

The 'unfolded' blank corner radius calculation in equation 6.2 assumes that material will flow into the corner uniformly from the blank radius. However, material is not uniformly drawn into the corner resulting in a difference in flange width around the formed component, as shown in figure 6.16.

To offset this effect, the blank radius is adjusted by a multiplier to keep the flange width constant. The flange width ratio is given in equation 6.3.

$$\text{Flange width ratio} = \text{Corner flange width} / \text{Edge flange width} \times 100 \qquad (6.3)$$

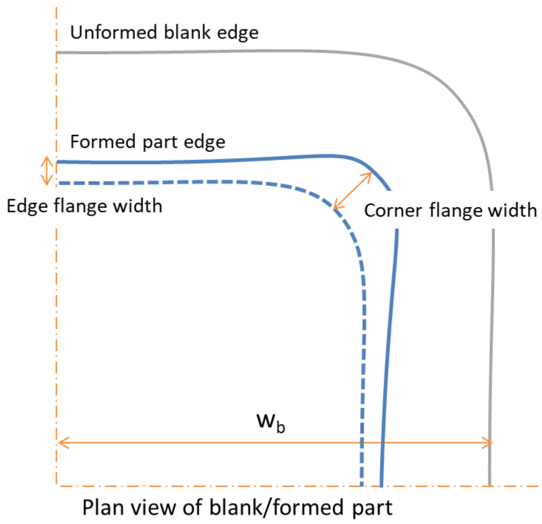



Figure 6.16 Uneven flange for a corner drawn from an 'unfolded' blank.

The blank radius multiplier was selected using FE experiments to trial multipliers of 1, 1.05, 1.1, 1.15 and 1.2 for the softest and tightest corner geometries studied in this trial. The optimum multiplier was identified for the extremes in geometry and the average value of 1.14 was determined, as shown in figure 6.17.

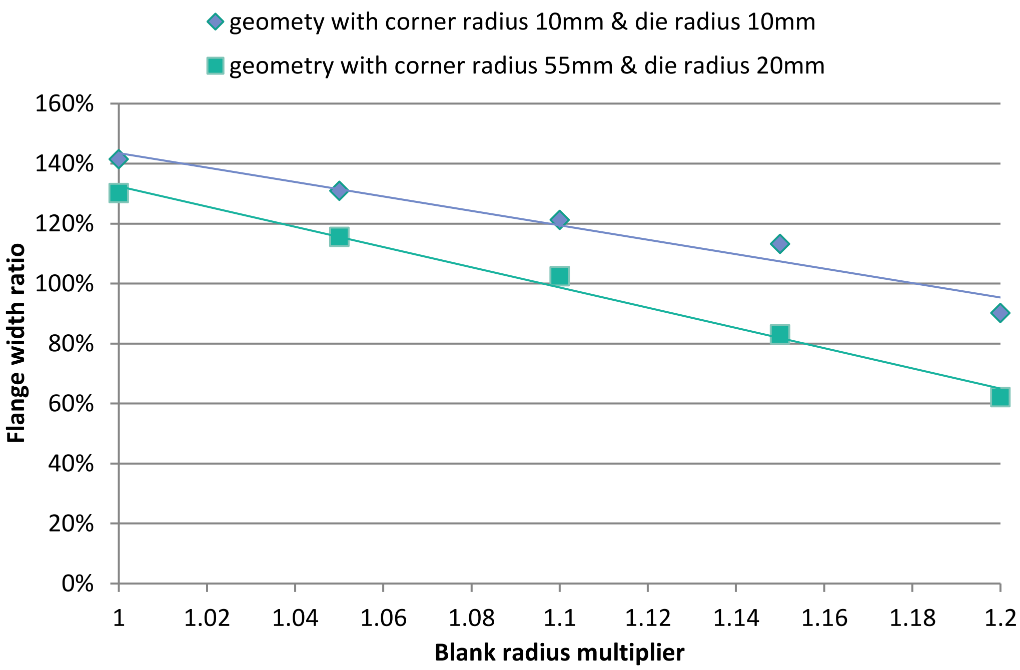



Figure 6.17 Calculating the optimum blank radius multiplier to offset the flange width variation.

The blank corner radius is therefore calculated as:

$$r_b = 1.14( r_c + r_p + W_b - W_p) \quad (6.4)$$

Where: Blank half width = $w_b$; Punch half width = $w_p$; Punch radius = $r_p$; Blank radius = $r_b$ and Part corner radius = $r_c$.

### 6.1.5 Outline of experiments

To investigate whether forming failure can be predicted from component geometry, failure draw depths are determined experimentally for multiple shrink corner geometries. 60 corner geometries are drawn with a blank holder force and 36 geometries are drawn without a blank holder force using the tools described in section 6.1.2. These experiments are then extended using FE simulations described in section 6.1.3 to investigate 288 different shrink corner geometries formed with an optimised blank holder and 144 shrink corner geometries without a blank holder. The experiments are conducted for two different material thicknesses. The geometric variables being changed for each forming process are described in table 6.4. The variables listed in brackets are investigated using FE analysis only, all other variables are studied both experimentally and using FE analysis.

Table 6.4 List of geometry variables for corner formed in the experiment.

| Forming process | Thickness (mm) | Corner radius (mm) | Die radius (mm) | Punch radius (mm) | Draw depth (mm) |
|---|---|---|---|---|---|
| Drawing with a blank holder | 0.535 | 10 | 10 | 4 | 15 |
| | 0.735 | 25 | 15 | (10) | 20 |
| | | 40 | 20 | (20) | 25 |
| | | 55 | | | 30 |
| | | | | | 35 |
| | | | | | (40) |
| | | | | | (45) |
| | | | | | (50) |
| Drawing without a blank holder | 0.535 | 10 | 10 | 4 | 5 |
| | 0.735 | 25 | 15 | (10) | 10 |
| | | 40 | 20 | (20) | 15 |
| | | 55 | | | (20) |

To allow direct comparison of the failure depth for each experiment all other forming variables are controlled. The experiment set up is informed by the literature review and the preliminary experiments detailed in section 6.1.4, these parameters are summarised in table 6.5.

**Table 6.5 Summary of parameters which remain constant.**

| | |
|---|---|
| **Blank width** | $W_b = w_p + ((\pi/2)\text{-}2)\ r_p) + ((\pi/2)\text{-}1)\ r_d) + d + w_f$ |
| **Blank corner radius** | $r_b = 1.14(\ r_c + r_p + W_b - W_p)$ |
| **Flange width** | 10mm |
| **Thinning failure strain** | 20% |
| **Thickening failure strain without bhf** | 2.5% |
| **Thickening failure strain with bhf** | 5% |
| **Tool clearance** | 10% |
| **Lubricant** | Oil based, coefficient of friction 0.1 |

The results for these experiments are now presented and analysed to determine the extent in which the failure draw depth can be estimated from the component geometry in forming processes for sheet metal shrink corners.

## 6.2 Results: Estimating failure draw depth from three critical radii

An estimate of the failure draw depth predicted from component geometry could be used early in the product development cycle to inform geometry and process selection decisions. The results from the physical experiments are now presented to identify the effect of changing the die and corner radius on the maximum draw depth of shrink corner. The results are then used to validate an FE model which extends the results to optimise the blank holder force and consider different punch radii. The results from the FE model are then analysed to identify any trends in the failure draw depth and the average radii to establish the extent in which the maximum draw depth can be estimated from the corner, die and punch radii for drawing processes with and without a blank holder.

### 6.2.1 Experimental results

Shrink corners with the geometries outlined in table 6.4 were drawn with and without a blank holder using the equipment and process described in section 6.2.2. Tables 6.6–6.9 summarise the results. P denotes an experiment which passed, FS denoted an experiment which failed by splitting or thinning, FW denotes an experiment which failed by wrinkling and FSW denotes an experiment which failed by both splitting and wrinkling.

Table 6.6 Results from drawing corners with a blank holder force.

| draw t0 = 0.55mm | | | | | |
|---|---|---|---|---|---|
| corner radius 10mm | 15mm | 20mm | 25mm | 30mm | 35mm |
| $R_{die}$ 10mm | P | FSW | FW | FS | FS |
| $R_{die}$ 15mm | FS | FS | FW | FW | FSW |
| $R_{die}$ 20mm | FS | FS | FSW | FSW | FSW |
| | | | | | |
| corner radius 25mm | 15mm | 20mm | 25mm | 30mm | 35mm |
| $R_{die}$ 10mm | P | FS | FW | FW | FW |
| $R_{die}$ 15mm | P | P | FW | FW | FW |
| $R_{die}$ 20mm | P | P | P | FW | FS |
| | | | | | |
| corner radius 40mm | 15mm | 20mm | 25mm | 30mm | 35mm |
| $R_{die}$ 10mm | P | P | FS | FS | FS |
| $R_{die}$ 15mm | P | P | P | FW | FW |
| $R_{die}$ 20mm | P | P | P | FW | FW |
| | | | | | |
| corner radius 55mm | 15mm | 20mm | 25mm | 30mm | 35mm |
| $R_{die}$ 10mm | P | P | P | FW | FW |
| $R_{die}$ 15mm | P | P | P | FW | FW |
| $R_{die}$ 20mm | P | P | P | P | FW |

Table 6.7 Results from drawing corners with a blank holder force.

| draw t0 = 0.75mm | | | | | |
|---|---|---|---|---|---|
| corner radius 10mm | 15mm | 20mm | 25mm | 30mm | 35mm |
| $R_{die}$ 10mm | P | P | FS | FSW | FSW |
| $R_{die}$ 15mm | FS | FS | FS | FSW | FS |
| $R_{die}$ 20mm | FS | FS | FS | FS | FSW |
| | | | | | |
| corner radius 25mm | 15mm | 20mm | 25mm | 30mm | 35mm |
| $R_{die}$ 10mm | P | FW | FW | FW | FW |
| $R_{die}$ 15mm | P | P | FW | FW | FW |
| $R_{die}$ 20mm | P | P | P | FW | FSW |
| | | | | | |
| corner radius 40mm | 15mm | 20mm | 25mm | 30mm | 35mm |
| $R_{die}$ 10mm | P | P | FW | FW | FW |
| $R_{die}$ 15mm | P | P | P | FW | FW |
| $R_{die}$ 20mm | P | P | P | FW | FW |
| | | | | | |
| corner radius 55mm | 15mm | 20mm | 25mm | 30mm | 35mm |
| $R_{die}$ 10mm | P | P | FW | FW | FW |
| $R_{die}$ 15mm | P | P | P | FW | FW |
| $R_{die}$ 20mm | P | P | P | P | FW |

