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Environmental impact assessment and comparative analysis of hot stamping and cold stamping processes: A cradle-to-gate lifecycle assessment study

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Abstract. This manuscript presents the results of a cradle-to-gate lifecycle assessment (LCA) conducted on a component manufactured through two distinct process routes: Hot stamping of AA6082-T6 and cold stamping of AA5251-H22. The primary objective of this study is to provide a detailed understanding of the environmental impact associated with these processes and to conduct a comparative analysis of their environmental profiles. A comprehensive process map was developed for each manufacturing route, delineating all inputs and outputs at each step. Forming trials were executed during the LCA, capturing equipment energy consumption. When immediate data was unavailable from trials, the LCA model was supplemented with information from the Ecoinvent 3.6 database. The analysis demonstrates that the adoption of advanced near-net-shape manufacturing, specifically hot stamping, can significantly diminish the environmental impact compared to traditional cold stamping processes. Despite the additional energy requirements for heating in hot stamping, the overall environmental savings, supported by uncertainty analysis, are considerable. In the case of the examined demonstrator part, hot stamping showcased a noteworthy 35% reduction in CO2 equivalent emissions, equivalent to 6 kg CO2e per part. This reduction is primarily attributed to two key factors: the decreased material thickness achievable in hot stamping while preserving equivalent mechanical characteristics in the final part and the recycling of any material waste after forming. The results underscore the environmental advantages of embracing advanced manufacturing techniques, contributing valuable insights for environmentally conscious decision-making in the manufacturing industry.

Introduction

Cold stamping is a metalworking process where a sheet metal is precisely shaped into desired forms using rigid dies and mechanical force, all at ambient temperature. This process involves the use of pressure to deform the sheet metal, typically using a press. The metal is first placed into a die, and then pressure is applied through hydraulic cylinder by press to shape it into the desired component shape. Cold stamping can be used to create various products, from small parts such as fasteners and washers to larger components such as automotive panels and aerospace structural components [1]. This process offers numerous advantages over other metal shaping methods, including improved material properties, increased productivity at lower costs. However, this process may not be suitable for all materials or shapes. For instance, high strength materials may not be easily cold-formed, and highly complex shapes might require other manufacturing methods. Also, the springback of the material after forming can present a significant technical obstacle in

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certain cases. Furthermore, for some materials, an intermediate stress relieve heat treatment may also be required to reduce the residual stresses.

A novel hot stamping process, also known as Hot Form Quenching (HFQ) has been reported to manufacture high-strength aluminium alloys into complex and lightweight components [2]. It involves several key steps, including solution heat treatment, forming, in-die quenching and artificial ageing. The high temperature makes the sheet material more ductile and easier to deform, resulting in products with more precise and consistent dimensions. HFQ can create intricate part geometries that are difficult to achieve through traditional cold-forming processes. It is also beneficial in reducing part counts and assembly requirements by combining multiple components into one part to save significant cost and increase sustainability [3].

A Life Cycle Assessment (LCA) is a systematic and comprehensive methodology used to evaluate the environmental impact of a product, process or service throughout its entire life cycle. This paper aims to present a LCA on the environmental impacts of cold and hot stamping processes. For this analysis, an identical demonstrator part will be manufactured with both processes. The LCA of this study follow the ISO 14040 [4] and 14044 [5] standards, and it was carried out in the four following stages:

1. Goal and scope definition, where the objective, systems boundaries, functional unit, and assumptions are defined.
2. Life cycle inventory, which includes the identification of all the inputs and outputs associated with all process steps.
3. Life cycle impact assessment, where the inputs and outputs of the previous phase are used to evaluate the potential environmental impacts of the manufacturing steps.
4. Interpretation, in which the results of the LCA are discussed and compared.

Material and Methods

The study is designed as a ‘cradle-to-gate’ LCA; in other words, it includes the extraction and production of raw materials, converting processes, transports to the manufacturing site and the manufacturing processes. A schematic representation of this can be observed in Fig. 1.

