Elsevier Editorial System(tm) for Resources, Conservation & Recycling
Manuscript Draft

Manuscript Number: RECYCL-D-18-02280R1

Title: Implementing material efficiency in practice: a case study to improve the material utilisation of automotive sheet metal components

Article Type: Full Length Article

Corresponding Author: Professor Julian Mark Allwood, PhD

Corresponding Author's Institution: University of Cambridge

First Author: Philippa Maia Horton

Order of Authors: Philippa Maia Horton; Julian M Allwood; Christopher Cleaver

Abstract: There is an opportunity to reduce the amount of sheet metal currently used to manufacture automotive components, despite the available cost and CO2 savings, the automotive industry has not realised the full potential of these saving opportunities. To understand why, a practical case study was set up with an automotive manufacturer. A cross-functional team was established with the scope to make changes to five components using a structured design process to improve material efficiency. The trial identified realistic opportunities to improve material utilisation by 20%pts, and save £9million and 5 kilotonnes of CO2 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%pts were actually implemented on the production vehicle, saving £1.8million and 1.5 kilotonnes of CO2 annually. The case study identified significant barriers to implementing material efficiency strategies in an industrial setting. To overcome these barriers material utilisation should be considered early in the product design process and high in the vehicle platform hierarchy. As a result of this investigation, new business processes are being generated to support design for material utilisation at the automotive manufacturer. This case study approach should be considered to increase implementation for other aspects of material demand reduction.

Response to Reviewers: Implementing material efficiency in practice: a case study to improve the material utilisation of automotive sheet metal components.
Resources, Conservation & Recycling
Philippa M. Horton, Julian M. Allwood, Christopher Cleaver.

Reviewer Comment	Authors Response (new text is shown in red)
Reviewer 1	Thank you for your helpful comments.
The authors discuss the literature and cite a number of papers that have identified and characterized barriers in the implementation of material efficiency. Yet, this is not used in the paper as you would expect. I would expect that the authors connect the results of this case study to the literature to validate (or not..) earlier findings on barriers, and approaches to reducing barriers. This can also help to extrapolate the findings of this case study to the broader knowledge base.	The following text has been added to the literature review. "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 6th 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." The following text has been added to the discussion section to refer back to the literature review. "The results complement previous studies on material efficiency in that the barriers identified in this case study are also recognised in previous research. 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)."
Not all figures are well presented. While this may have to do with confidentiality, there must be ways to better present the results in such a way, that it is possible to understand the implications of the research.	Figures 1(b), 7 and 8(b) have been updated to give more information. The layout in figure 3 has been modified to a regular structure. The text discussing figure 4 has been restructured to make the figure easier to interpret.
The authors mention 300+ metal sheet components, and have looked at 5. What share of total steel/aluminium in the car is covered by the selected 5 parts. Why were these five selected?	The following detail has been added. "These parts were selected as they required modification and re-tooling due to the move from combustion engines to battery powertrain technology; this provided an opportunity to review the design and manufacturing processes to improve material utilisation. Ten components are produced from these parts as the left hand and right hand components are manufactured together. 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." In the results section, table 4 has been extended to include an estimate for the saving opportunity for all 300+ components.

You report savings of 24 and 20%, and I am not sure how you come from 24 to 20. Yet, in the abstract you quote 14%, which does not come from this study. How should I interpret all these different numbers?	This is a very helpful comment. The following clarification has been added to the paper. "The part average material utilisation improvement opportunity of 24% is calculated as the average of the percentage point improvement for the 5 parts. In order 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 $\%_{pts}$ saving opportunity was less for the larger parts. The annual weighted saving opportunity for the five case study components is shown in table 4." 14% improvement refers to the industry average opportunity and is not relevant to this specific cases study vehicle, to avoid confusion this value has been removed from the abstract.
Only 3% of the identified 24% is implemented, i.e. only on 1/8th of the potential. This suggests huge barriers, and this would warrant more attention to understand how only this 3% is left at the end. What are the key barriers that made this happen?	The discussion section has been restructured and extended to address this. The following text has been added. "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 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 time is made available to implement 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."
There is a wide body of literature on barriers in energy efficiency improvement in industry. While this may be easier to implement than material efficiency (as in products the supply chain is more interlinked), why have you not also looked at this body of literature to understand the knowledge on change processes in industry?	Thank you for this suggestion, consideration of energy efficiency has now been made. The following text has been added to the introduction. "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 6th 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."
I am not sure how you came to the savings in	The following statement has been added to table 2 to give the source of this data "These values were

CO2 emissions. Can you show how you got to the resulting emission reductions?	estimated using cost and environmental profiles from the automotive manufacture partner in this study." In the results section the following note is given to the reader. "The environmental saving is calculated as the reduction in embodied CO_2e as a direct result of using less metal to manufacture the part."
The sheets are made of steel and aluminum. Yet, in the discussion of the options there is no information about the two metals. And this is needed to understand the CO2 savings, as well as the relative value of the saved material. Why do you not make this distinction?	The following consideration has been added to the discussion. "The saving opportunity is sensitive to the material mix of steel and aluminium. If the process is expanded to other vehicles, the size of the saving opportunity would depend on material selection. The financial saving opportunity would be greater if more aluminium is used as aluminium is more expensive than steel, as detailed in table 2. In contrast the CO_2 saving would be greater if more steel was used."
Abstract: the 14% savings potential does not come from this study. Why mention it in the abstract?	This reference has been removed from the abstract.
P.4, line 77: you claim that the industry is motivated to improve material utilization, the results beg to differ (if only 1/8th of the potential is implemented). What is this claim based on? As long as material costs are really small, you might also argue that automotive companies can still shift the marginal costs to consumers…	The claim has been softened to read "The automotive industry should be motivated to improve material utilisation alongside other product development requirements."
P.5: several improvement potentials for material efficiency are discussed here. But I am not sure how to relate them. Please write this in such a way that readers understand the relationship between the different figures.	This section has been re-written using consistent values for material utilisation rather than yield losses and the material type which each value is measuring is clarified to allow the reader to understand the relationship between the figures. E.g. "When considering the material utilisation of steel and aluminium in all forms, sheet, plate and bulk, (Milford et al. 2011) quantified that the material utilisation is an average of 74% for steel and 59% for aluminium. Focusing on sheet metal used across all industries, (Carruth & Allwood 2013) found that material utilisation is even lower at approximately 50%. "
P.8, line 157: you are quite secretive about the company, yet in the acknowledgements you mention Jaguar Land Rover…	Unfortunately this is the terms of publication from Jaguar Land Rover. We were not given permission to name the company or the vehicle being studied in the body of the text, but we are able to acknowledge their support and funding.
P.8, Fig.2: what is the basis for the approach? How is this related to earlier work or to the literature review?	More detail on this flow chart has been added. "This flow chart was developed with the automotive manufacturer for this material utilisation case study…. Whilst this methodology has no direct overlap to the studies reviewed in the literature review, the themes and individual activities shown in figure 2 are commonly applied 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."
P.15/16: I do not understand how you go from	The following clarification has been added to the paper.

Table 3 to Table 4 (and reduce the potential from 24 to 20%).	"The part average material utilisation improvement opportunity of 24% is calculated as the average of the percentage point improvement for the 5 parts. In order 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 $\%_{pts}$ saving opportunity was less for the larger parts. The annual weighted saving opportunity for the five case study components is shown in table 4."
P.18, line 312: why does the proximity of the numbers suggest that most options have been identified? Maybe the top-down approach gives a very conservative number?	This claim has been rephrased to focus on the effectiveness of the trial. The sentence now reads. "The proximity of the two approaches suggests that it is possible to achieve the bench mark best practice material utilisation value through applying the trial process, therefore the case study activities are an effective method of identifying improvement opportunities"
P.22, line 377: indeed, there are significant barriers. Therefore, it is necessary to understand which those are. This is not mentioned in the conclusion, making this sentence quite obvious, and not adding much insight.	The following sentence has been removed. "The implemented saving opportunity is significantly lower than the total identified opportunity suggesting the implementation barriers are significant. In order to exploit the full potential of material utilisation opportunities, the automotive industry must overcome these barriers." The discussion section has been restructured and expanded to address this, the changes are detailed above.
There are a few typos here and there in the paper. Do a final check before resubmitting	The paper has been carefully checked to identify and remove typos.
Reviewer 2	Thank you for your comments.
1.The authors should be more careful about writing and avoid typos. For example, there are two capital letters in the fourth highlight.	The paper has been carefully checked to identify and remove typos.
2.Line 34 - It is too simple for readers that do not know this field well. The importance of this study should be emphasized at the beginning, not in the end.	This sentence has been extended to explain the concept of material efficiency in greater detail. It now reads "Material efficiency is a method of reducing industrial CO_2 emissions by meeting service requirements with less material (Allwood et al. 2010). 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. This strategy can provide savings with no knock-on effect for the consumer."
3.Line 45 - The authors should first explain why they just analyze metals. How about other materials such as glass, plastic, rubber?	The following sentence has been added to provide this information. "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.”
4.Figure 1(b) - The authors should avoid using reduplicate diagrams. There are three "vehicle line designs", three "model variant designs" and two "model year refresh designs"	More detail has been added to figure 1(b) to demonstrate the differences between the duplicate diagrams.
5.Line 80 - Metal processing techniques vary. Steel, aluminum and iron undertakes different surrogate processes including stamping, extrusion, casting, forging and machining. The authors should identify the difference and explain how and why they classify them into blanking and forming.	More information has been added, this sentence now reads “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.” Further definition of bulk forming processes (such as extrusion, casting, forging and machining) is not provided as these techniques are not used in sheet metal forming so their inclusion may confuse the reader.
6.Line 146-152 - Not necessary.	The following test has been removed. “As far as the authors are aware, material demand reduction has not been researched in this context. Section 2 introduces the case study methodology, a summary of the results is given in section 3 and the findings are interpreted in the discussion in section 4. More detailed results and examples of the optimisation activities are included for reference in the appendix.”
7.Line 190 - What is the exact parameters of the existing production vehicle, especially the curb weight, powertrain system and weight composition?	The following information has been provided to give context of the case study 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”
8.Line 239 - What are the sources for Table 2?	The following statement has been added to give the source of this data “These values were estimated using cost and environmental profiles from the automotive manufacture partner in this study.”
9.Figure 4 - It is too informative and a little confusing because the exact activities cannot be read directly.	The results section has been restructured to provide more clarity and context to support figure 4. A table which details the average saving opportunity for each activity has been moved from the appendix to the results section. The following text has been added. “Table 5 summarise 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 Fig. 4... The largest saving opportunities occur in the early phases of both part and blanking design strategy