**Table 6.8** **Results from drawing corners without a blank holder force.**

| draw t0 = 0.55mm | | | |
|---|---|---|---|
| corner radius 10mm | 5mm | 10mm | 15mm |
| $R_{die}$ 10mm | P | F | F |
| $R_{die}$ 15mm | P | F | F |
| $R_{die}$ 20mm | P | F | F |
| | | | |
| corner radius 25mm | 5mm | 10mm | 15mm |
| $R_{die}$ 10mm | P | F | F |
| $R_{die}$ 15mm | P | F | F |
| $R_{die}$ 20mm | P | F | F |
| | | | |
| corner radius 40mm | 5mm | 10mm | 15mm |
| $R_{die}$ 10mm | P | F | F |
| $R_{die}$ 15mm | P | F | F |
| $R_{die}$ 20mm | P | F | F |
| | | | |
| corner radius 55mm | 5mm | 10mm | 15mm |
| $R_{die}$ 10mm | P | F | F |
| $R_{die}$ 15mm | P | F | F |
| $R_{die}$ 20mm | P | F | F |

**Table 6.9** **Results from drawing corners without a blank holder force.**

| draw t0 = 0.75mm | | | |
|---|---|---|---|
| corner radius 10mm | 5mm | 10mm | 15mm |
| $R_{die}$ 10mm | P | F | F |
| $R_{die}$ 15mm | P | F | F |
| $R_{die}$ 20mm | P | F | F |
| | | | |
| corner radius 25mm | 5mm | 10mm | 15mm |
| $R_{die}$ 10mm | P | F | F |
| $R_{die}$ 15mm | P | F | F |
| $R_{die}$ 20mm | P | F | F |
| | | | |
| corner radius 40mm | 5mm | 10mm | 15mm |
| $R_{die}$ 10mm | P | F | F |
| $R_{die}$ 15mm | P | F | F |
| $R_{die}$ 20mm | P | F | F |
| | | | |
| corner radius 55mm | 5mm | 10mm | 15mm |
| $R_{die}$ 10mm | P | F | F |
| $R_{die}$ 15mm | P | F | F |
| $R_{die}$ 20mm | P | F | F |

The results from these experiments are plotted in figure 6.18 and 6.19. Since the tools are designed to draw corners with depths at 5mm increments, the failure depth is plotted as 2.5mm below the depth of the first failure recorded with an error bar of ±2.5mm.

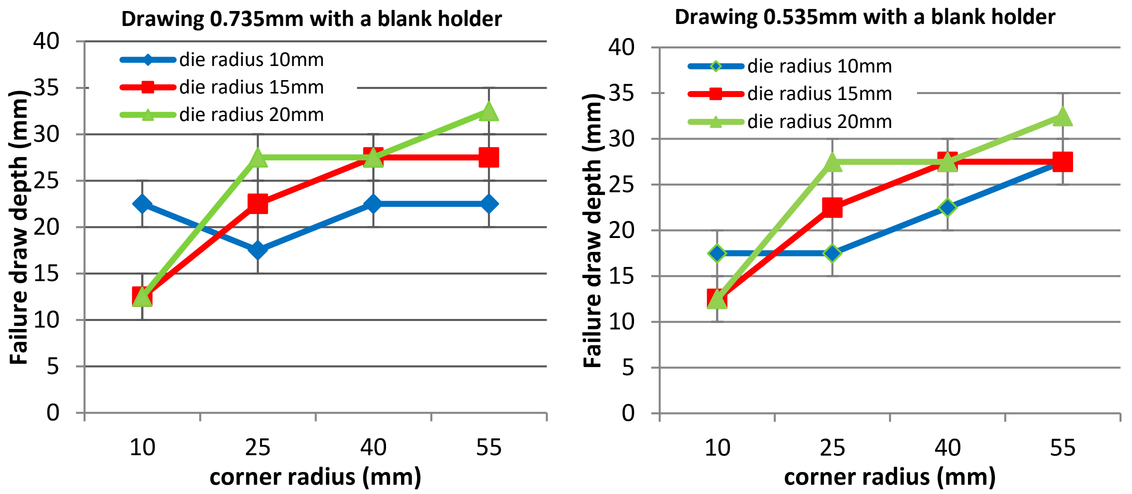



**Figure 6.18** Experimentally determined maximum draw depth plotted for different shrink corner geometry, with a blank holder force.

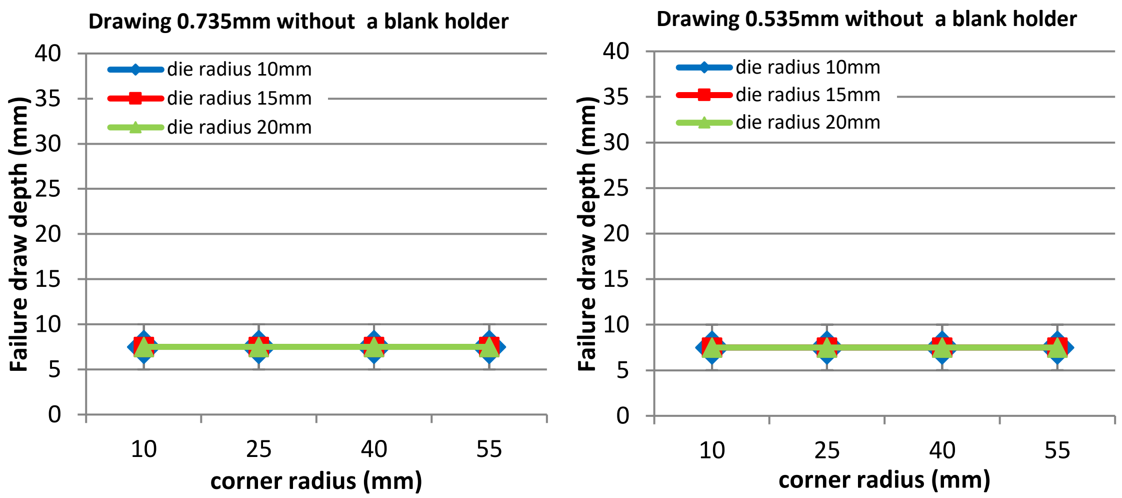



**Figure 6.19** Experimentally determined maximum draw depth plotted for different shrink corner geometry, without a blank holder force.

As expected from the literature review, the failure draw depth is greater when a blank holder force is applied during the drawing process as the tension from the blank holder delays the onset of wrinkling. These experimental results suggest a trend exists between the failure depth and the radii of a shrink corner drawn with a blank holder since increasing the die and corner radii increases the failure draw depth. When drawing without a blank holder force, all failures occurred between the draw depths of 5mm and 10mm. Therefore a trend could not be identified from the sets of experiments. This trend will be investigated with the FE simulations. Increasing the material thickness from 0.535mm to 0.735mm had very little effect on the maximum draw depth.

These results are rationalised in figure 6.20 to identify any trends between the failure draw depth and the average radii.

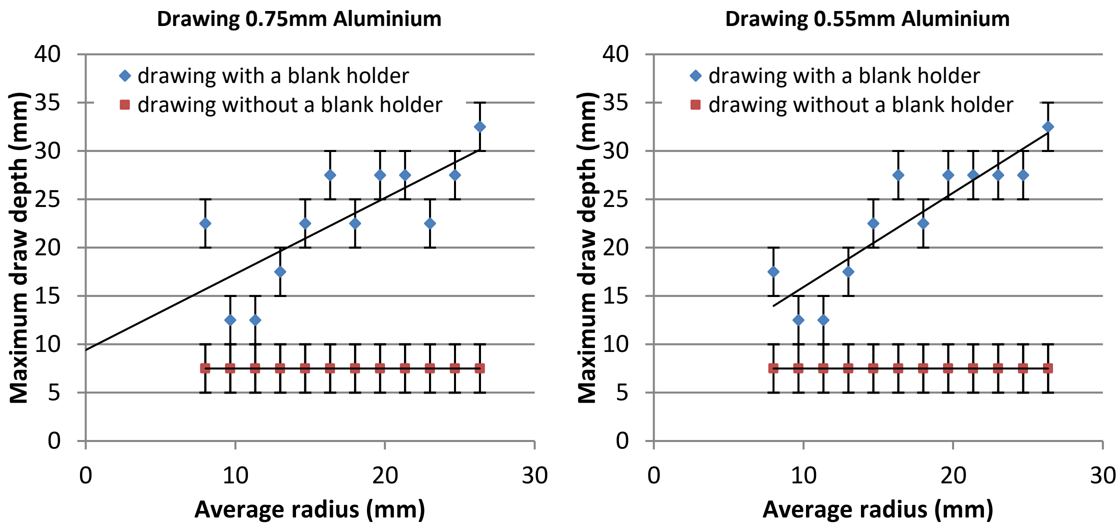



**Figure 6.20** Experimentally determined maximum draw depth plotted against the average of the corner, die and punch radii for different shrink corner geometry.

These physical results suggest a trend might exist between the failure depth and the average radii of a shrink corner drawn with a blank holder. There is insufficient data to conclude whether such a trend exists when drawing without a blank holder. If such a trend exists when the blank holder force is optimised, this relationship could be used as a design guideline in the early stages of the product development process. To test this hypothesis, the experiments are extended to optimise the blank holder force and include more geometry using Finite Element (FE) simulations. The FE model described in section 6.1.3 is first validated against the experimental results.

### 6.2.2 Validating the FE model

The FE model is validated through comparing the simulated maximum and minimum material thickness with measurements taken at 5mm intervals from corners drawn in the physical experiments. This comparison is made for two shrink corner geometries, for both drawing with and without a blank holder. The simulated failure depth is then compared to the experimental failure depth for all shrink corner geometries.

### Comparing the material thickness during drawing

To validate the FE model the material thickness of two different shrink corner geometries are compared the experimental values at draw depth increments of 5mm until failure occurs by thinning or wrinkling. The error margin for measuring the material thickness of the physical experiments is ±0.02mm as described in the preliminary experiments in section 6.1.4.

Comparisons of material thickness for drawing shrink corners with a blank holder force are shown in figures 6.21 and 6.22. The value of the blank holder force simulated is the same value as the blank holder force applied in the experiments, as described in table 6.2.