In general, the study includes the following steps:

1. Production, transportation, and conversion of the raw materials
2. Transportation of the raw materials to the manufacturing site
3. Manufacturing of the demonstrator part using the selected process

Additionally, the study does not include the following steps:

1. Production and disposal of the infrastructure (machines, transport media, roads, etc.) and their maintenance as no significant impact is expected
2. Environmental effects from accidents
3. Transport of the demonstrator part from the manufacturing site to the customer
4. Use phase of the demonstrator part at the customer site
5. External manufacturing processes such as painting
6. Final disposal and recycling of the primary materials used and the demonstrator part

Below, Fig. 2 and Fig. 3 illustrate the simplified flowcharts and system boundaries for the cold-forming and hot-forming processes, respectively.

The function examined in this study is the manufacturing of a demonstrator part. Thus, the functional unit has been selected to be one demonstrator part. The reference flow is also one demonstrator part and has been used in the allocation of the tooling wear and production, the caption of the energy while the equipment is in standby and in some other auxiliary data.

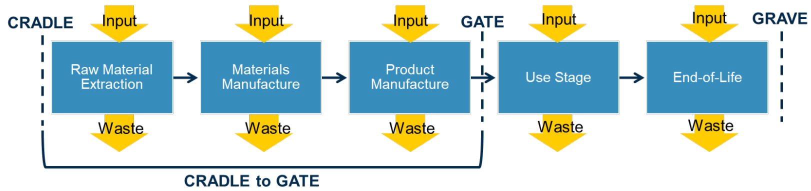

Fig. 1. LCA Stages.

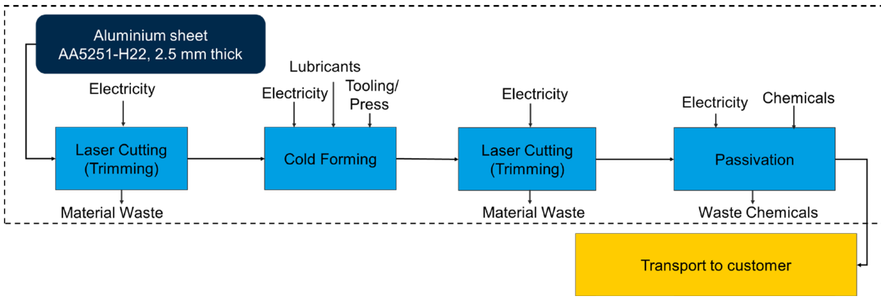

Fig. 2. Cold Stamping Process Map and System Boundaries.

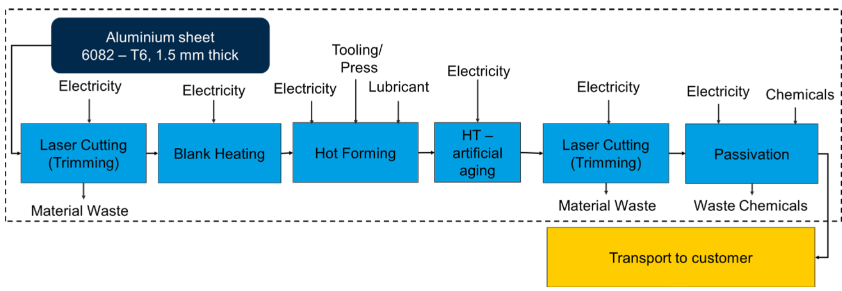

Fig. 3. Hot Stamping Process Map and System Boundaries.

Fig. 4. Formed Demonstrator Parts.

To maintain the study within a feasible scope, it's necessary to limit the detail in system modelling using cut-off criteria. ISO standard [ISO 14044] states that cut-off criteria should consider mass, energy, or environmental significance. Prechains with an input material share less than 1% of the total mass input of a considered process are excluded from the study for mass-related cut-offs. However, the total cut-off cannot exceed 5% of input materials based on the functional unit. All energy inputs are considered, except for energy-related to material inputs from prechains that are cut off due to the mass-related rule.
In the next sections, more details are given on the assumptions and data used for modelling the environmental impact of the two manufacturing processes.