	identified from activities 2 and 11, designing the joints and blank shape. However, it can be seen from fig 4. 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.”
10.Figure 7 - The same problem as Fig 1(b)	More detail has been added to figure 7 to demonstrate the differences between the duplicate diagrams.
11.Line 346 - What are the potential impacts of this barrier on each activity?	Discussion of implementation barriers has been rewritten as detailed above.
12.Figure 8(b) - It contains little information. Consider about modification.	This figure reinforces the importance of collaboration between departments. To provide more context the following text has been added. “To extend the case study to all components, the collaborative environment illustrated in the Venn diagram in Fig. 8b would have to be embedded to the normal business process. This collaborative environment was essential to identify realistic saving opportunities.”
13.Line 373 - In the conclusion section, the methodology should be briefly stated before results.	The following overview has been added to the conclusion “To investigate the extent in which material utilisation opportunities can be realised in an industrial setting, this paper developed a case study to design and manufacture five sheet metal automotive components and observed 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.”

Implementing material efficiency in practice: a case study to improve the material utilisation of automotive sheet metal components

Abstract

There is an opportunity to reduce the amount of sheet metal currently used to manufacture automotive components, despite the available cost and CO_2 savings, the automotive industry has not realised the full potential of these saving opportunities. To understand why, a practical case study was set up with an automotive manufacturer. A cross-functional team was established with the scope to make changes to five components using a structured design process to improve material efficiency. The trial identified realistic opportunities to improve material utilisation by 20%pts, 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%pts were actually implemented on the production vehicle, saving £1.8million and 1.5 kilotonnes of CO_2 annually. The case study identified significant barriers to implementing material efficiency strategies in an industrial setting. To overcome these barriers material utilisation should be considered early in the product design process and high in the vehicle platform hierarchy. As a result of this investigation, new business processes are being generated to support design for material utilisation at the automotive manufacturer. This case study approach should be considered to increase implementation for other aspects of material demand reduction.

Key words: material utilisation, material efficiency, stamping, blanking, forming, design-for-manufacture

Highlights:

- This study implements a structured design process to improve material utilisation
- Improving five automotive components identified annual savings of £9million
- Significant barriers exist for implementing these saving opportunities
- Material utilisation should be considered early in the product design process
- This approach could be considered for other aspects of material demand reduction

Declarations of interest: none

1 Introduction

Material efficiency is a method of reducing industrial CO_2 emissions by meeting service requirements with less material (Allwood et al. 2010). 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. This strategy can provide savings with no knock-on effect for the consumer. (Engert & Baumgartner 2016) identified a gap between sustainability strategies and implementation in an industrial setting. This paper aims bridge this gap, testing the hypothesis that material utilisation opportunities could be realised in an industrial setting Working in partnership with an automotive manufacturer, the study explored how much of the potential saving opportunity 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.

Previous studies are now reviewed to establish the motivation for improving sheet metal material utilisation within the automotive industry, existing knowledge of the opportunity to improve and barriers which prevent these opportunities from being realised.

1.1 Material utilisation and automotive component design

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, (Cullen et al. 2012) approximate 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. Previous research has identified environmental and financial motivation to improve material utilisation of this sheet metal, 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 develop a checklist for considering sustainability in the automotive industry, material efficiency is included within this checklist. Raw material, in particular steel, is the greatest cost driver for automotive manufacturers, this cost is even more significant when Aluminium is used, (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.

Automotive design activities follow a stage-gate process to organise product development from concept to component manufacture, shown in Fig. 1(a), and described in (Ettlie & Elsenbach 2007). This paper considers the matertial utilisation at each of these stages in the product development cycle. Automotive manufactures design multiple vehicles to be made on one platform, as shown in Fig. 1(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.

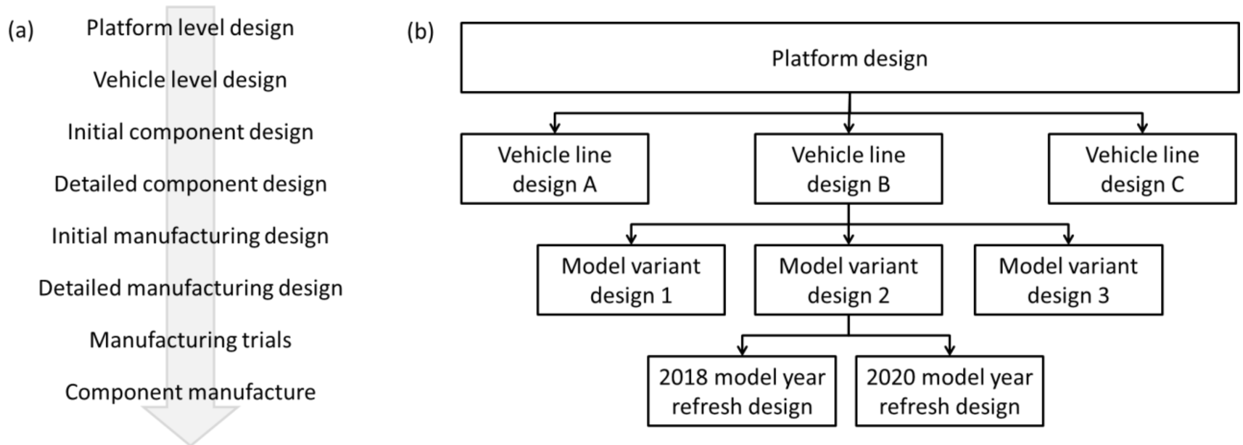

Fig. 1 - structure of product design activities in the automotive industry

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 pressure to meet cost and strength requirements. Material efficiency is not specifically included in their review. (Azevedo 2013) also evaluate the performance criteria in the design of automotive components, they include environmental cost in their analysis.

The automotive industry should be motivated to improve material utilisation alongside other product development requirements. Existing research into how this can be achieved is now considered.

1.2 The opportunity to use less metal

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 a production process using the metric material utilisation (MU) which is defined as:

$$\text{MU(\%)} = (1 - \text{Production Yield Loss}) \times 100 \qquad (1)$$

Where;

$$\text{Production yield loss} = \frac{\sum \text{Manufacturing Scrap}}{\sum \text{Coil Mass}} \qquad (2)$$

When considering the material utilisation of steel and aluminium in all forms, sheet, plate and bulk, (Milford et al. 2011) quantified that the material utilisation is an average of 74% for steel and 59% for aluminium. Focusing on sheet metal used across all industries, (Carruth & Allwood 2013) found that material utilisation is even lower at approximately 50%. Through an industry review (Horton & Allwood 2017) predicted that material utilisation improvement opportunities of 14%pts are available to the automotive industry. Through an evaluation of a case study vehicle, they summarised that the material required to manufacture sheet metal automotive components could be reduced through consideration of the stamping process, blank design and component design. These opportunities are now described in turn.

Material utilisation in stamping 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) evaluate how limiting the 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).

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.

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. However, the opportunity at each stage in the product development process has not 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 studies have shown that it is possible to reduce production scrap to achieve environmental and financial benefits to the automotive industry. Implementation of these material saving opportunities does not require a strategic change in the way cars are designed, made, sold or used. Prior research into the barriers for implementing these opportunities is now reviewed.

1.3 Implementation barriers

Despite the automotive industry having the knowledge and motivation to improve, material saving opportunities have not been widely implemented and industry average material utilisation stands at 56% (Horton & Allwood 2017). 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 closed loop recycling potential in and a successful example of implementation of closed loop recycling is described in (JLR et al. 2016). As described by (Horton et al. 2018) the greatest financial and environmental savings are generated by preventing this scrap rather than recycling it. Since the opportunity to use less material has not been exploited it is sensible to assume that implementation barriers must exist.

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 through (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 6th 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 authors' knowledge no study has yet reported on direct involvement in implementation of material efficiency.

This paper presents a case study to investigate the extent in which the automotive industry is able to realise the technical potential of material utilisation improvement strategies. The case study will quantify material saving opportunities and any barriers which prevent these savings from being implemented.

2 Case study methodology

The literature review demonstrated 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 paper presents a case study developed in partnership with an automotive manufacturer as a means to demonstrate the realistic saving opportunity from material efficiency strategies. The partner company formed a cross-functional team and invested approximately 300 man-hours of engineering time into a trial process led by the first author. As a result the findings of the case study should accurately reflect the challenges of implementing material efficiency strategies in an industrial setting. The component engineers involved followed a multi-step optimisation process and 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.

Fig. 2 shows the steps undertaken to set up, gain permission for, and implement the case study. This flow chart was developed with the automotive manufacturer for this material utilisation case study.