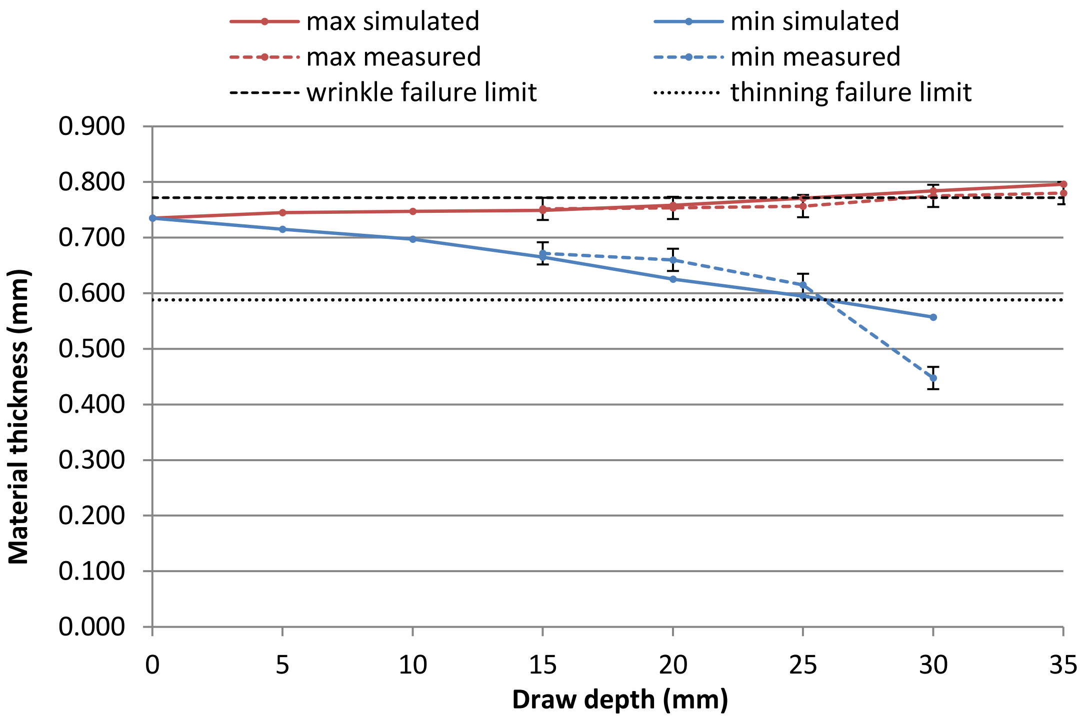



**Figure 6.21 Comparison of physical and simulated material thickness with increasing draw depth for drawing with a blank holder. Die radius = 20mm, corner radius = 25mm, punch radius = 4mm, initial thickness = 0.735mm.**

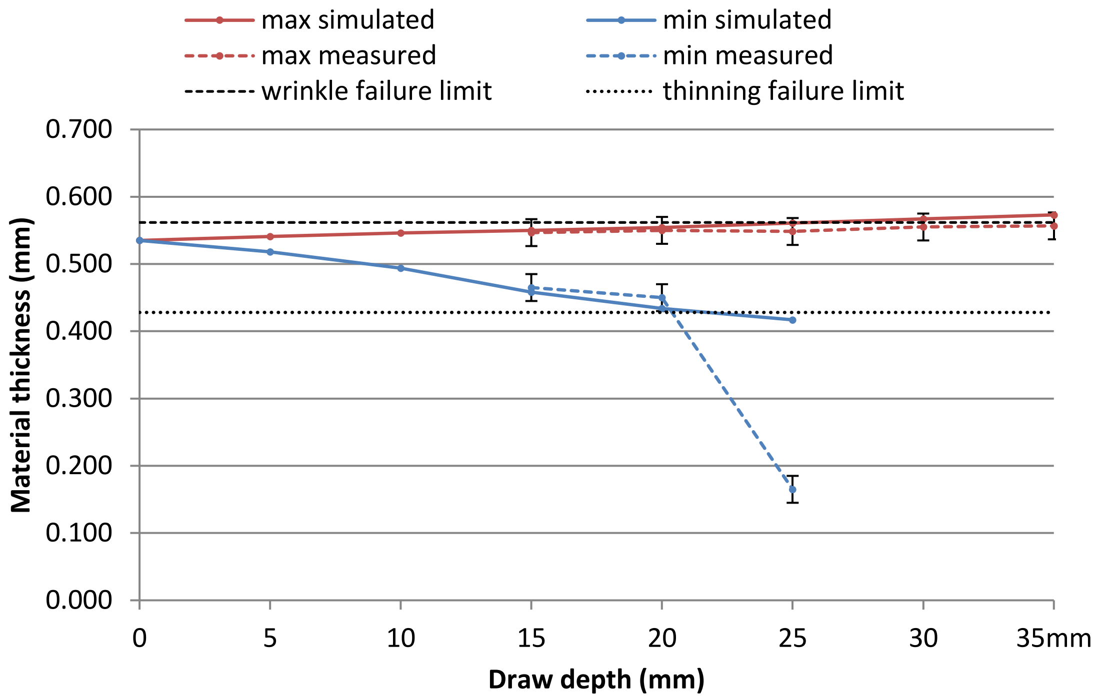



**Figure 6.22 Comparison of physical and simulated material thickness with increasing draw depth for drawing with a blank holder. Die radius = 10mm, corner radius = 40mm, punch radius = 4mm, initial thickness = 0.535mm.**

Figures 6.21 and 6.22 show a correlation between the material thicknesses predicted with the simulation and the material thicknesses measured from the physical experiments. These results demonstrate that the FE model is able to predict the failure of shrink corners drawn with a blank holder force. The FE model does not include damage mechanics therefore the thinning rate after the failure criteria has been reached is greater for the physical experiments than the simulations. This FE model discrepancy can also be observed in Sener & Kurtaran (2016) and is judged not to effect the thinning failure depth of 20% thinning strain.

The same shrink corner geometries are now evaluated for the process of drawing without a blank holder force. The results are shown in figures 6.23 and 6.24. These graphs demonstrate that the FE model was able to accurately predict material thickness for drawing shrink corners without a blank holder. For both geometries, failure occurs by wrinkling.

The FE model is validated further through comparing the failure draw depth for each experiment.

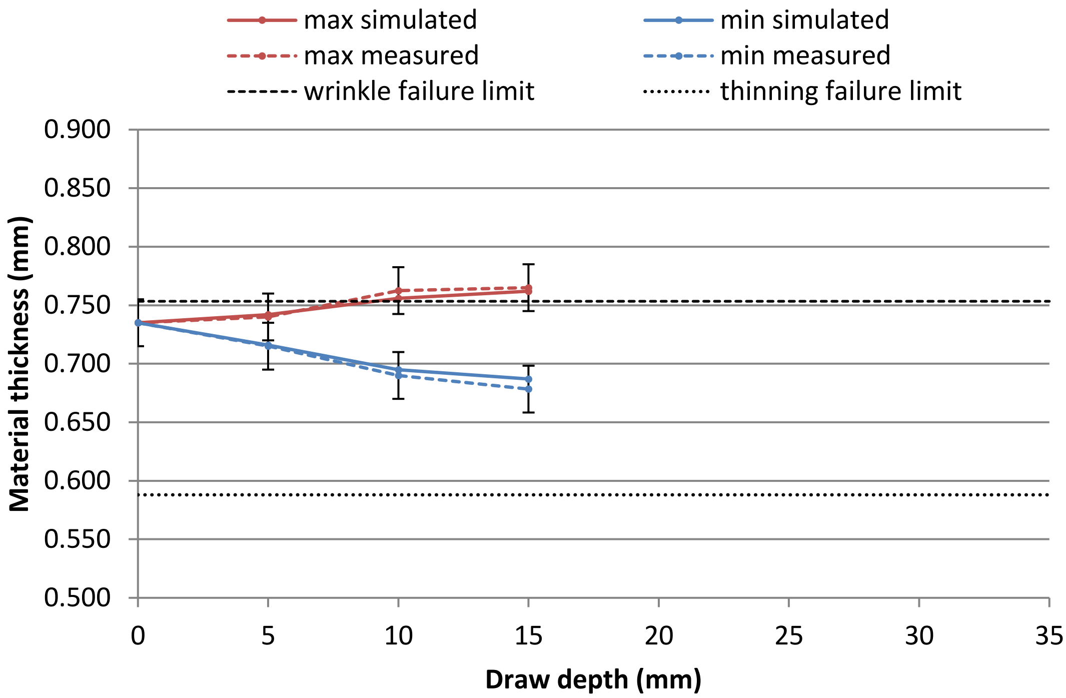



Figure 6.23 Comparison of physical and simulated material thickness with increasing draw depth for drawing without a blank holder. Die radius = 20mm, corner radius = 25mm, punch radius = 4mm, initial thickness = 0.735mm.

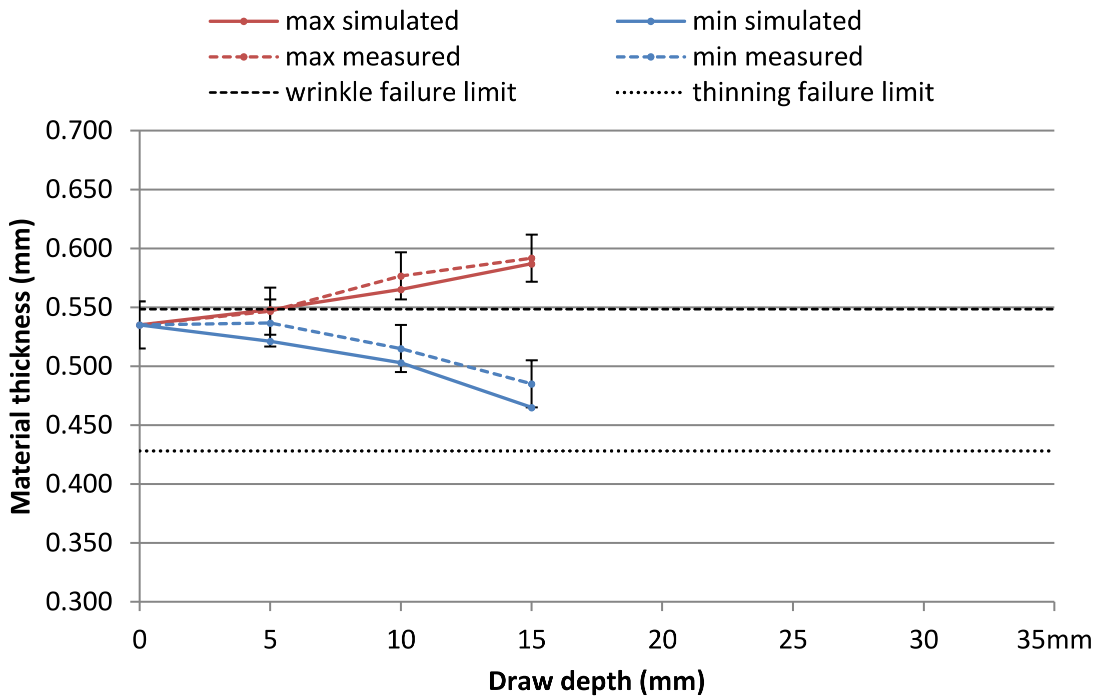



Figure 6.24 Comparison of physical and simulated material thickness with increasing draw depth for drawing without a blank holder. Die radius = 10mm, corner radius = 40mm, punch radius = 4mm, initial thickness = 0.535mm.