Data gathering and data quality
The data in this study have been meticulously chosen based on key criteria for collection. Specifically, data reliability is confirmed through validated sources and non-validated sources within selected databases. These data are deemed representative of all pertinent market sites over

a sufficient timeframe to mitigate typical fluctuations, ensuring high completeness. Temporal correlation is robust, as primary data were acquired in the study, while secondary data originate from databases relevant to the study period. Geographically, the data exhibit a strong correlation, with industry experts consulted to guide regional data selection. Furthermore, primary data collected pertain closely to the study's objectives, encompassing equipment, technologies, and materials. Similarly, secondary data selection adheres to this principle. Overall, the data are of high quality. In Table 1 and Table 2, the primary and secondary data are illustrated.

Table 1. Cold-forming data.

	Resources	Input	Output
Freight, lorry, for raw materials in China	Other	secondary data	
Freight, sea, container ship, China to UK	Other	secondary data	
Initial Laser cutter	Resources- Material	primary data	primary data
	Resources- Other	secondary data	
	Waste		primary data
500T Press	Resources- Electricity	primary data	
	Resources- Other	secondary data	
	Resources- Other	secondary data	
	Waste		secondary data
Laser Cutting	Resources- Other	secondary data	
	Waste		primary data
Anodising, aluminium sheet	Resources- Other	secondary data	

Table 2. Hot-forming data.

	Resources	Input	Output
Freight, lorry, for raw materials in China	Other	secondary data	
Freight, sea, container ship, China to UK	Other	secondary data	
Initial Laser cutter	Resources- Material	primary data	primary data
	Resources- Other	secondary data	
	Waste		primary data
Furnace (blank preheating)	Resources- Material		
	Resources- Electricity	primary data	
500T Press	Resources- Electricity	primary data	
	Resources- Other	secondary data	
	Resources- Other	secondary data	
	Waste		secondary data
Furnace (Artificial ageing)	Resources- Electricity	primary data	
Laser Cutting	Resources- Other	secondary data	
	Waste		primary data
Anodising, aluminium sheet	Resources- Other	secondary data	

Starting Material. The demonstrator parts are fabricated using aluminium AA5251-H22 for cold stamping and AA6082-T6 for hot stamping. Due to the distinct mechanical properties of these alloys, with AA5251-H22 having a minimum tensile strength of 190 MPa and AA6082-T6 having a minimum of 310 MPa [6], a fair comparison between the two parts necessitates adjustments. It was assumed that for both parts to possess equivalent structural integrity, the AA5251-H22 part would need to be approximately 1.6 times thicker than the AA6082-T6 part. As such, for this study, the part thicknesses were standardised at 2.5 mm for AA5251-H22 and 1.5 mm for AA6082-T6. Also, based on data from the industry [6], the composition of the Alloys has been modelled using Global values, as seen in Table 4. The composition of the alloys is crucial for capturing the environmental impacts related to the extraction of the different raw materials, the refinement processes for the production of the elements, and any average travel in between stages.

Laser Trimming – electricity and waste material. To make the demonstrator part, two trimming operations are needed: one for cutting the blank to the required size and another one for trimming the formed component to the required shape.

Laser cutting is a widely used method across industries for precise material trimming. Utilising a high-powered laser beam, this technique offers accuracy in cutting various materials. Its precision enables the creation of intricate designs effortlessly, making it suitable for diverse applications. Laser cutting boasts advantages such as minimal waste, high accuracy, and reduced risk of material damage, making it a favoured choice for cutting materials. It is important to note that, the laser cutting eliminate the need of two additional trimming tools which makes the process cheaper, efficient, and sustainable.