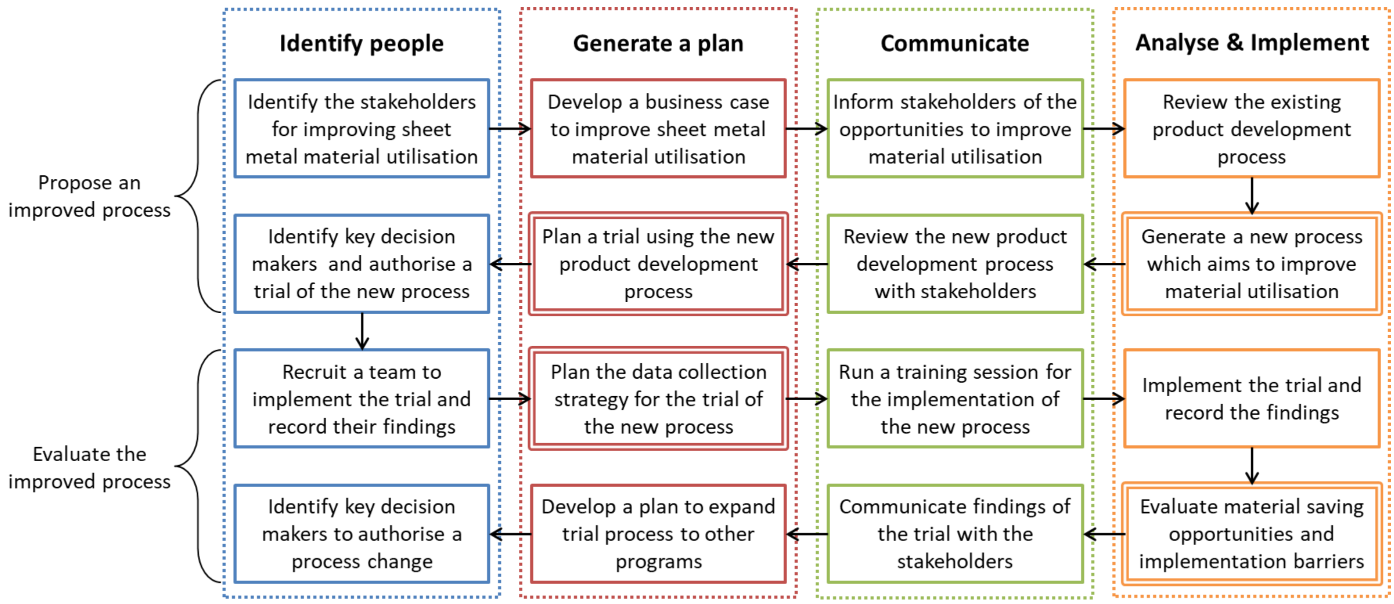

Fig. 2 - flow chart of steps taken to implement a trial for improving material utilisation

These steps were essential to ensure the opportunities and barriers identified were a true reflection of decision making in an industrial setting. Whilst this methodology has no direct overlap to the studies reviewed in the literature review, the themes and individual activities shown in figure 2 are commonly applied 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 paper.

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

2.1 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 is designed to ensure the team consider all available strategies to improve sheet metal material utilisation in their decision making. This new design process was generated by breaking down the nine material utilisation improvement strategies detailed in (Horton & Allwood 2017) into individual activities which could be undertaken to improve the material utilisation of a component throughout the product development cycle. Sixteen activities are required to consider all material utilisation improvement strategies. This material utilisation improvement process is described in table 1. 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&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 the appendix.

Table 1 - Summary of material utilisation improvement process proposed in this paper

Activity	Description	Timing
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 design strategy
2. Design Joints between components	Evaluate whether the location and method of joining to neighbouring components can be changed to improve material utilisation.	Component design strategy
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 design strategy
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 design
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 design
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 design
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.	Manufacturing process design
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.	Manufacturing process design
9. Design addendum surface	Evaluate whether the design of the addendum surface can be modified to reduce the size of the blank.	Manufacturing process design
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.	Manufacturing process design
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.	Manufacturing process design
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.	Manufacturing process design
13. Nest blanks flexibly on the coil	Consider complex blank layouts which can be nested more tightly on the coil to reduce blanking scrap.	Manufacturing process design
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.	Manufacturing process design
15. Total savings identified	Consider the interaction between activities 2-14 to identify the greatest available material saving opportunity.	Component design strategy
16. Total savings implemented	Feedback the material used in the final production component to record the saving opportunity which was able to be implemented.	Component design strategy

2.2 Trial of the new material utilisation improvement process

The vehicle selected to trial the proposed product development process was an existing production vehicle which was undergoing a model year refresh. 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

As shown in Fig. 1, a model year refresh changes some of the sheet metal components, making it possible to compare the modified components to the original components. Five sheet metal parts were investigated for improved material utilisation. For the parts selected, Fig. 3 shows the final component (a) and the scrap generated from the sheet used to manufacture each part (b).

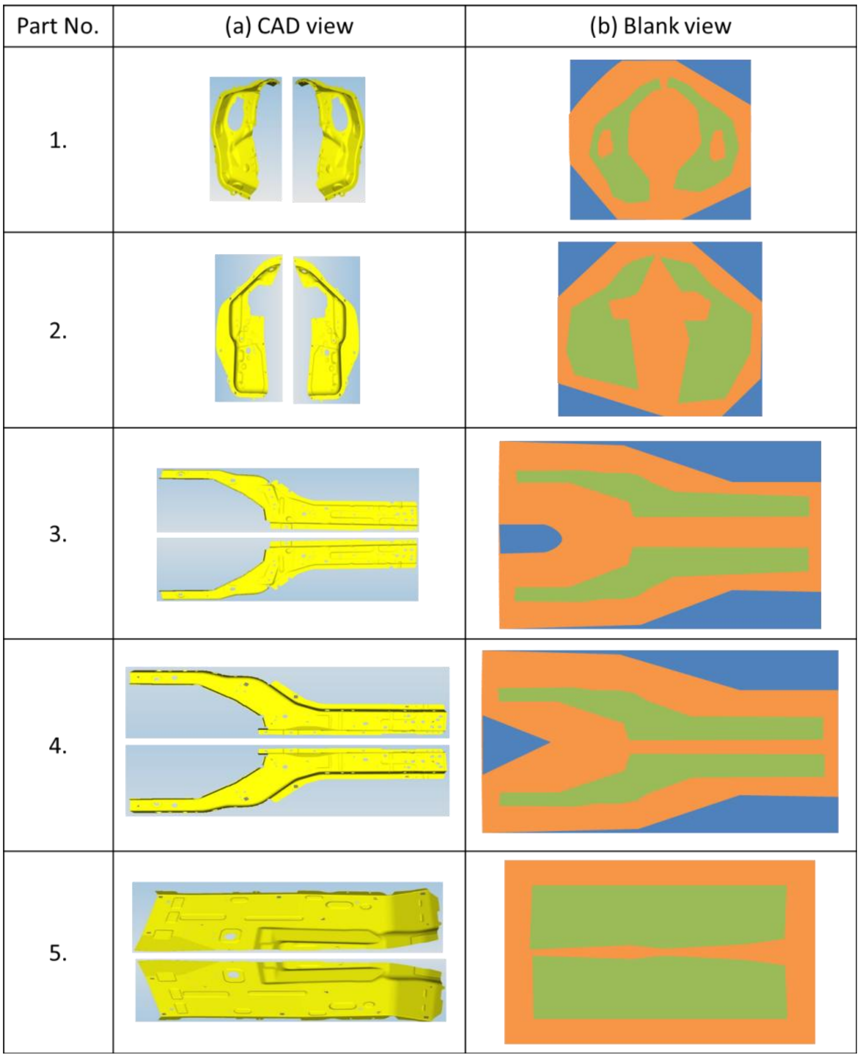

Fig. 3 - Parts investigated in the case study. (a) CAD of the final component, (b) a diagram showing how much blanking scrap (blue) and stamping scrap (orange) is generated to make the final component (green) from the sheet metal blank.

These parts were selected as they required modification and re-tooling due to the move from combustion engines to battery powertrain technology; this provided an opportunity to review the design and manufacturing processes to improve material utilisation. Ten components are produced from these parts as the left hand and right hand components are manufactured together. 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. 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 Fig. 3b.

The case study process was implemented over a 6 month period alongside the existing product development process. The only exception is activity 14 which could not take place until the tools are manufactured. Since this would not happen for another year, surrogate data from another vehicle was used to estimate the saving opportunity for this activity.

Improving material utilisation required an iterative approach to product design and manufacturing engineering with feedback loops between multiple business areas. The activities described in table 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 activities are evaluated independently so the savings could be compared. How this information was collected and processed is outlined in section 2.3.

2.3 Data collection and evaluation of the savings opportunity

In order to evaluate the new 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 3, 4 and 5. Percentage point change is the industry recognised performance measure for material utilisation; 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 is recorded as $5\%_{pts}$.

$$MU_{initial} = \frac{Initial\ part\ mass}{Initial\ coil\ mass} \times 100 \qquad (3)$$

$$MU_{new} = \frac{\text{New}\ part\ mass}{New\ coil\ mass} \times 100 \qquad (4)$$

$$MU_{increase} = MU_{new} - MU_{initial} \qquad (5)$$

The changes proposed during each activity were costed. The implemented saving opportunity is calculated by comparing the starting material utilisation value with the implemented value which is 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_2e. 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 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. The exact values for material and processing costs vary between components and organisations so an approximate value of the correct order of magnitude is used for the analysis, as detailed in table 2. These values were estimated using cost and environmental profiles from the automotive manufacture partner in this study.

Table 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 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 change was implemented. 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 exists the missed saving opportunity is allocated in whole to every appropriate barrier. This method of allocation was 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.

The results are reported in the appendix as raw data, and are collated in section 3 to give the average saving opportunity for each activity and the average cost for each of the implementation barriers.