### Comparing the draw depth at failure

To further validate the FE model, the simulated failure draw depth is compared to the experimental failure depth for all geometries. To allow a direct comparison with the experiments, the simulated blank holder force is not optimised and the experimental blank holder force, shown in table 6.2, is applied. Figures 6.25–6.28 present these results where the width of the bubble is proportionate to the draw depth. For the FE model to be in agreement with the physical experiments, the FE failure depth shown with an orange bubble should lie within the 5mm band predicted by the physical experiments, denoted with blue lines.

The comparison of failure draw depths shows that the simulated failure depth is in agreement with experimental failure depth for all shrink corner geometries without a blank holder force. When a blank holder is applied the simulations reflected the physical experiments for corner radii of 25mm, 40mm and 55mm, but the 10mm corner was not accurately simulated with the FE model. It is possible that for small radii the drawing mechanics are more complex than the FE model predicts. Since the model did not accurately predict failure for the tight corner radii the FE results for these geometries were excluded in the following analysis. The maximum draw depth identified did not scale with an increase in material thickness from 0.535mm to 0.735mm. Further investigation into material thickness is required to understand its impact on maximum draw depth.

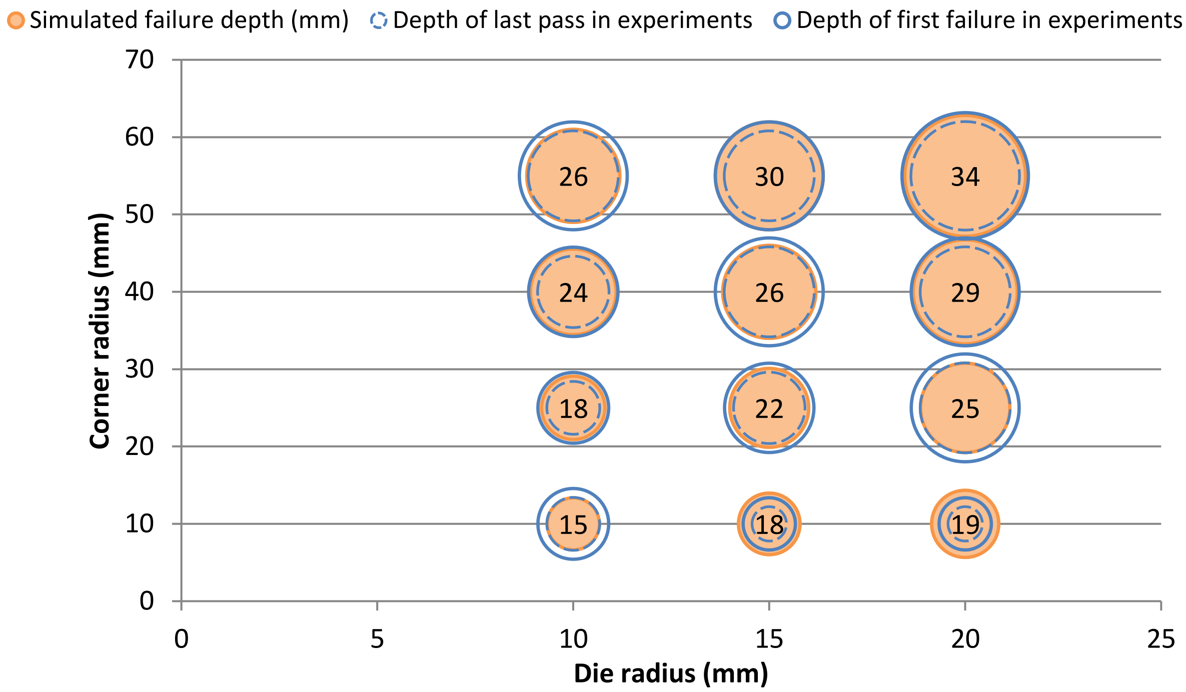



Figure 6.25 Comparison of simulated failure depth and physical experiment results for drawing 0.535mm aluminium with a blank holder. For scale, the data label gives the simulated failure draw depth value.

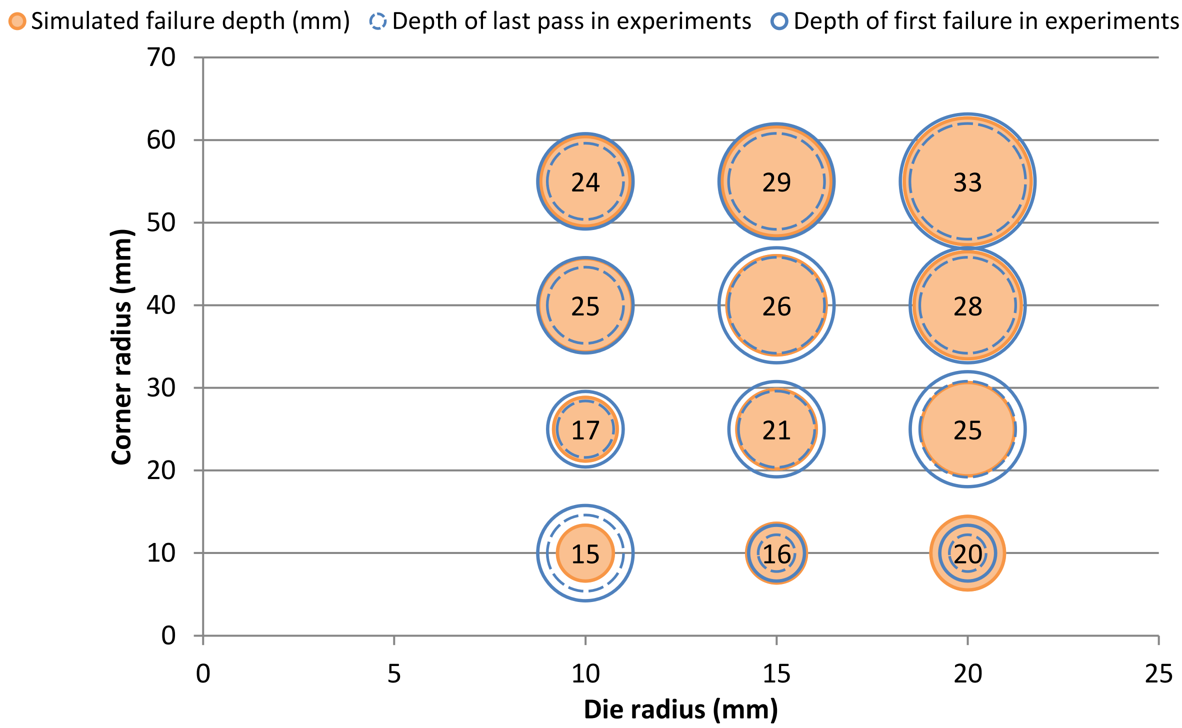



Figure 6.26 Comparison of simulated failure depth and physical experiment results for drawing 0.735mm aluminium with a blank holder. For scale, the data label gives the simulated failure draw depth value.

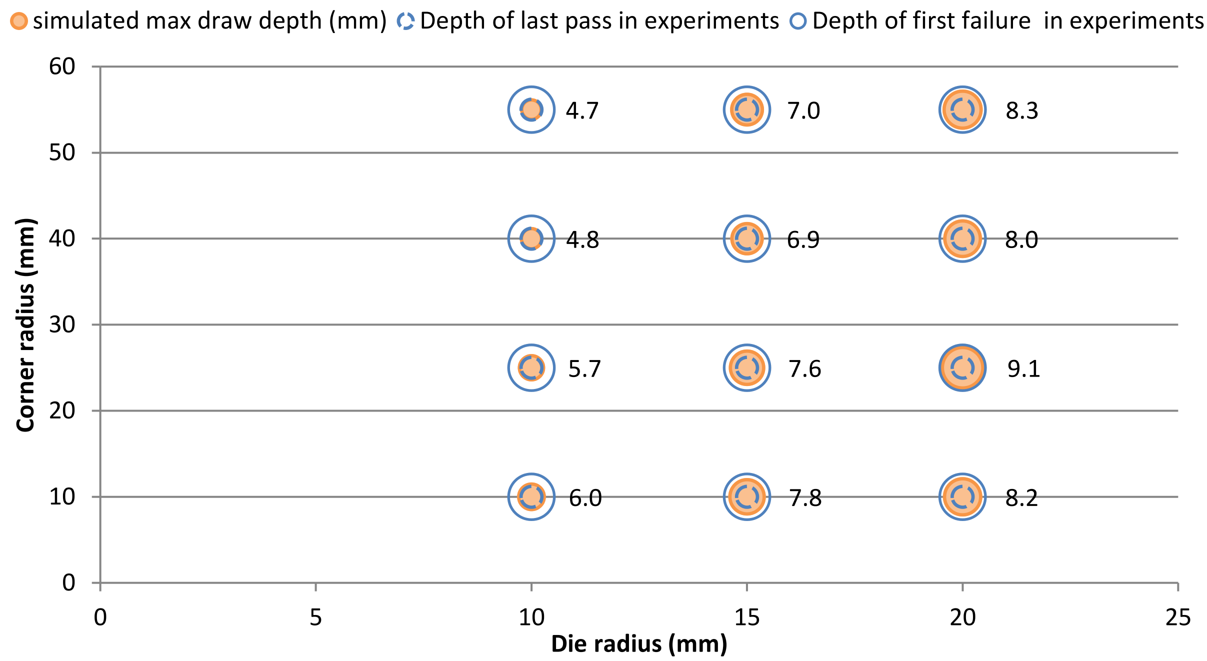



Figure 6.27 Comparison of simulated failure depth and physical experiment results for drawing 0.535mm aluminium without a blank holder. For scale, the data label gives the simulated failure draw depth value.