For the manufacture of the demonstrator parts, a 4kW laser and a cycle time of 10 seconds were assumed. The literature [7] suggests that, on average, 35% of the sheet material is wasted during the initial and final laser cutting. In this work, it was assumed that 10% of the starting sheet thickness is trimmed off to make the starting blank, and 25% is cut after formation. The waste material, i.e. the off-cuts, is assumed to return to the production loop and be recycled. Table 3 summarises the weights of the starting material, blank, part, and off-cuts that can be recycled.

Forming – Electricity. To determine the quantity of electricity used by the two forming processes, manufacturing trials were run using a 500T hydraulic press. The electricity consumed from the equipment was collected for each process on four parts formed.

For the hot stamped parts, the press consumed, on average, 0.082kWh per part, including the forming operation and standby between parts.

For cold stamping this value increased to 0.085kWh per part.

Forming – Lubricant. The lubricant used in the manufacturing trials was the graphite lubricant Durcol W1010 – 01. The project team estimate an initial lubricant volume of 23.2 g/m^2 for best lubrication during the forming trials [8]. As a result, the weight of lubricant used per part has been calculated to be 2.5 g.

Forming – Tooling. For both the forming processes, the same forming tool was utilised. One of the model's assumptions for this LCA is that the tooling is considered consumable. This study was not aimed at conducting a detailed LCA on the tool but to capture the additional environmental impact from the normal wear of the tool used.

The tool used in the analysis is made of H13 steel, and its composition [9] is captured in Table 4. Vanadium (V) could not be modelled since data were not available and lithium was used as a replacement.

Table 3. Weights of input-output material.

	Hot stamping of AA6082-T6 1.5mm	Cold stamping of AA5754-H22 2.5 mm
Weight of initial sheet	400 g	670 g
Weight of blank	360 g	603 g
Weight of off-cuts after first trim	40 g	67 g
Weight of part	260 g	435 g
Weight of off-cuts after last trim	100 g	168 g
Total weight of off-cuts	**140 g**	**235 g**

Table 4. Aluminium alloy AA6082, AA5251 and H13 tool steel composition.

Aluminium alloys [6]			**Tool Steel**	
Element	Average in **Alloy 5251** [%]	Average in **Alloy 6082** [%]	Element	Average in **H13** [%] [9]
Silicon	0.20	1.00	Carbon	0.39
Magnesium-alloy	2.05	0.90	Chromium	5.13
Manganese	0.30	0.70	Molybdenum	1.43
Iron pellet	0.25	0.25	Vanadium	1.00
Chromium	0.075	0.125	Silicon	1.00
Zinc	0.075	0.10	Manganese	0.35
Titanium	0.075	0.075	Phosphorus	0.03
Copper	0.075	0.05	Sulphur	0.03
Aluminium	Balance	Balance	Steel	Balance

The exact manufacturing processes used for production of the tooling are not captured; instead, average global data for metal working have been selected from the database Ecoinvent 3.6. It was assumed that the tool could produce 150,000 parts and 100,000 parts in hot and cold stamping processes, respectively; the environmental impacts for production, wear, and waste management of the tool have been calculated and allocated per part.

Blank Heating – Electricity. The hot stamping method involves controlled heating of the blank before shaping. This heating occurs in a furnace, ensuring precise temperature and time control for uniformity. Energy usage in this step was evaluated through manufacturing trials. Parts were preheated to 535°C for 8 minutes, with energy consumption measured via an electricity meter connected to the furnace. Three key stages were identified during the preheating of the demonstrator part:

1. Direct energy. This is the energy used to heat blanks during an 8-minute heating phase. The study involved measuring energy usage for four parts and averaging the values.
2. Set up energy for furnace heat up. This is the energy required by the furnace to reach the necessary process temperature from room temperature, and it has to be split among all the parts that will be processed in the same batch before the furnace is cooled down again. For this study, it was assumed that a factory works on two 8-hour shifts a day Mon-Fri; a part is formed every 9 minutes; and the furnace is shut down after Friday’s last shift and heated back up on Monday. Five hundred thirty parts will be heated up each week. In the trials, the energy consumption during the four hours required to reach a steady process temperature in the furnace was measured.
3. Stand by energy. This corresponds to the energy used by the furnace to maintain temperature during non-heating periods. The energy used during the 32 weekly standby

hours has to be divided by the 530 parts that will be preheated each week. Energy consumption was measured during one hour of steady-state furnace operation.