3 Results from the material utilisation improvement case study

The trial was carried out over the period November – April 2018, using the new material utilisation improvement process outlined in Section 2. The trial aimed to investigate the opportunities and barriers the automotive industry faces for improving the material utilisation of components. Results for the total and implemented saving opportunities for each of the five parts are first presented, followed by a graphical summary of the average improvement opportunity for each activity, and the weighted importance of each implementation barrier. A detailed breakdown of the savings identified by activity for each part can be found in the appendix along with tabulated results for the saving opportunities and barriers.

3.1 Total saving opportunity

Table 3 shows the total saving opportunity identified and implemented for each part in terms of $\%_{pts}$ change, material demand reduction in kilograms, financial saving in GBP and environmental saving in kilograms of CO_2e. The environmental saving is calculated as the reduction in embodied CO_2e as a direct result of using less metal to manufacture the part. On average, the case study identified a significant average saving opportunity of 24%pts, but only 3%pts were able to be implemented.

Table 3 – 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 5 parts. In order 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 $\%_{pts}$ saving opportunity was less for the larger parts. The annual weighted saving opportunity for the five case study components is shown in table 4. The saving opportunity realised is substantial considering only 5 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.

Table 4 – 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

The saving opportunity is now analysed by activity.

3.2 Breakdown of saving opportunity by optimisation activity

Table 5 summarise the material utilisation saving opportunity for each activity averaged across the five components.

Table 5 - Material utilisation saving opportunity breakdown by 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

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 Fig. 4, 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 be reduced by designing a shaped blank or 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 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 Fig 4. weights the relative importance of these implementation barriers.

The largest saving opportunities occur in the early phases of both part and blanking design strategy identified from activities 2 and 11, designing the joints and blank shape. However, it can be seen from fig 4. 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.

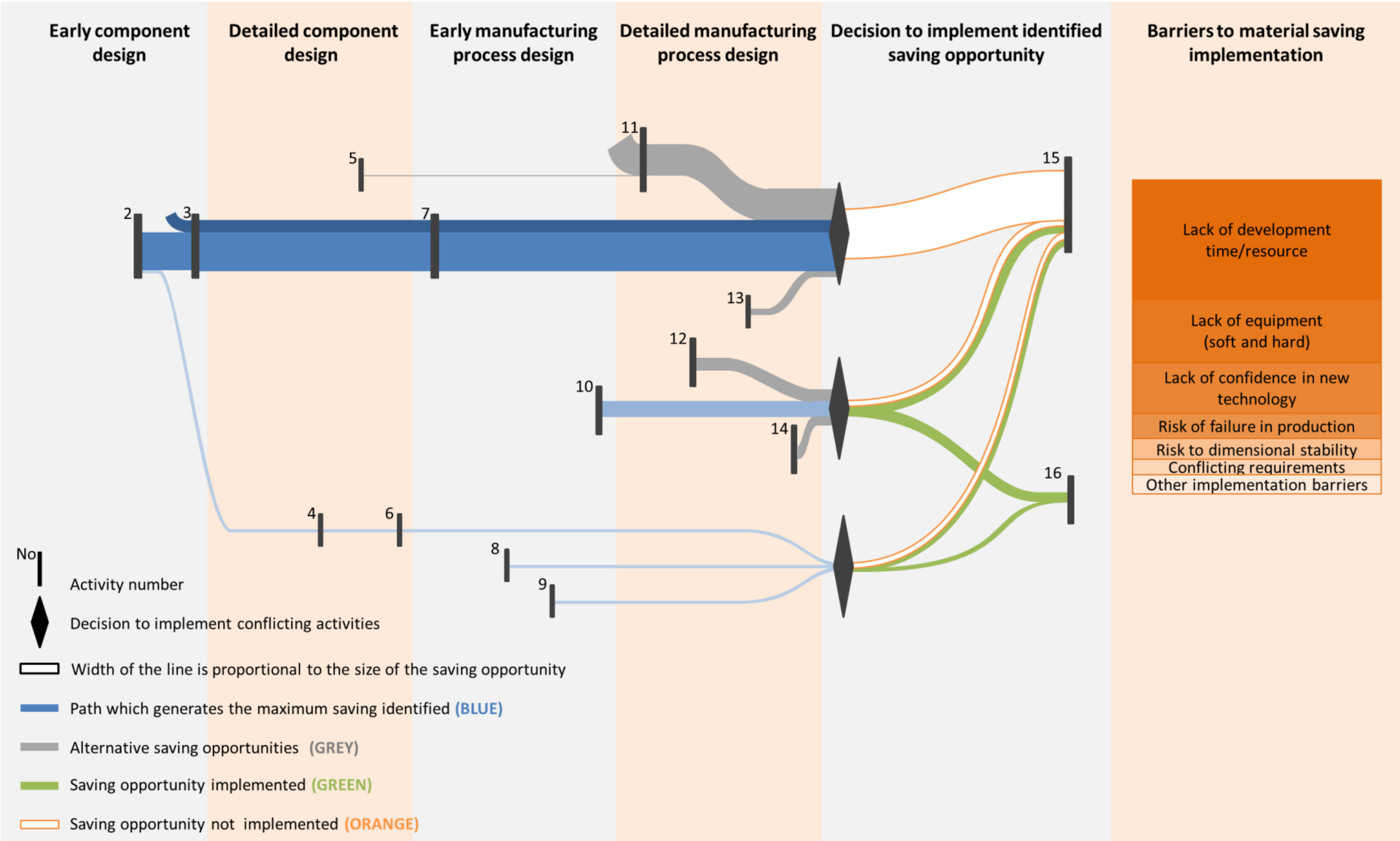

Fig. 4 - Interaction diagram showing the saving opportunity identified for each activity, the combination of activities which generates the maximum saving opportunity identified (blue), the saving opportunities implemented (green) and the saving opportunities which could not be implemented due to implementation barriers (orange). The width of the line is proportional to the size of the saving opportunity identified.

4 Discussion

The trial process found 24%pts material utilisation improvement, estimated at £1.8 million savings annually on the five selected parts. The extent to which these results capture the opportunity for automotive sheet metal components is first considered. Only 3%pts of the savings opportunities were implemented; the barriers to implementation are next discussed in light of which recommendations are made for future activities. Finally, observations are provided on the use of case studies to support material efficiency strategies more generally.

4.1 To what extent was the case study able to capture the 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. Previous research 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(Horton & Allwood 2017). Fig. 5 compares the two approaches.

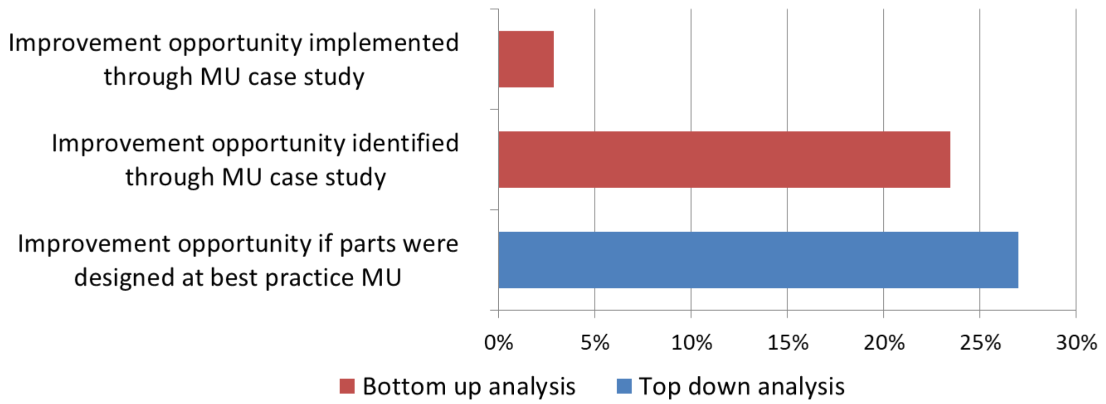

Fig. 5 - bar chart showing material utilisation improvement opportunities from this trial (red) compared with other benchmark research by (Horton & Allwood 2017) **(blue)**

As shown in Fig. 5, 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 (Horton & Allwood 2017). The proximity of the two approaches suggests that it is possible to achieve the bench mark best practice material utilisation value through applying the trial process, therefore the case study activities are an effective method of identifying improvement opportunities. The material utilisation opportunities and implementation barriers shown in Fig. 4 are now discussed to make recommendations on when and how material utilisation should be considered.

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, therefore material utilisation should 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 resources and training to improve material utilisation should be reprioritised from the end of the product development cycle to the start, as illustrated in Fig. 6. This would enable design for material utilisation at the early stages of product development.

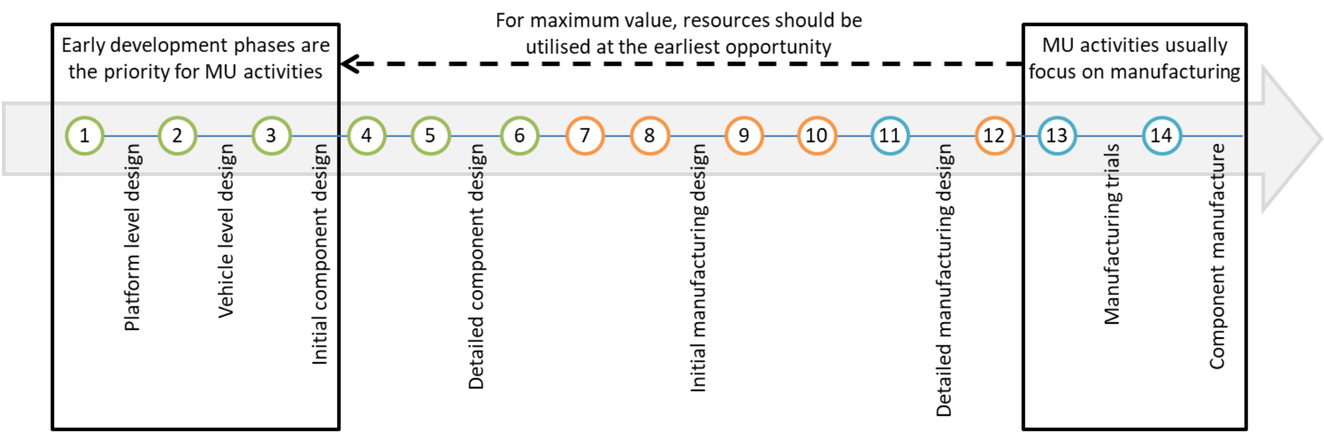

Fig. 6 – material utilisation activities are mapped onto a product development timeline, coloured to represent the focus of the activity. Component design activities are shown in green, stamping is orange and blanking is blue.