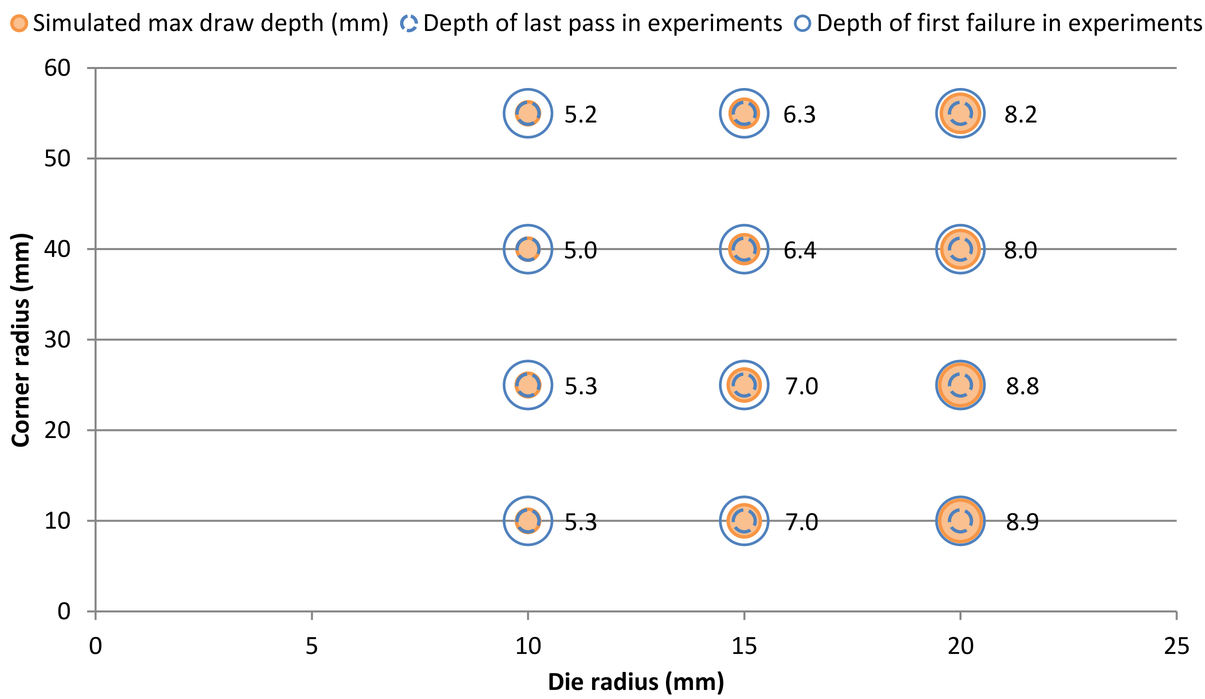



Figure 6.28 Comparison of simulated failure depth and physical experiment results for drawing 0.735mm aluminium without a blank holder. For scale, the data label gives the simulated failure draw depth value.

### 6.2.3 Extending the results using simulations

The experimental results are now extended to consider shrink corner geometry with different punch radii, as described in table 6.4. The maximum draw depths displayed in figures 6.25–6.28 represent the maximum draw depth without optimising the blank holder force. These simulations for these geometries are repeated using the validated FE model to find the maximum draw depth with an optimised blank holder force.

As described in section 6.1.2, the FE model is set up to draw sheet aluminium with an initial material thickness of 0.735mm. The simulations are repeated with different blank holder forces to determine the maximum failure draw depth. The maximum failure depth is recorded when wrinkling and splitting occurs simultaneously, the point in which the two lines cross in figure 6.29. This optimisation process is repeated find the maximum draw depth for all shrink corner geometries.

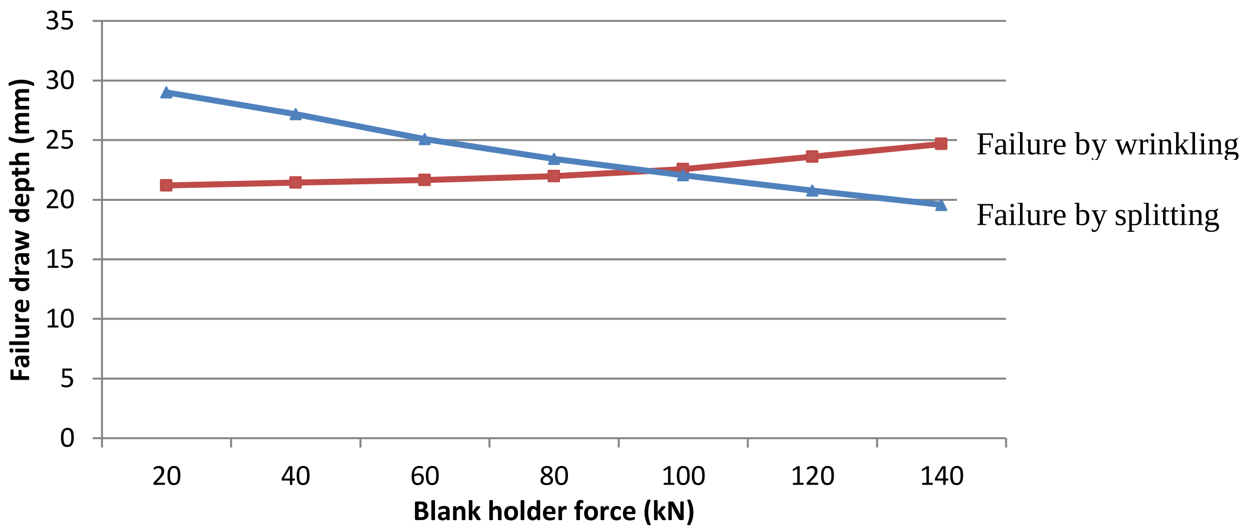



**Figure 6.29 Optimising the blank holder force to find the maximum draw depth when the corner radius is 25mm, die radius 15mm and punch radius 4mm.**

The results for the simulated maximum failure depth and optimised blank holder force are presented in table 6.10 and plotted in figures 6.30. and 6.31.

**Table 6.10 Simulation results for identifying the maximum draw depth with and without a blank holder.**

| $R_{die}$ (mm) | $R_{corner}$ (mm) | $R_{punch}$ (mm) | Blank holder force at max draw depth (kN) | Failure height with a bhf (mm) | Failure height without a bhf (mm) |
|---|---|---|---|---|---|
| 10 | 25 | 4 | 70 | 21 | 5.3 |
| 10 | 40 | 4 | 100 | 25 | 5.0 |
| 10 | 55 | 4 | 130 | 29 | 5.2 |
| 15 | 25 | 4 | 90 | 22 | 7.0 |
| 15 | 40 | 4 | 115 | 26 | 6.4 |
| 15 | 55 | 4 | 130 | 32 | 6.3 |
| 20 | 25 | 4 | 100 | 25 | 8.8 |
| 20 | 40 | 4 | 120 | 29 | 8.0 |
| 20 | 55 | 4 | 140 | 33 | 8.2 |
| 10 | 25 | 10 | 100 | 25 | 6.4 |
| 10 | 40 | 10 | 160 | 32 | 6.6 |
| 10 | 55 | 10 | 240 | 31 | 6.6 |
| 15 | 25 | 10 | 90 | 27 | 7.8 |
| 15 | 40 | 10 | 170 | 33 | 8.1 |
| 15 | 55 | 10 | 180 | 37 | 10.0 |
| 20 | 25 | 10 | 140 | 29 | 9.6 |
| 20 | 40 | 10 | 180 | 33 | 9.9 |
| 20 | 55 | 10 | 190 | 39 | 10.1 |
| 10 | 25 | 20 | 200 | 31 | 8.4 |
| 10 | 40 | 20 | 250 | 34 | 8.9 |
| 10 | 55 | 20 | 260 | 41 | 10.0 |
| 15 | 25 | 20 | 200 | 35 | 8.9 |
| 15 | 40 | 20 | 240 | 40 | 10.8 |
| 15 | 55 | 20 | 300 | 42 | 11.8 |
| 20 | 25 | 20 | 160 | 39 | 13.4 |
| 20 | 40 | 20 | 230 | 38 | 14.5 |
| 20 | 55 | 20 | 220 | 47 | 14.5 |

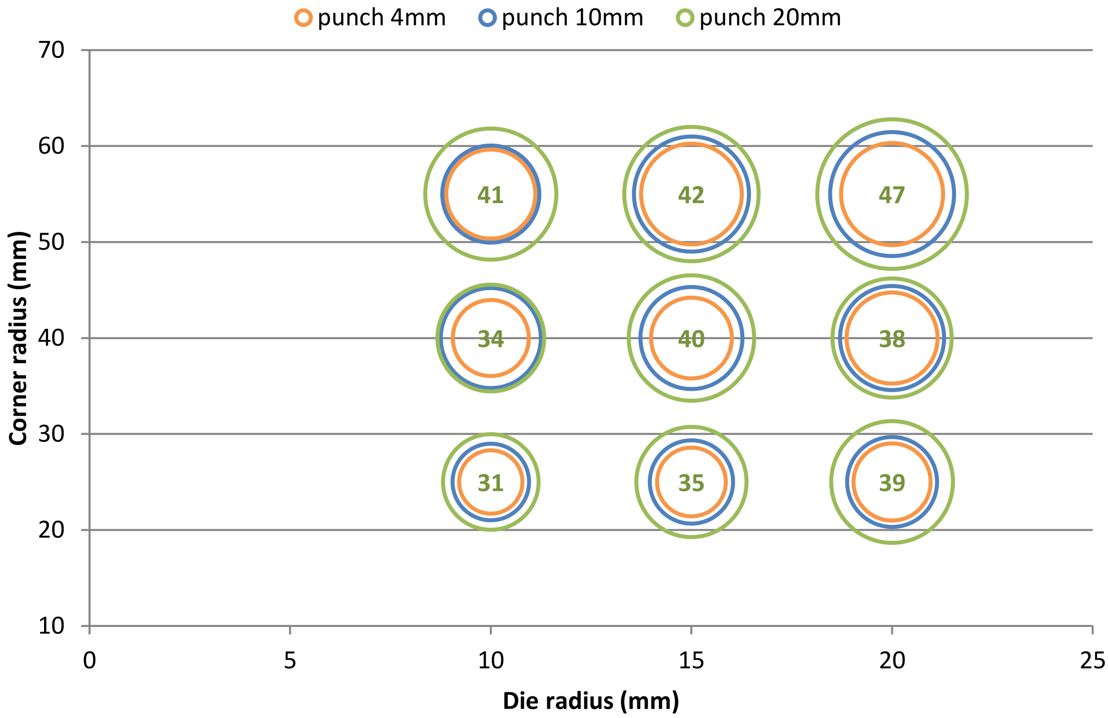



**Figure 6.30** **Comparison of simulated failure depths for different punch, die and corner radii, for drawing 0.75mm aluminium with a blank holder. The width of the circle represents maximum draw depth, the data label is given for the 20mm punch (green).**