A model was built upon the assumptions above for each stage. In addition to these assumptions, primary data were gathered during manufacturing trials of the demonstration part. Table 5 presents these data, including energy consumption at key stages and total energy consumption per part.

Artificial Ageing – Electricity. In the hot stamping process, a post-forming heat treatment known as artificial ageing is employed for heat-treatable aluminium alloy components like AA6082. To quantify energy consumption in this stage, manufacturing experiments were conducted, with energy measured using an electricity meter connected to the furnace. Parts were subjected to heat treatment at 180°C for 3 hours, followed by air cooling. Three key stages in the furnace operation were identified during the heat treatment process:

1. Direct Energy: This is the energy utilised to heat parts during the 3-hour heat treatment. Given the production capacity of 530 parts per week and factory operation on two 8-hour shifts, Monday to Friday, each batch averages 21.2 parts. Therefore, energy allocation per part is calculated by dividing the total energy used for each heat treatment cycle by 21.2.
2. Set up energy for furnace heat up: This represents the energy needed by the furnace to reach process temperature from room temperature. This energy is distributed among all parts processed in the same batch before furnace cooldown, considering the production capacity of 530 parts.
3. Stand by energy. This corresponds to the energy used by the furnace to maintain temperature during non-heat treatment periods. The weekly standby energy, used in the 32 weekly standby hours, has to be divided by the 530 parts processed each week. Energy consumption was measured for one hour with the furnace in a steady state.

A dedicated model has been created to allocate emissions from each stage to the final products, utilising the described assumptions. In addition to these assumptions, primary data was gathered during the manufacturing trials of the demonstration part. Table 5 presents this data, including energy consumption for each key stage and the overall energy consumption for the part.

Anodising. This is a chemical process commonly used to protect aluminium surfaces from corrosion. It involves submerging the metal in an acid electrolyte bath and passing an electrical current through it. The process forms an aluminium oxide layer on the surface, known as the anodic layer, which provides protection. The quality of this layer depends on factors such as bath temperature, solution concentration, and current density. For both the hot- and cold-formed part, a current density of 8–12 mA/cm^2 is assumed, resulting in an energy consumption of 0.35–0.40 KWh/m^2 [10].

Table 5. Energy consumption blank preheating and part heat treatment.

Step	Phase	Average Energy measured (kWh)	Batch size	Energy used per part (kWh/part)
Blank Preheating	Direct energy	1	1	1
	Set up energy	42	530	0.08
	Stand by energy	160	530	0.3
	Total			**1.38**
Part Heat Treatment	Direct energy	7	21.2	0.33
	Set up energy	6	530	0.01
	Stand by energy	56.3	530	0.12
	Total			**0.46**

Results and Discussion

In this section the results for hot stamping and cold stamping are discussed.

Hot stamping. In Fig. 5, the network of hot stamping of AA6082-T6 for the demonstrator part is depicted, highlighting several key points. The main contributor to the environmental impact is identified as aluminium alloy AA6082, with each part having a total carbon footprint 11 kg CO2 equivalent. Laser-cutting processes are highlighted for their positive environmental impact despite generating waste, as they benefit from recycling and have relatively low energy consumption. The diagram selectively illustrates sources contributing more than 1.52% to the total impact, focusing on the most significant contributors to the manufacturing process's environmental footprint.