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 time is made available to implement 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 saving opportunities, and so the underlying opportunity is even greater. Best practice guidance and skill development is required to increase the confidence in using new technology such as tailor welded blanking.

The results complement previous studies on material efficiency in that the barriers identified in this case study are also recognised in previous research. 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).

4.3 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 sheet metal parts. Therefore, the opportunity for material utilisation improvement identified in table 4 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 Fig. 7.

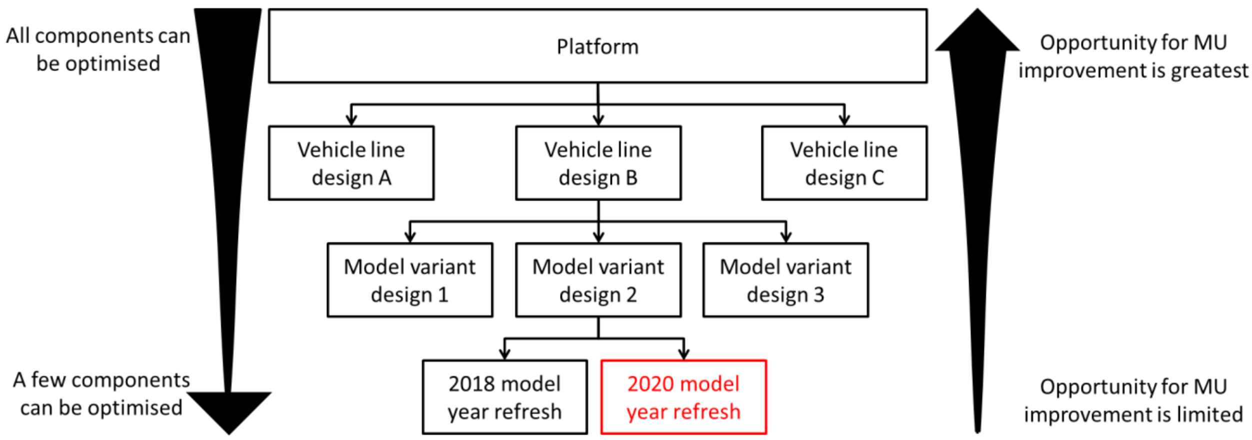

Fig. 7 – The earlier the intervention the greater the opportunity for material utilisation improvement

The saving opportunity is sensitive to the material mix of steel and aluminium. If the process is expanded to other vehicles, the size of the saving opportunity would depend on material selection. The financial saving opportunity would be greater if more aluminium is used as aluminium is more expensive than steel, as detailed in table 2. In contrast the CO_2 saving would be greater if more steel was used.

Fig. 8a groups the saving opportunities identified split 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 Fig. 8b would have to be embedded to the normal business process. This collaborative environment was essential to identify realistic saving opportunities. 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

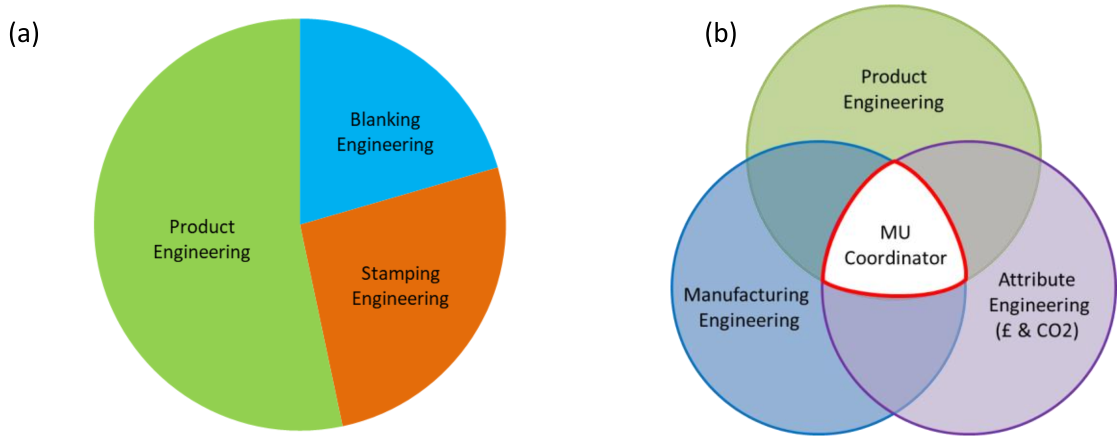

Fig. 8 – implementation of material utilisation required collaboration between multiple business areas, this is illustrated through (a) a pie chart showing the split of material utilisation improvement opportunity by the business activity and (b) a Venn diagram of how different team worked together to identify and implement savings.

On the whole, the case study 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 early in the production process and subsequently implement process change to achieve material utilisation improvement on a wider scale. The case study has shown the importance of overcoming industrial barriers when implementing material demand reduction strategies. Evaluating case study components with an industrial partner created greater momentum for change compared to previous theoretical studies. This approach should be considered in other material demand reduction projects.

5 Conclusions

To investigate the extent in which material utilisation opportunities can be realised in an industrial setting, this paper 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.

As shown in Fig. 4, through focusing effort in the upfront design for material utilisation and flexible blanking equipment, a motivated organisation could significantly improve the material utilisation of sheet metal parts, saving money and reducing the embodied CO_2e of the components. The case study identified availability of resources and technology as the most significant barriers to implementing material efficiency strategies in an industrial setting. To overcome these barriers material utilisation should be considered early in the product design process and high in the vehicle platform hierarchy. Training and best practice guidelines are required to ensure material utilisation is considered throughout the product development cycle, not just during manufacturing. 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.

This study demonstrates that it is advantageous to use a 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.

6 Acknowledgements

This research is sponsored and supported by Jaguar Land Rover and EPSRC Grant No. EP/N02351X/1 authors would like to thank all the engineers who participated in the case study, especially Maninder Arora, Paul Cassell, Alan Hunt, James Icke, Stephen Manley, Anthony Riley, Farhad Riyahi, Ian Slee, Niall Shimmin and Alexander Watson. The authors would also like to thank Jim Harper, Mark Clifton & Gethin Davies from Jaguar Land Rover; Dan Marinac from Forming Technologies Inc; and Trevor Dutton and Paul Richardson from Dutton Simulations for their ongoing project support.

7 References

Allwood, J.M., Cullen, J.M. & Milford, R.L., 2010. Options for Achieving a 50 % Cut in Industrial Carbon Emissions by 2050. *Environmental Science & Technology*, 44(6), pp.1888–1894.

Alvarez-Valdes, R., Martinez, a. & Tamarit, J.M., 2013. A branch & bound algorithm for cutting and packing irregularly shaped pieces. *International Journal of Production Economics*, 145(2), pp.463–477. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0925527313001692.

Atherton, J., 2007. Life Cycle Management Declaration by the Metals Industry on Recycling Principles. *Int J LCA*, 12(1), pp.59–60.

Azevedo, S., 2013. Using interpretive structural modelling to identify and rank performance measures An application in the automotive. *Baltic Journal of Management*, (April), pp.208–230.

Baumgartner, R.J., Hofer, D. & Sch, J., 2017. Improving sustainability performance in early phases of product design : A checklist for sustainable product development tested in the automotive industry. *Journal of Cleaner Production*, 140, pp.1602–1617.

Behrens, B.-A. & Lau, P., 2008. Key performance indicators for sheet metal forming processes. *Prod. Eng. Res. Devel.*, 2, pp.73–78.

Belecheanu, R., Riedel, J. & Kulwant, S., 2006. A conceptualisation of design context to explain design trade-offs in the automotive industry. *R&D Management*, 36(5), pp.517–529.

Carruth, M.A. & Allwood, J.M., 2013. CIRP Annals - Manufacturing Technology A novel process for transforming sheet metal blanks : Ridged die forming. *CIRP Annals - Manufacturing Technology*, 62(1), pp.267–270. Available at: http://dx.doi.org/10.1016/j.cirp.2013.03.052.

Cullen, J.M., Allwood, J.M. & Bambach, M.D., 2012. Mapping the Global Flow of Steel : From Steelmaking to End-Use Goods. *Environmental Science & Technology*, 46, pp.13048–13055.

Edwards, K.L., 2003. Designing of engineering components for optimal materials and manufacturing process utilisation. *Materials & Design*, 24(03), pp.355–366.

Engert, S. & Baumgartner, R.J., 2016. Corporate sustainability strategy - bridging the gap between formulation and implementation. *Journal of Cleaner Production*, 113, pp.822–834. Available at: http://dx.doi.org/10.1016/j.jclepro.2015.11.094.

Ettlie, J.E. & Elsenbach, J.M., 2007. Modified Stage-Gate Regimes in New Product Development. *Product Development & Management Association*, 24, pp.20–33.

Horton, P. et al., 2018. Material Demand Reduction and Closed-Loop Recycling Automotive Aluminium,. *MRS Advances*, 3(25), pp.1393–1398.

Horton, P.M. & Allwood, J.M., 2017. Yield improvement opportunities for manufacturing automotive sheet metal components. *Journal of Materials Processing Tech.*, 249(May), pp.78–88. Available at: http://dx.doi.org/10.1016/j.jmatprotec.2017.05.037.