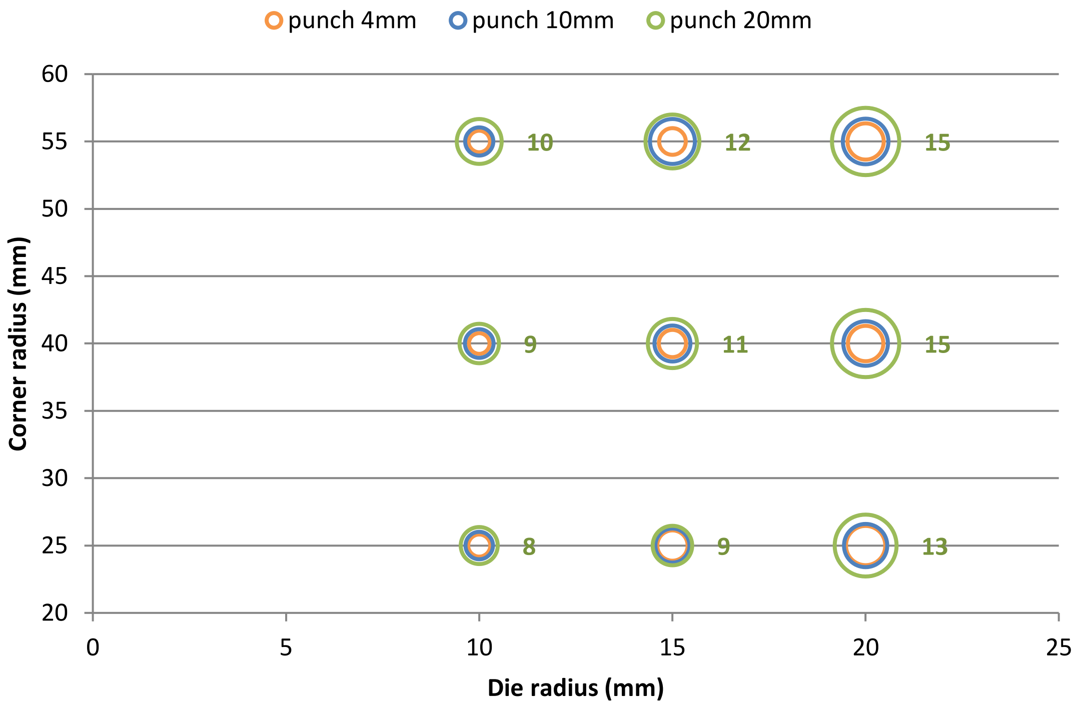



**Figure 6.31 - Comparison of simulated failure depths for different punch, die and corner radii, for drawing 0.75mm aluminium without a blank holder. The width of the circle represents maximum draw depth, the data label is given for the 20mm punch (green).**

The FE simulations results are plotted in figure 6.30 where the width of the bubble represents the maximum draw depth. For scale the bubble size for 20mm punch is given as a data label. Figure 6.30 shows that when drawing with a blank holder the maximum draw depth increases as the punch, die and corner radii are increased. Figure 6.31 gives the equivalent results for drawing without a blank holder. The data labels represent the maximum draw depth for the 20mm punch and the maximum draw depth values for all geometries can be read from table 6.10.

The maximum draw depth is less than when a blank holder force is applied for all geometries. The maximum draw depth increases as the punch radius and die radius increase, but unlike drawing with a blank holder, increasing the corner radius has very little effect on the maximum draw depth, in fact larger corner radii are more prone to wrinkling and fail earlier.

These FE simulation results generated with an optimised blank holder force are now analysed to determine to what extent the maximum draw depth can be estimated from the corner, die and punch radii. The failure draw depths for different shrink corner geometries are collated to generate an estimate of the maximum draw depth for generic shrink corner geometry. Such a guide could be used in early the product development process to inform component geometry and process selection decisions.

## 6.3 Analysis: Rationalising results to generate a geometry based guideline for formability

The FE simulations from section 6.2 are now evaluated to determine the extent in which component geometry can be analysed to predict the failure draw depth of a shrink corner. This information could be used to inform component design decisions in the early stages of product development, to support design for material efficiency.

A single term which describes the shrink corner geometry would be a useful simplification to generate a design guideline similar to the forming limit graph plotted from Suschy (2006) in the literature review. The results in section 6.2 are analysed to propose simple relationships between the maximum draw depth and the three critical radii which could be tested to establish whether trends could be applied to form geometry based forming guidelines. The FE simulation results plotted in figure 6.30 show that when drawing a shrink corner with an optimised blank holder force, the corner, die and punch radii can all be increased to increase the maximum draw depth. The average of these three radii is therefore tested as a potential geometry measure to create a forming limit guideline. In contrast, figure 6.31 demonstrated that when drawing without a blank holder force, the corner radius has little effect on the maximum draw depth. Therefore, it is appropriate to exclude the corner radius when calculating a simple 'average radius' for a component being drawn without a blank holder force.

Figure 6.32 presents the simulation results from section 6.2 as this average radius to test whether the average radius generates a useful forming process limit. The graph identifies an upward trend where the maximum draw depth increases with an increasing average radius is increased for both forming processes, drawing with and without a blank holder force. Since the simulations for a tight corner radii drawn with a blank holder force were not validated by physical experiments, these results were omitted from figure 6.32. Experimental results are not plotted on this graph; as these experiments were not performed with an optimised blank holder force so the failure draw depth is not directly comparable.

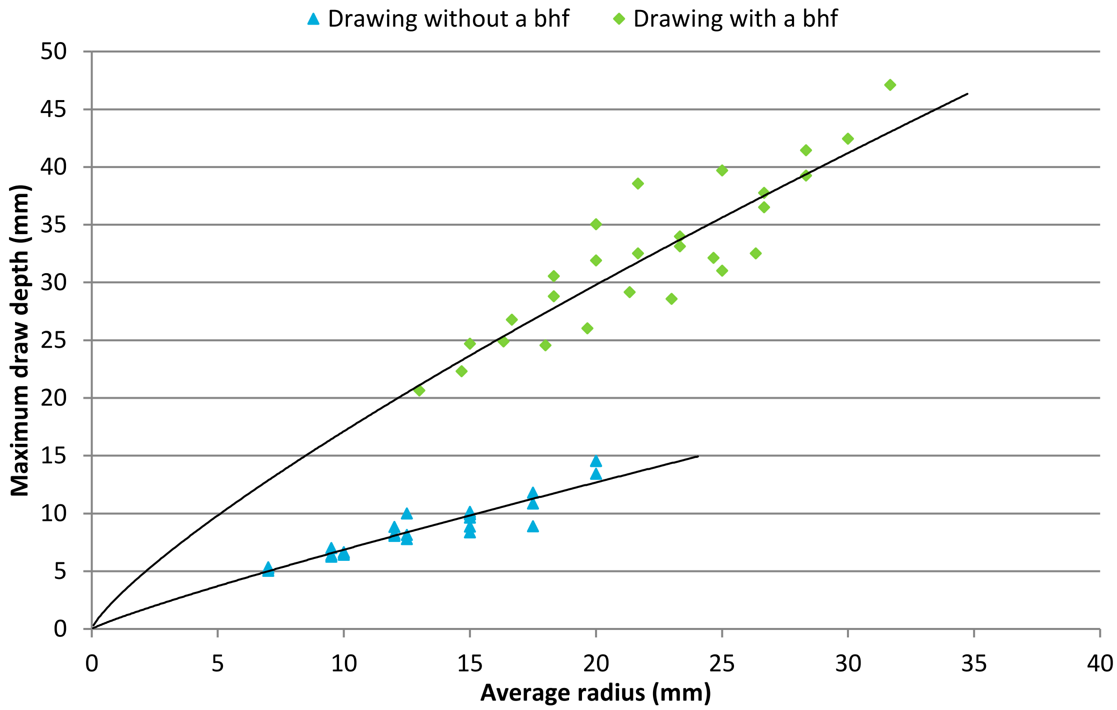



**Figure 6.32 – Rationalising results to generate a design guideline for drawing shrink corners with and without a blank holder.**

The trends in figure 6.32 suggest that geometry based guidelines for drawing with and without a blank holder force can be generated from these trends. The correlation of this data is good and can be used to provide a set of guidelines for component designers. These design guidelines are not intended to replace CAE analysis (Computer Aided Engineering), but as an additional tool to support design for manufacture before the component geometry has been determined. To provide the most benefit in industry, such a guideline could be embedded into the material data card for CAD (Computer Aided Design) packages to give formability guidance as live information during geometry development. The designer can interpret this information to modify the component geometry to a position below the forming process limit and improve the material efficiency of the component, without having to undertake a full CAE analysis of component forming stresses.

This study investigated the failure depths of shrink corners drawn from 0.75mm 5251 H22 aluminium sheet. The identification of this relationship between the component geometry and failure draw depth creates an opportunity for further investigation in this field. The failure draw depths identified from the experiments did not scale with an increase in material thickness from 0.55mm to 0.75mm. Further investigation into material thickness could identify trends for thicker materials. The study could be repeated to determine geometry based forming guidelines for other sheet metal alloys. Alternatively, an investigation to find a link between the failure depth and material properties could be conducted to allow geometry based forming guidelines to be predicted for different materials. Geometry based forming processes guidelines could be extended to other forming processes such as drawing with a draw bead, hot forming and explosive forming. This would allow component designers to compare forming processes and select the most appropriate manufacturing route. This study focused on the forming limits of stretch corners. Further research is required to identify the maximum draw depth for very tight radii. This research could explore why material flow for tight corner radii behaves differently to more open corners. The process could be repeated to identify the limits of shrink corners and developed further to include the interaction of the two features. This study assumed that all corners angles and flange angles are at right angles. Forming limits will increase if these angles are greater, the forming process limit study could be extended to include these additional variables to develop design guidelines for complex components.

## 6.4 Conclusions: Design for material efficiency in automotive sheet metal components

There are currently no suitable tools which allow component geometry to be evaluated against process forming limits to inform process selection decisions and allow design for material efficiency. To address this, a novel set of physical and simulated experiments were conducted to investigate the extent in which the failure draw depth could be predicated from component geometry for different forming processes. The three hypotheses proposed at the start of this chapter are now considered in turn to conclude the findings of this research.

### Can sheet metal component geometry be designed to select a forming process which improves the material utilisation?

Research in this chapter has evaluated the material utilisation of sheet metal components used to manufacture the vehicle case study from chapter 3. The analysis showed that parts which were manufactured without a blank holder were more material efficient than those which were manufactured with a blank holder. Designing component geometries which are able to be formed without the requirement for a blank holder would improve material utilisation.