Cold stamping. The network diagram for cold stamping (Fig. 6) of the demonstrator part highlights key aspects of its environmental impact. Aluminium alloy AA5251 is identified as the primary contributor, resulting in a 17 kg CO2 equivalent carbon footprint per part. Similarly to hot stamping, laser cutting steps also contribute positively to the environment, thanks to recycling and low energy consumption. Notably, AA5251 stands out as the largest factor in the process's environmental impact, emphasizing its significant role in the manufacturing process's overall environmental footprint.

Comparison of hot and cold stamping processes. The following sub-sections will include a comparison between the two processes under the assumption that both will produce a part with the same (or very similar) properties.

Impact Assessment. The characterisation, as illustrated in Fig. 7, allows the reader to quickly identify how each process contributes to the total impact of each of the environmental categories. It becomes evident that hot stamping has a lower environmental impact in almost all environmental categories than cold stamping. The only exception is the ionising radiation category, where there is a small difference due to the extra carbon-14 emitted in the air due to the difference in composition of AA6082 and AA5251.

Uncertainty Analysis. In Figure 8, the uncertainty analysis is illustrated for this work. The results are based on 200 runs, with 58.7% of secondary data providing values that contain uncertainty-related data. For this data, lognormal distribution was used in 58.6% and undefined one for 41.3%. The primary data are considered of high quality with very limited uncertainty. Based on these assumptions, with a confidence interval of 95%, A- a part manufactured through hot forming, is always better environmentally than B- a part manufactured through cold forming.

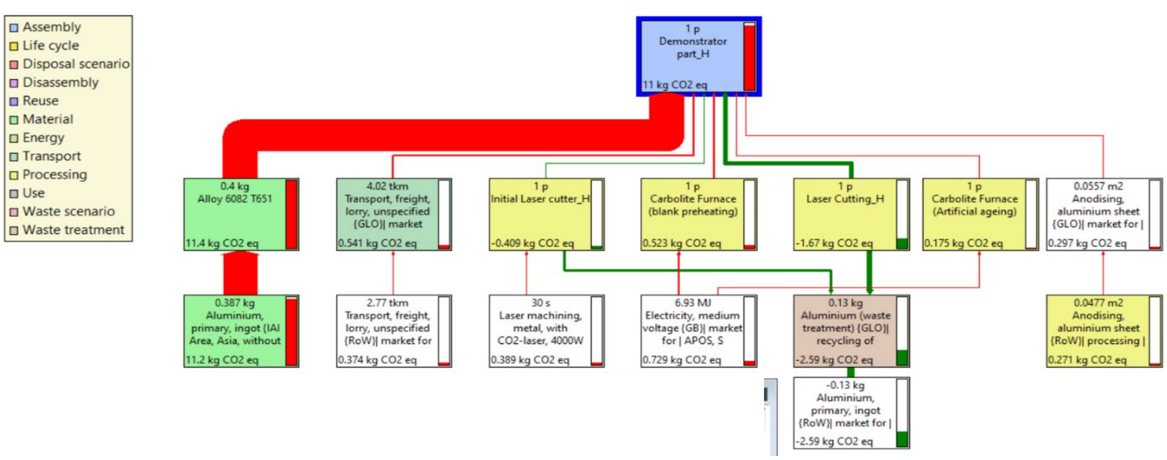

Fig. 5. NETWORK diagram for hot stamping of AA6082-T6.