Ingarao, G., Lorenzo, R. Di & Micari, F., 2011. Sustainability issues in sheet metal forming processes : an overview. *Journal of Cleaner Production*, 19(4), pp.337–347. Available at: http://dx.doi.org/10.1016/j.jclepro.2010.10.005.

JLR, Novelis & University of Cambridge Institute For Sustainability Leadership (CISL), 2016. *Collaboration for a closed-loop value chain*, Available at: http://www.cisl.cam.ac.uk/publications/publication-pdfs/cisl-closed-loop-case-study-web.pdf.

Kallstrom, H., 2015. Raw materials – the biggest cost driver in the auto industry. *Market Realist, Inc.*, p.Part 8. Available at: http://marketrealist.com/2015/02/raw-materials-biggest-cost-driver-auto-industry/ [Accessed May 10, 2017].

Kitayama, S. et al., 2015. Multi-objective optimization of blank shape for deep drawing with variable blank holder force via sequential approximate optimization. *Struct Multidisk Optim*, 52, pp.1001–1012.

Kumar, S. et al., 2016. The Management of Operations Barriers in green lean six sigma product development process : an ISM approach. *Production Planning & Control*, 7287, pp.1–17. Available at: http://dx.doi.org/10.1080/09537287.2016.1165307.

Lewis, H. et al., 2001. *Design + Environment: A Global Guide to DEsigning Greener Goods*, Sheffield: Greenleaf Publishing.

Linton, J.D., Klassen, R. & Jayaraman, V., 2007. Sustainable supply chains : An introduction. *Journal of Operations Management*, 25, pp.1075–1082.

Luthra, S., Garg, D. & Haleem, A., 2016. The impacts of critical success factors for implementing green supply chain management towards sustainability : an empirical investigation of Indian automobile industry. *Journal of Cleaner Production*, 121, pp.142–158. Available at: http://dx.doi.org/10.1016/j.jclepro.2016.01.095.

Milford, R.L., Allwood, J.M. & Cullen, J.M., 2011. Assessing the potential of yield improvements , through process scrap reduction , for energy and CO 2 abatement in the steel and aluminium sectors. *Resources, Conservation & Recycling*, 55(12), pp.1185–1195. Available at: http://dx.doi.org/10.1016/j.resconrec.2011.05.021.

Naceur, H., Guo, Y.Q. & Batoz, J.L., 2004. Blank optimization in sheet metal forming using an evolutionary algorithm. *Journal of Materials Processing Technology.*, 151, pp.183–191.

Penna, C.C.R. & Geels, F.W., 2012. Technological Forecasting & Social Change Multi-dimensional struggles in the greening of industry : A dialectic issue lifecycle model and case study. *Technological Forecasting & Social Change*, 79(6), pp.999–1020. Available at: http://dx.doi.org/10.1016/j.techfore.2011.09.006.

Sattari, H., Sedaghati, R. & Ganesan, R., 2007. Analysis and design optimization of deep drawing process. Part II: Optimization. *Journal of Materials Processing Technology*, 184(1-3), pp.84–92.

Shahbazi, S. et al., 2016. Material ef fi ciency in manufacturing : swedish evidence on potential , barriers and strategies. *Journal of Cleaner Production*, 127, pp.438–450.

Shim, H.B., 2015. Applications of digital tryout to stampings of hard-to-form parts. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 229(6), pp.990–1001. Available at: http://pib.sagepub.com/lookup/doi/10.1177/0954405414535582.

Shim, H.B., 2004. Determination of optimal blank shape by the radius vector of boundary nodes. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 218(9), pp.1099–1111.

Shim, H.B., 2013. Digital tryout based on the optimal blank design toward realization of beadless stamping. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 227(10), pp.1514–1520.

Stewart, R., Bey, N. & Boks, C., 2016. Exploration of the barriers to implementing different types of sustainability approaches. *Procedia CIRP*, 48, pp.22–27. Available at: http://dx.doi.org/10.1016/j.procir.2016.04.063.

Trianni, A. & Cagno, E., 2012. Dealing with barriers to energy ef fi ciency and SMEs : Some empirical evidences. *Energy*, 37(1), pp.494–504. Available at: http://dx.doi.org/10.1016/j.energy.2011.11.005.

Verhoef, P.C., Pauwels, K.H. & Tuk, M.A., 2012. Assessing Consequences of Component Sharing across Brands in the Vertical Product Line in the Automotive Market *. *Product Development & Management Association*, 29(4), pp.559–572.

Veshagh, A. & Li, W., 2015. SURVEY OF ECO DESIGN AND MANUFATURING IN AUTOMOTIVE SMES. *310 PROCEEDINGS OF LCE2006*, pp.305–310.

Zaki, M. et al., 2014. Jurnal Teknologi The Sustainability Challenges in the Adoption of Cleaner Production System : A Review. *Jurnal Teknologi (Science & Engineering)*, 70(1), pp.117–123.

Zhang, S.H. et al., 2004. Some new features in the development of metal forming technology. *Journal of Materials Processing Technology*, 151, pp.39–47.

Zhong-qin, L., Wu-rong, W. & Guan-long, C., 2007. A new strategy to optimize variable blank holder force towards improving the forming limits of aluminum sheet metal forming. *Journal of Materials Processing Technology*, 183(2-3), pp.339–346.

8 Appendix

A: Breakdown of results

Tables A.1 and A.2 summarise the material utilisation saving opportunity for each activity and the implementation barriers identified averaged across the five components.

Table A.1 - Material utilisation saving opportunity breakdown by 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 A.2 - 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

The following five tables summarise the material utilisation saving opportunities for each part identified using the process described in section 2.

Table A.3 - 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	-
Total savings identified	**29**	**3.38**	**3.71**	**3.18**	-	-
Total savings implemented	**3**	**0.55**	**0.16**	**0.52**	-	-

Table A.4 - 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 A.5 - 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 A.6 - 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 A.7 - 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**	**-**	-

B: Examples of Each Optimisation Activity

This section provides an example of each of the material utilisation improvement activities described in section 2.

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 2.

Table B.1 - 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, 65% was therefore considered to be an appropriate benchmark value.

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 Fig. B.1. For part 5 this design change improves material utilisation by 5%$_{pts}$.

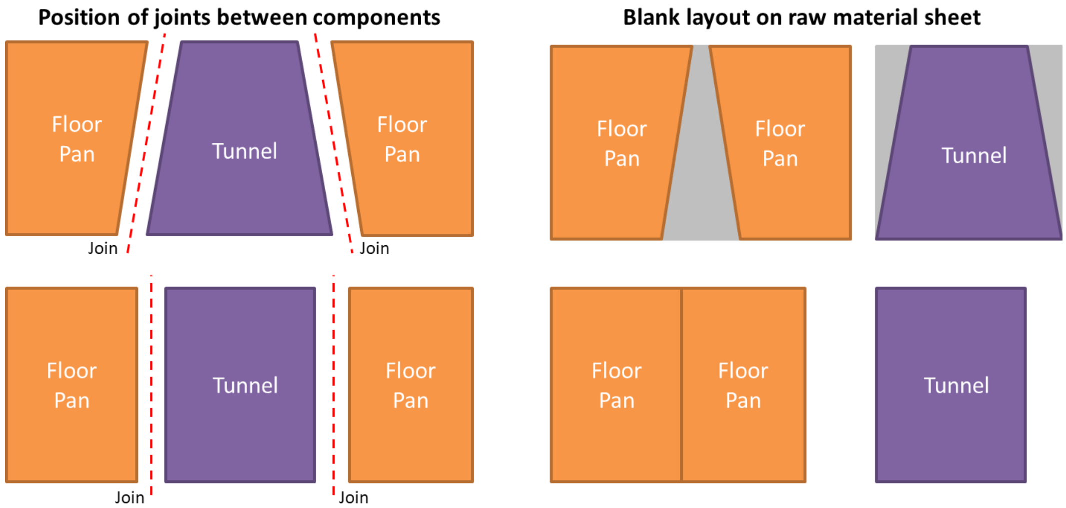

Fig. B.1 – Straightening the joints within the assembly reduces blanking scrap (grey) to improve the material utilisation by 5%$_{pts}$

Alternatively the components in the assembly could be combined and manufactured as one part, as shown in Fig. B.2. This would reduce stamping scrap to increase the material utilisation of the assembly by 17%$_{pts}$.

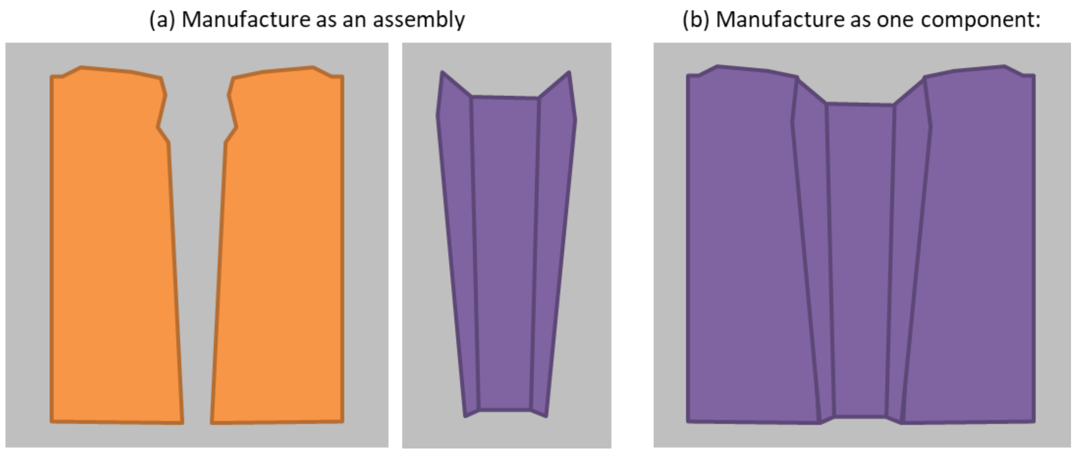

Fig. B.2 – Representation of the stamping scrap (grey) generated in manufacturing individual components for an assembly (a), compared to one combined part (b). Combining the assembly improved the material utilisation by 17%$_{pts}$

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 three and four improves the material utilisation of part 3 by $12\%_{pts,}$ as shown in Fig. B.3. The component geometry requires modification to implement this saving opportunity, in order to maintain the structural performance of the component.