### To what extent can the maximum draw depth be predicted from component geometry in sheet metal forming with and without a blank holder?

To investigate this hypothesis, the maximum draw depth of shrink corners with different geometry was determined experimentally for drawing with and without a blank holder force. These experiments identified a trend between the maximum draw depth and a function of three critical radii. Physical experiments were extended using a validated FE model to consider a wider range of shrink corner geometries. The experiments found that trends exist between the average radii and the maximum draw depth.

### Can these findings be extended to support implementation of design for material efficient manufacture in an industrial environment?

The trends identified in this study enables further research into different component geometry to consider how these features interact to generate geometrical forming limits for complex parts. With further research into thicker materials and alternative alloys this approach could be adopted in an industrial setting to enable a more efficient design and manufacturing process for sheet metal components.

This chapter has created a significant opportunity for further research into geometry based forming limits. This opportunity is now discussed in greater depth in chapter 7.

# Chapter 7 Recommendations and Conclusions

Reducing sheet metal yield losses in automotive manufacturing would reduce material demand, providing both environmental and financial benefits. This thesis has explored material efficiency in automotive manufacturing from four perspectives; the opportunity for improvement, the potential to realise this opportunity, the requirement for effective target setting in the context of the circular economy and design for material efficiency. This chapter identifies the opportunities for further research to make more cars from less metal and summarises the contributions to knowledge made in this thesis.

## 7.1 Recommendations for further work

Opportunities for further research have been identified throughout the text. The most significant of these is the expansion of the design for material efficiency potential from chapter 6. The experiments conducted in chapter 6 identified a relationship between shrink corner geometry and the failure depth in drawing 0.75mm 5251 H22 aluminium sheet with and without a blank holder. With some further development this relationship could be applied in industry to support design decisions which improve material utilisation. Future studies in this area should expand the guidelines to include more complex component geometry, alternative materials and different forming processes. Once these relationships are understood, a project undertaken in collaboration with a software provider would be beneficial to test whether geometry based guidelines could be implemented within design and manufacturing software to improve the material efficiency of sheet metal components. How this could be developed is now discussed.

### 7.1.1 Developing more complex design guidelines

This project would test the hypothesis that a formula can be developed to rationalise complex geometries into a single measure which can be plotted against draw depth to provide an expanded version of the formability guide shown in figure 6.32.

The study in chapter 6 focused on the geometric forming limits of stretch corners. The process could be repeated to identify the limits of shrink corners and developed further to include the interaction of the two features to develop design guidelines which can be applied to complex components, as shown in figure 7.1.

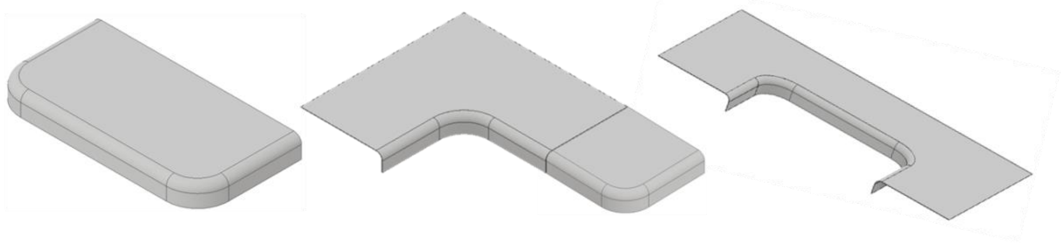



Figure 7.1 Interaction of shrink and stretch corners to represent complex geometries.

The study in chapter 6 assumed that all corner and flange angles are at right angles. Forming limits will increase if these angles are softer, as shown in figure 7.2. The geometric forming guidelines could be extended to include these additional variables.

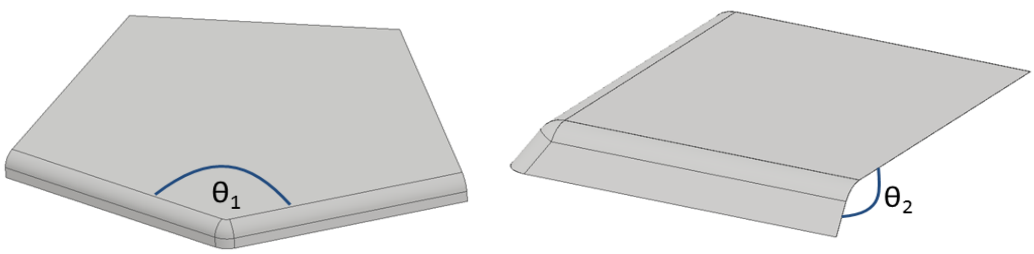



Figure 7.2 Increasing the corner angle (left) and flange angle (right).

Further investigation into material thickness could identify formability trends for thicker materials. The study in chapter 6 could be repeated to determine geometry based forming guidelines for other sheet metal alloys. Alternatively, an investigation to find a link between the failure depth and material properties could be conducted to allow geometry based forming guidelines to be predicted for different materials. Geometry based forming processes guidelines could be extended to other forming processes such as drawing with a draw bead, hot forming and explosive forming. This would allow component designers to compare forming processes and select the most appropriate manufacturing route.

To be suitable for complex geometries, the geometry based forming guideline would combine the effects of the corner, die and punch radii; corner interaction; corner and flange angles; material properties and thickness; and forming process selection to estimate the maximum draw depth before failure. To achieve this, a guideline could plot an 'adjusted average radius' against the maximum draw depth of the component. A formula for the adjusted average radius might be similar to equation 7.1.

$$r_{aa} = \frac{\left(r_c \frac{\theta_c}{2\pi}\right) + \left(r_d \frac{\theta_d}{2\pi}\right) + \left(r_p \frac{\theta_c}{2\pi}\right)}{3} \, p \; m \; (i \; r_{aa2}) \qquad (7.1)$$

Where:

$r_{aa}$ = adjusted average radius

$r_c$ = corner radius

$\theta_c$ = corner angle

$r_d$ = die radius

$\theta_d$ = die angle

$r_p$ = punch radius

$\theta_p$ = punch angle

p = constant for forming process (e.g. drawn with/without a blank holder force and with/without draw beads)

m = constant for material properties including material thickness

i = constant for interaction with other corners

$r_{aa2}$ = adjusted average radius for interacting neighbouring corner

### 7.1.2 Embedding guidelines into industry software

To provide the most benefit in industry the formability guideline described in section 7.1.1 would be embedded into CAD packages to give formability guidance as live information during component geometry development. The designer could interpret this information to modify the component geometry to position below the forming process limit and improve the material efficiency of the component, without having to undertake a full CAE analysis of component forming stresses.

An example to demonstrate the use of forming guidelines is now described for the component shown in figure 7.3. The geometry of this component is evaluated using the results generated in section 6.3 to enable design for material efficient manufacturing.

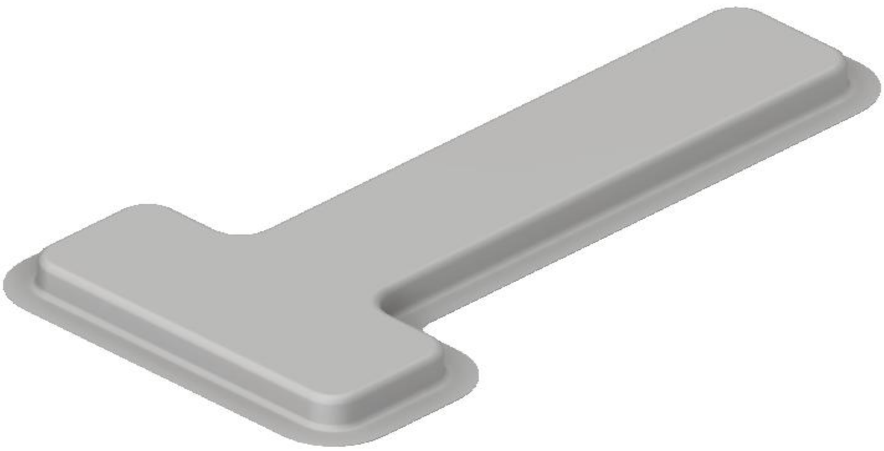


Figure 7.3 Component used to demonstrate the potential of geometric forming limits for design for manufacture.

Table 7.1 shows three forming scenarios. Scenario 1 is the initial geometry which has tight radii requiring a large addendum surface and draw beads to be manufactured resulting in a poor material utilisation. Scenario 2 is designed with softer radii which can be draw without an addendum, improving material utilisation. Scenario 3 is designed to be formed which enables a much simpler manufacturing process and would have the best material utilisation. These scenarios are potted on the geometry based forming guideline in figure 7.4.

Table 7.1 Scenarios for testing geometric forming limits.

| Scenario. | Draw depth (mm) | Corner radius (mm) | Die radius (mm) | Punch radius (mm) | Adjusted radius |
|---|---|---|---|---|---|
| Tight radii | 25 | 10 | 5 | 5 | 6 |
| Soft radii | 25 | 35 | 15 | 15 | 19 |
| Shallow part | 10 | 35 | 15 | 15 | 19 |

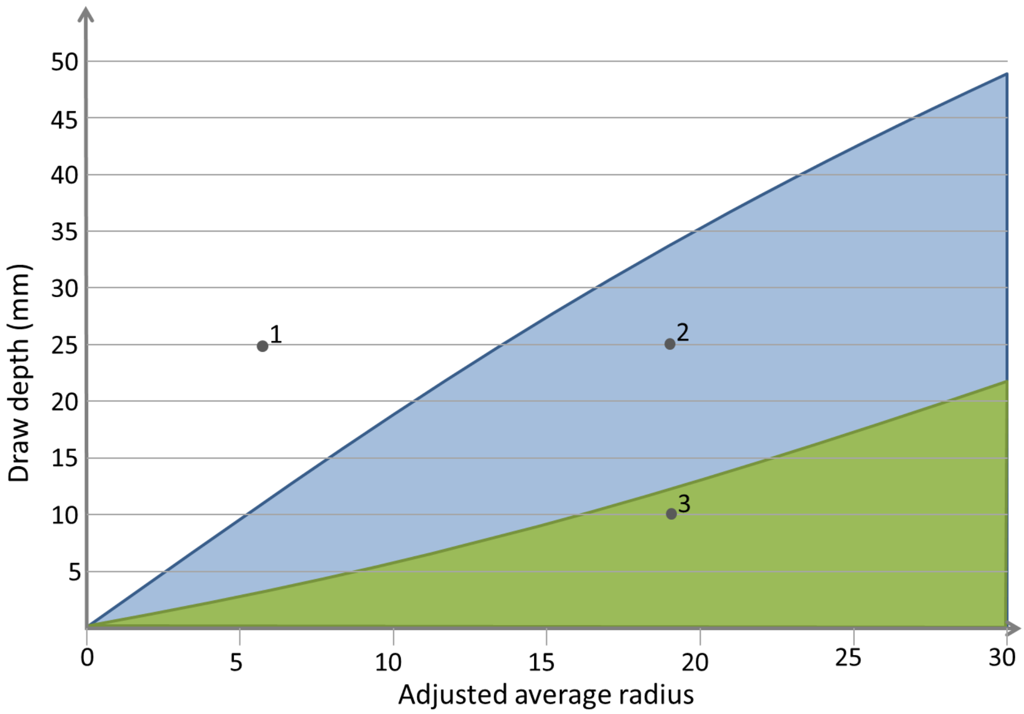



Figure 7.4 Geometric forming limit diagram. The area under the blue line is considered to be formable without additional addendum surface material. The area under to green line is considered to be formable without additional blank holder material.