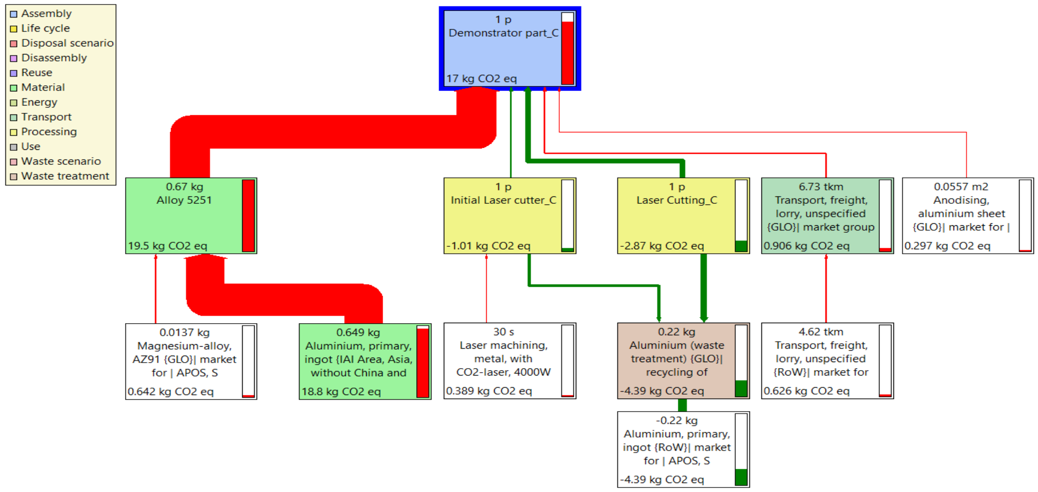

Fig. 6. NETWORK diagram for cold stamping of AA5251-H22.

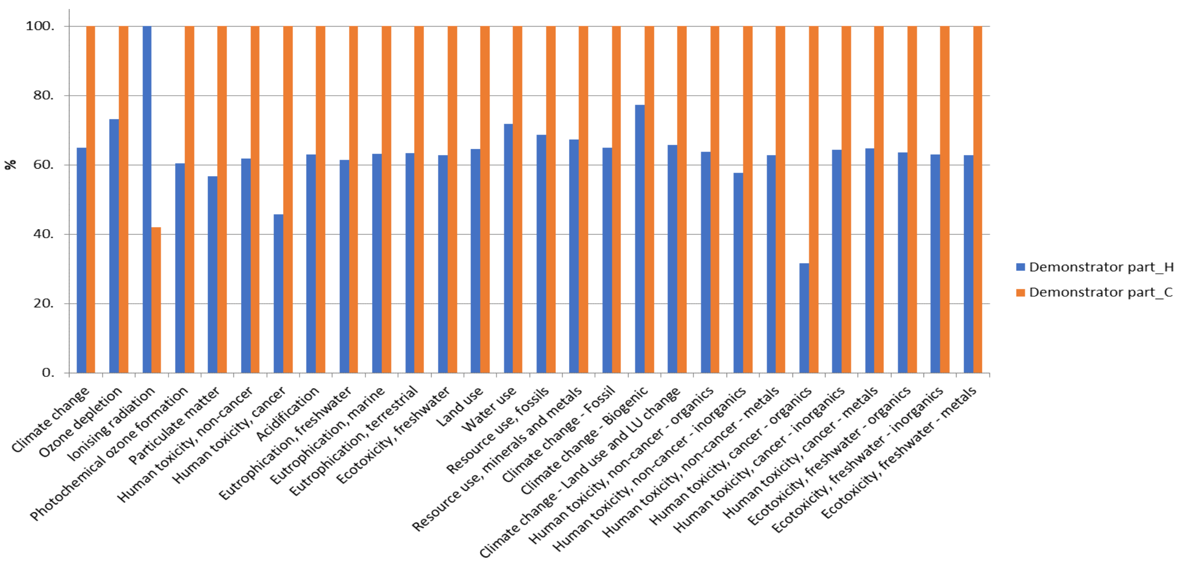

Fig. 7. Impact Assessment Characterisation Hot Stamping Vs Cold Stamping.