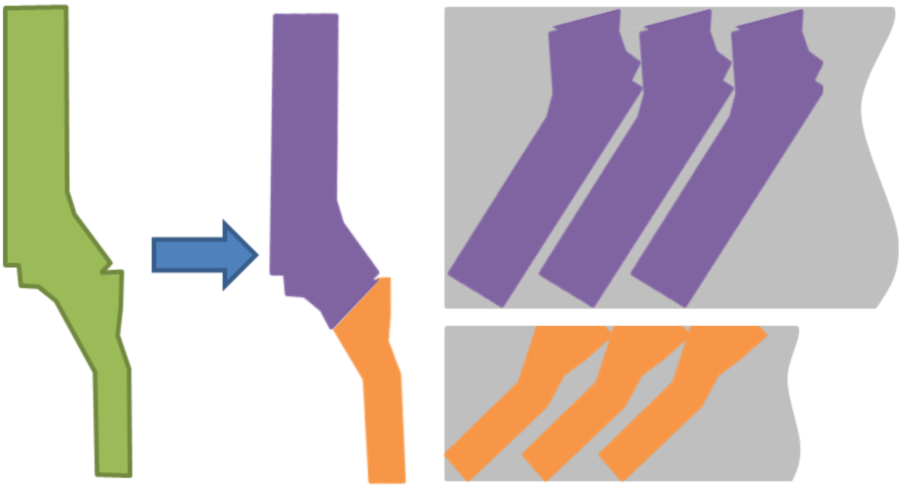

Fig. B.3 – Splitting the blank reduces blanking scrap to improve the material utilisation by $12\%_{pts}$

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 Fig. B.4. This change improves material utilisation by $18\%_{pts}$.

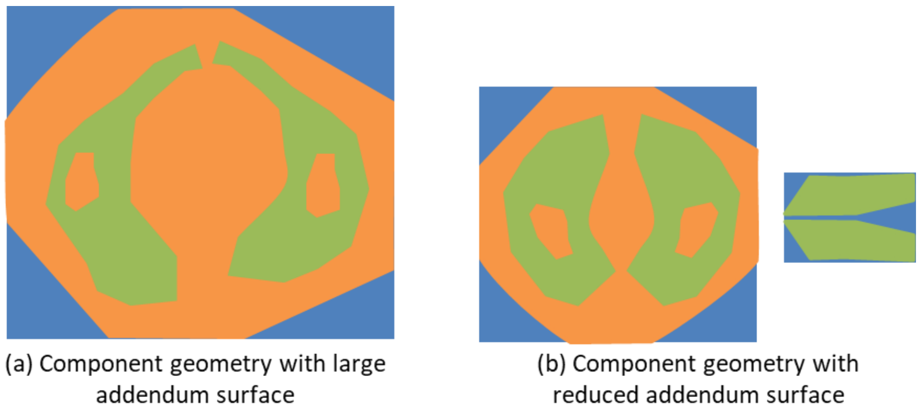

Fig. B.4 – designing the geometry to reduce the addendum surface improves the material utilisation by $18\%_{pts}$

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 Fig. B.5. This change improves the material utilisation by $0.3\%_{pts}$ and has been implemented.

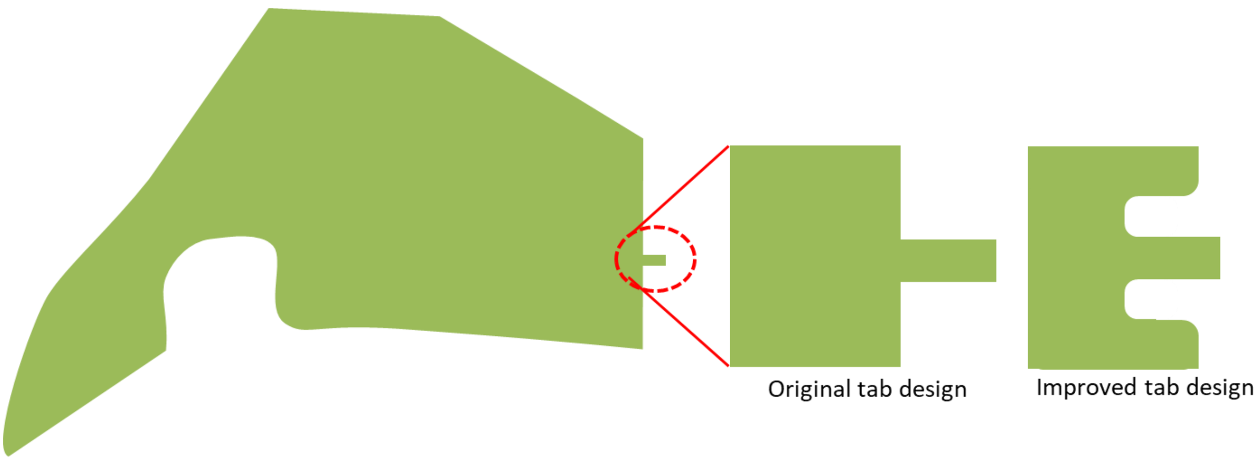

Fig. B.5 – redesigning the tab of part 2 reduces the pitch by 10mm.

Activity 6: Design part radii for formability

The 10mm radius highlighted with a red dotted line in Fig. B.6 is not constraint by neighbouring components. This radius on can be opened up to 20mm, making the part is easier to draw to reduce the size of the addendum surface required. This change improves the material utilisation by $0.1\%_{pts}$.

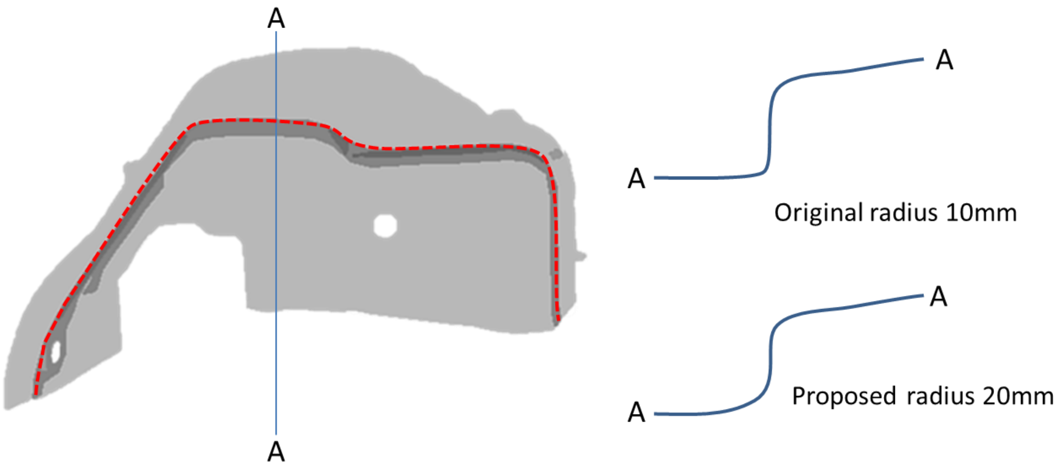

Fig. B.6 – opening the radius reduced the requirement for draw beads from a double bead to a single bead

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 Fig. B.7.

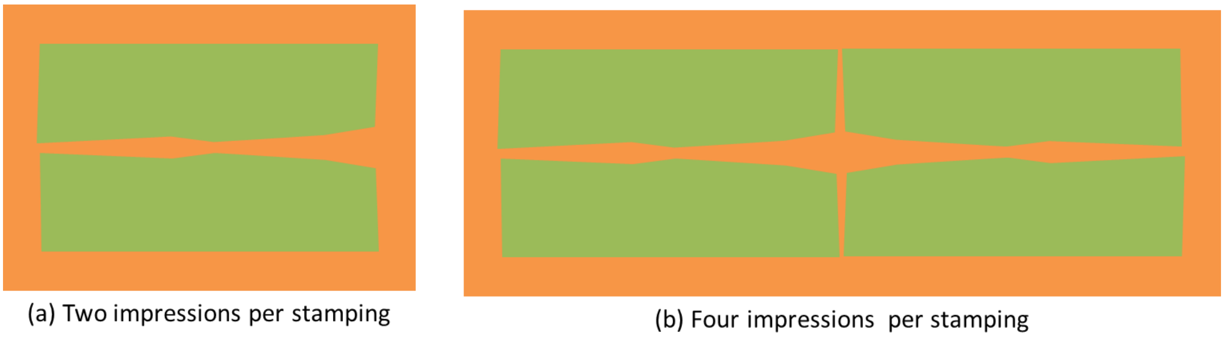

Fig. B.7 - increasing the number of impressions formed in one hit improves material utilisation by $6\%_{pts}$

Implementing this change may reduce the dimensional stability of the components, as the replicated parts may not be identical to the originals, and requires an increase tool size. Increasing the number of parts per provides the manufacturing saving of 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 Fig. B.8. This change has been implemented.