To demonstrate the application of the geometric forming limit guidelines, the forming process for each scenario has been processed using the FTI one-step solver to predict failure against the forming limit curve. Figure 7.5 compares the formability of drawing the geometry in scenario 1 and 2 with a blank holder. It can be seen that designing the component to draw with a blank holder reduces the failure zones in forming so would not require additional material in the form of an addendum surface and draw beads.

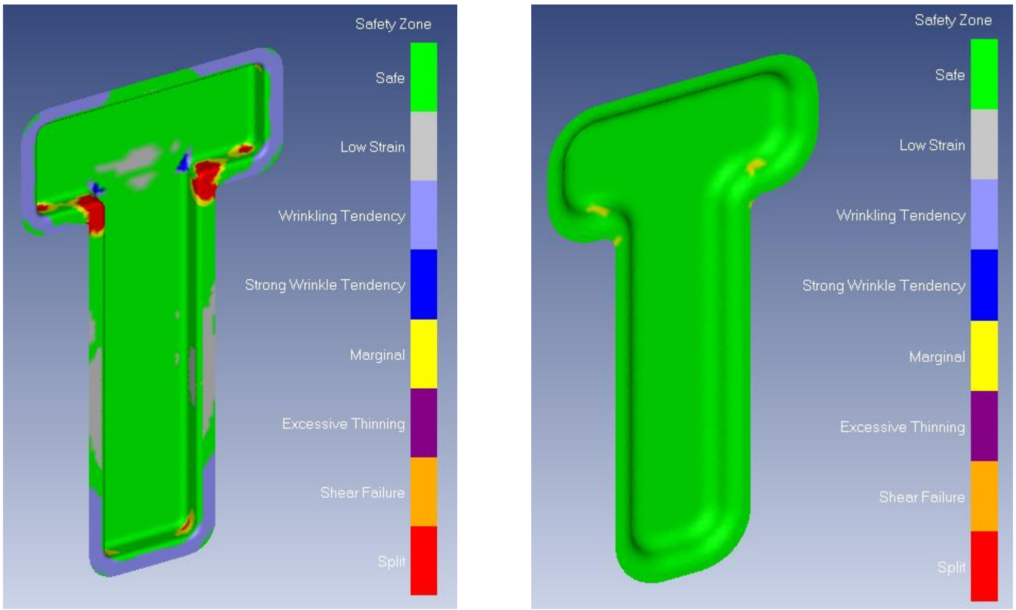



**Figure 7.5** FTI one-step solver results showing failure zones for drawing with a blank holder a geometry with tight radii (left) compared to a geometry with soft radii (right). Designing for forming limits has reduced failure zones and therefore reduces the requirement for additional material in drawing.

Figure 7.6 compares the formability of drawing the geometry in scenario 1 and 3 without a blank holder. It can be seen that designing the component to draw without a blank holder reduces the failure zones in forming and would reduce material demand.

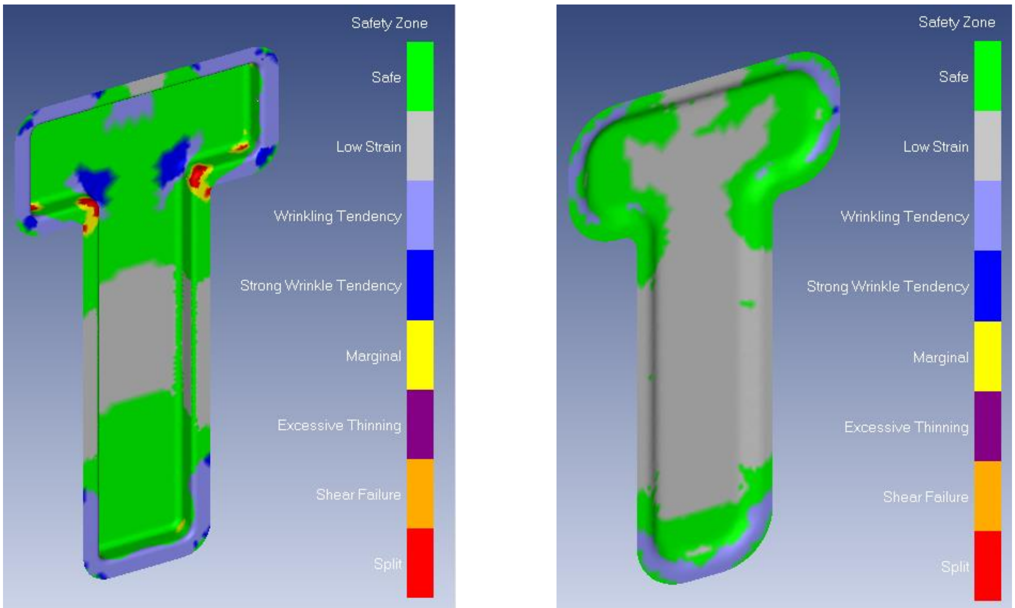



**Figure 7.6** FTI one-step solver results showing failure zones for drawing without a blank holder a geometry with tight radii (left) compared to a geometry with soft radii and reduced draw depth (right). Designing for forming limits has reduced failure zones and therefore reduces the requirement for additional material in drawing.

The effectiveness of forming guidelines to improve material utilisation could be tested using the methodology developed in chapter 4. The geometry guidelines could be embedded into design and manufacturing software and tested in the product development environment of a component manufacturer. This project would quantify the material utilisation improvement opportunity and identify implementation barriers for geometry based design guidelines.

To conclude on the research presented in this thesis, the contributions to knowledge made are now summarised.

## 7.2 Contributions to knowledge

This thesis had revealed how the automotive industry is able to increase production volumes without increasing the demand for sheet metal through exploitation of material efficiency strategies. It has provided a greatly expanded evidence base and demonstrates a new pathway for future research in geometry based forming guidelines which could be expanded to achieve further material efficiencies. Through this investigation the following contributions to knowledge have been made:

1. For the first time, a part by part analysis has evaluated the yield losses which occur in the manufacture of every sheet metal component in the body-in-white of a passenger vehicle. The material utilisation values for these components ranged from 4% to 82%. An evaluation of these yield losses highlighted nine strategies for material efficiency and revealed that previous research, which focuses on blank nesting, only captures part of the opportunity. Greater savings are achievable through considering the design of the stamping process, the part geometry and the blank shape. In conjunction with the detailed part analysis, an industry wide study of 46 passenger vehicles found that on average only 56% of sheet metal purchased is used on the vehicle, the remaining material is scrapped during the manufacturing process. Improving the material utilisation of passenger vehicles to current best practice of 70% would save £8 billion and 25 million tonnes of $CO_2$ annually, without the requirement of technological innovation. This high resolution analysis of yield losses gives greater certainty of the saving opportunity for sheet metal material efficiency and clarifies the priority of material efficiency compared to other strategies, such as fuel efficiency and electrification, to meet global climate change goals.

2. The nine strategies for material efficiency identified in the component analysis were expanded to propose a novel design process which considers material efficiency in the design of the component geometry,

blanking and stamping processes. The proposed design process has been validated through an industrial trial, in which the partner company invested 300 man-hours to follow the proposed design process for 10 components. This industrial trial identified that in practice the material utilisation of these components could be improved by 20%, but only 3% improvement was actually implemented.  Lack of time and resources were reported as being the critical set of barriers which prevented material efficiency opportunities from being implemented. Analysing these opportunities and barriers revealed that two thirds of the opportunity is locked in at the start of the component design phase, were resource is not currently allocated to material efficiency activities. Earlier consideration of material utilisation in the product development cycle is required to realise the technical potential of sheet metal material efficiency.

3. For the first time, all existing metrics for material use and recycling in sheet metal forming processes have been mapped onto a single diagram. Creating this structure of performance metrics helps to organise future claims about the environmental impact of material use. Evaluation of a case study vehicle demonstrated that existing recycling metrics, which are based on the mass of recycled material purchased to manufacture the vehicle, do not promote the reduction of yield losses to improve material efficiency. For example, when all production yield losses are closed loop recycled, the case study vehicle made with a recycled content of 50% contributes 12% more embodied emissions than when the same car is manufactured with an improved material efficiency and so contains only 30% recycled material.  In this scenario, reducing recycled content is favourable, since avoiding scrap generates greater savings than recycling it. Through updating their performance metrics to consider recycling process efficiency for both production scrap and end-of-life scrap, the automotive industry could measure recycling rates without penalising material efficiency strategies. This would enable implementation of both material demand reduction and closed loop recycling to generate greater

financial and environmental savings than is currently achieved through recycling alone.

4. The first contribution, demonstrated how major yield losses occur during the stamping process for sheet metal components. Material efficiency could be improved by reducing the requirement for draw beads, addendum surfaces and large blank holder areas. There are currently no suitable tools which allow component geometry to be evaluated against process forming limits to inform process selection decisions and allow design for material efficiency. To address this, a novel set of physical and simulated experiments were conducted to investigate process limits for two material efficient drawing processes. These processes are drawing without a blank holder and drawing with a blank holder, but without draw beads and an addendum surface. These experiments identified a trend between the maximum draw depth and a function of three critical radii. When extended to complex components, this trend could form a geometry based formability guideline which would enable material efficiency to be considered earlier in the product development cycle than is currently achievable through existing methods of formability analysis, such as forming limit diagrams. Such a guideline would support the automotive industry to overcome the implementation barriers identified in contribution 2 and unlock the technical potential of material efficiency strategies through earlier analysis of material efficiency.

These contributions to knowledge demonstrate that is it possible to make more cars with less metal. The evidence presented in this thesis provides a knowledge base for future research and industrial policy to promote material efficiency in the effort to meet global climate change ambitions.

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