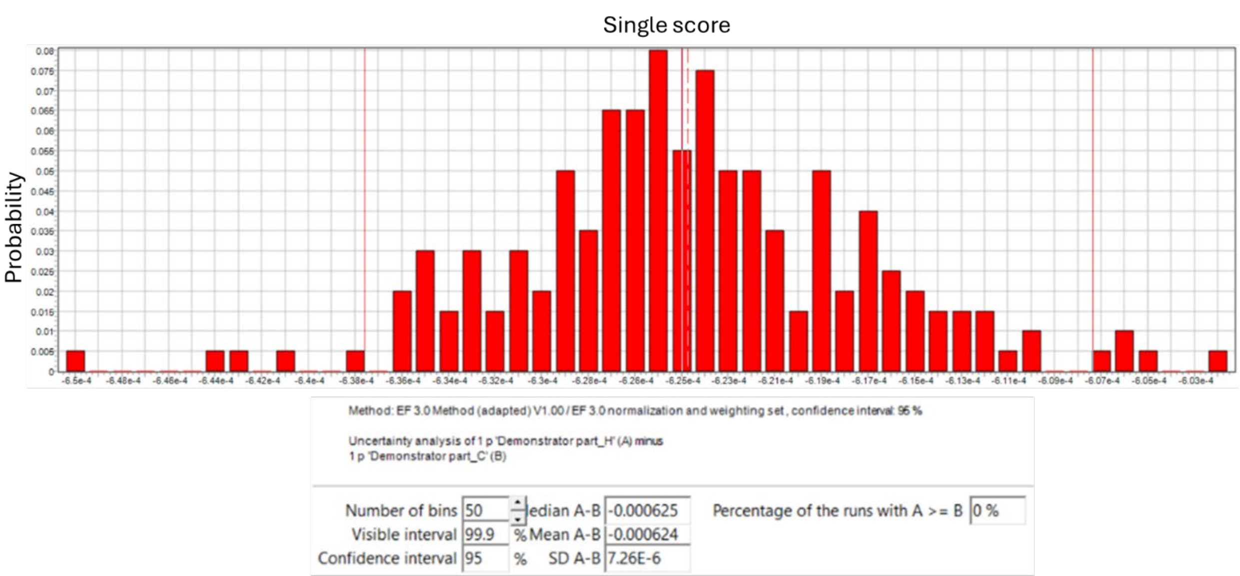

Fig. 8. Uncertainty Analysis.

Conclusions

The conclusions drawn from this 'cradle to gate' LCA study, designed to assess the environmental impacts of hot and cold stamping processes, have successfully met the goals. The study has generated updated insights into both forming processes' environmental strengths and weaknesses. Detailed process mapping and the development of initial LCA modelling has provided a clearer understanding of the environmental inputs and outputs associated with each process.

Moreover, the research has contributed significantly to the existing body of knowledge on the environmental performance of hot and cold forming processes. By conducting an in-depth LCA for each process and comparing the results, the study has highlighted the importance of specific data collection for accurately quantifying their environmental impacts.

Based on the ‘cradle to gate’ LCA, the total emissions for manufacturing the demonstrator part amount to 11 kg CO2 eq. for hot stamping, and 17 kg CO2 eq. for cold forming. It becomes evident that the difference between hot and cold stamping when a similar demonstration part is manufactured is equal to 6 kg CO2 eq. Hot stamping saves up to 35.3% for each manufactured part, compared with cold stamping. The observed difference is primarily attributed to material savings in the hot-formed parts. Specifically, hot forming requires 400g of AA6082-T6 per part, while cold forming necessitates 670g of AA5251-H22 for the same structure and strength, leading to a reduction of 40.3% in material usage for hot forming. The overall environmental savings are noteworthy despite the additional energy demand from furnaces in the hot stamping process. An uncertainty analysis was conducted to validate these results. The findings suggest that hot stamping is environmentally preferable, primarily due to material efficiency and, to a lesser extent, energy use, with the potential impact varying by the energy sources of the manufacturing country. This study underlines the importance of considering both material and energy efficiencies in reducing manufacturing processes' environmental footprint. The potential impact of the energy grid in the manufacturing country on this equilibrium is acknowledged.

Acknowledgement

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