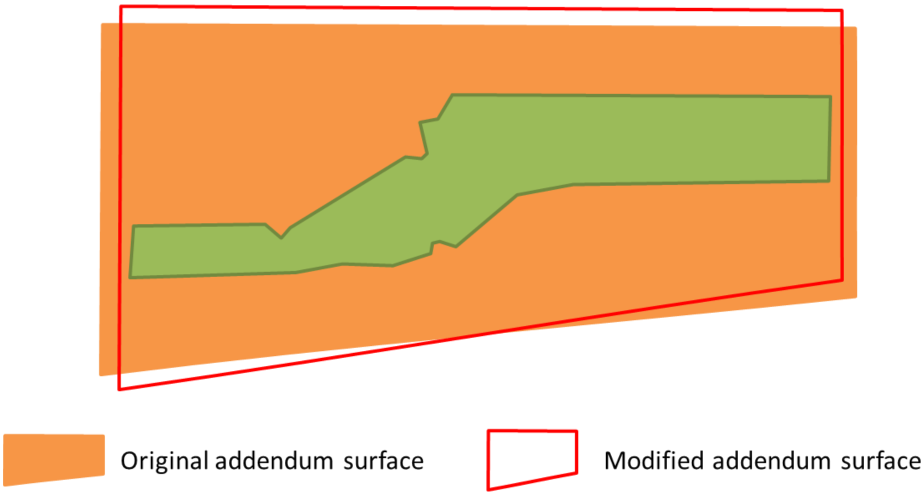

Fig. B.8 – the blank profile is shown in orange and the part is shown in green. Modifying the addendum surface creates a smaller blank profile (not to scale)

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 Fig. B.9. The blank edge of the formed part finishes 40mm from the draw bead. Material which finishes outside of the draw bead provides no benefit during 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 $9\%_{pts}$.

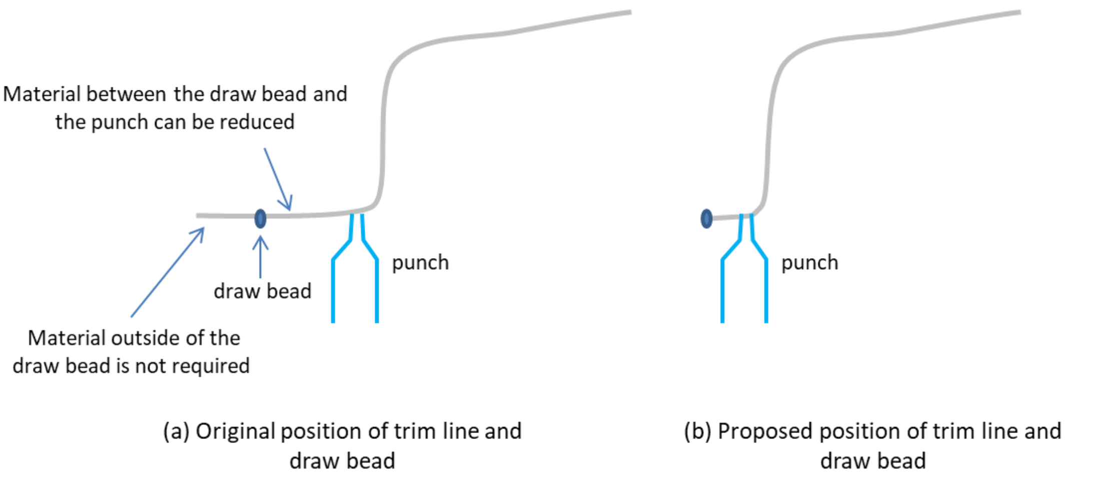

Fig. B.9 – modifying the position of the draw bead and trim line improves the material utilisation of part 4 by $9\%_{pts}$

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 Fig. B.10. This change was not implemented due to technology limitations restricted by size of blank on blanking line.

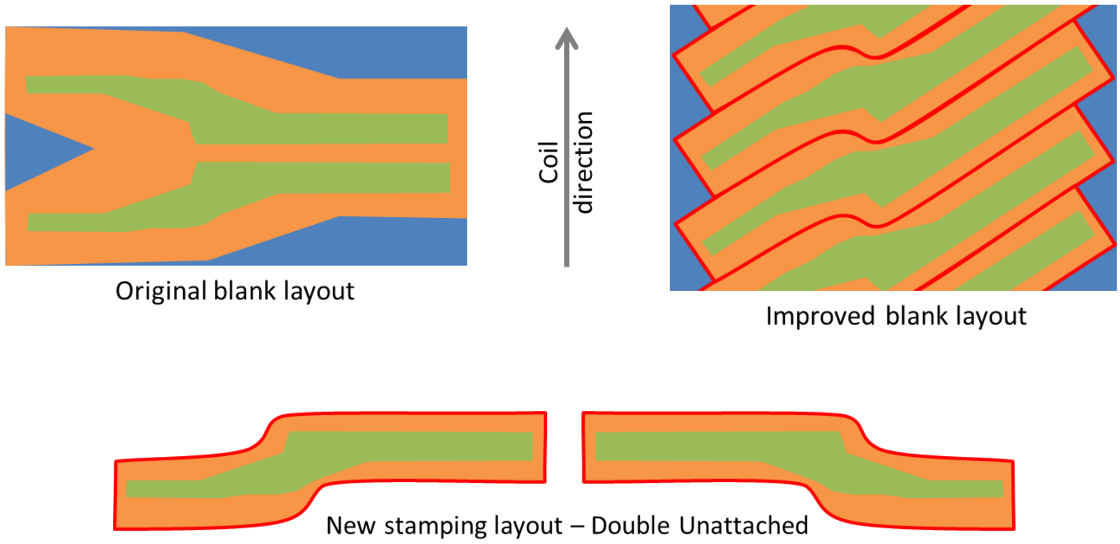

Fig. B.10 – a shaped blank improves the material utilisation by 26%$_{pts}$ compared to a rectangular blank.

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 Fig. B.11. 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.

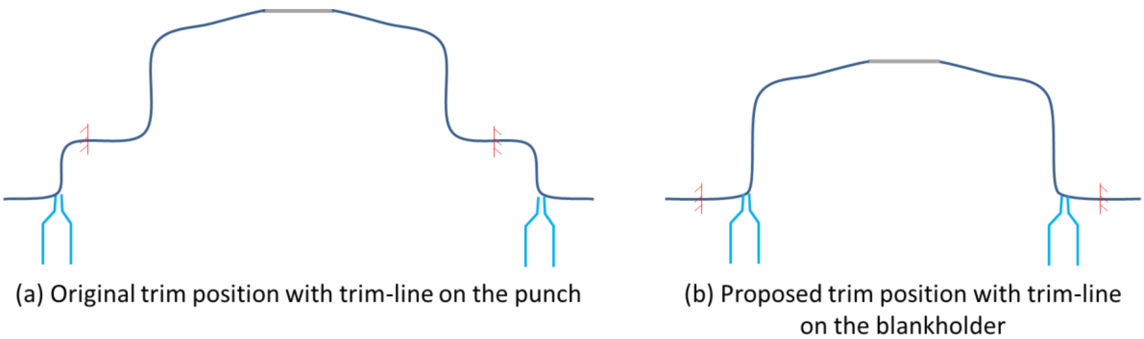

Fig. B.11 – forming the component flange on the blank holder rather than the punch improves the material utilisation of part 1 by 15%$_{pts}$

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 Fig. B.12. 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.

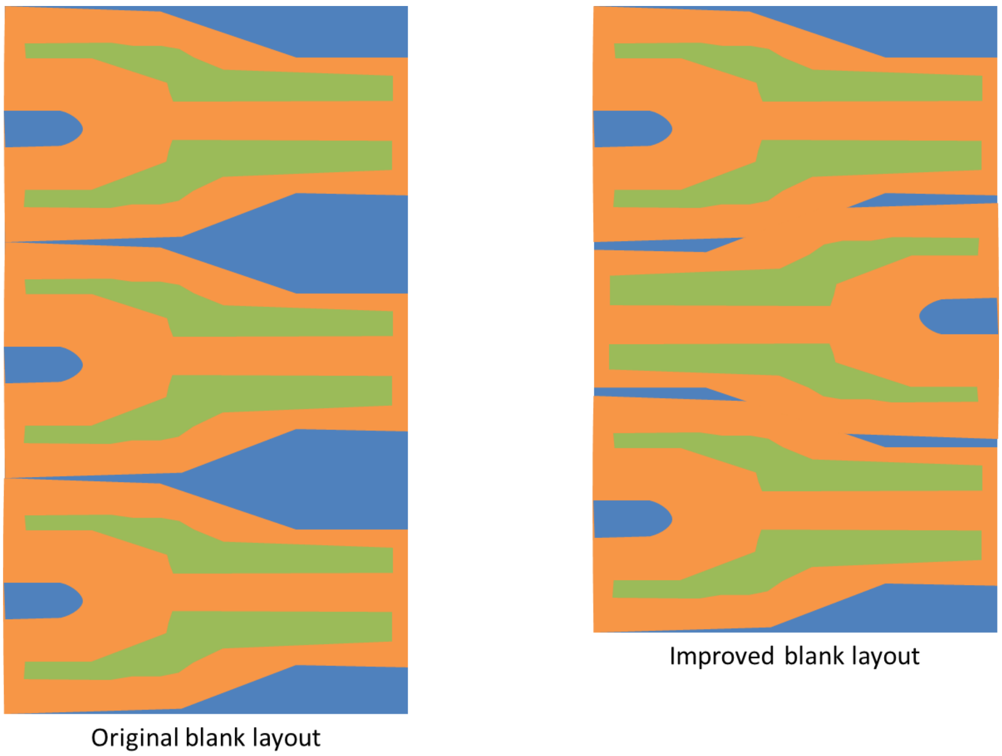

Fig. B12 - alternating the blank orientation improves the material utilisation by 4%$_{pts}$

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 am material utilisation improvement opportunity of 2.6 %$_{pts}$.

Graphical Abstract