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Is AM always the green manufacturing alternative? A comparative study of carbon footprint

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Abstract

Additive manufacturing is often being hyped as a green alternative to traditional manufacturing of parts, claiming that the reduction in the requirement for raw materials results in a greener footprint. While this may be true, the claims are often unsubstantiated. This paper presents a means to substantiate the claims via a case-study of the carbon dioxide emission, CO_2e, in a comparative analysis of a repair scenario, comparing the CO_2e of (re)manufacturing a worn metal part using DED additive technology compared to the manufacture of a new spare part, using conventional production techniques, such as casting and machining. The resulting CO_2e is observed to be strongly dependent on the choice of alloying elements in the alloy applied in the repair, as well as on the regional origin of the sourcing of materials. The alloy chosen in the AM repair affects the lifetime of the component making apples-to-apples comparisons difficult.

Keywords: Carbon footprint; CO_2e; DED; Remanufacturing;

1. Replace or remanufacture – Which is greener?

Additive manufacturing methods are being heralded as inherently green due to their efficient material usage when compared to traditional subtractive methods. In a society overheating not only from carbon dioxide emissions but also with demand for products and spare parts, additive manufacturing (AM) applied in the remanufacturing of worn components therefore provides a candidate as a means to circumvent materials shortage, while at the same time reducing the environmental impact. In addition, AM allows for tailored properties, as combinations of alloys in the printing process can be chosen to obtain certain properties.

This paper presents a comparative study of the carbon footprint of two methods for replacing a spare part for passenger trains: AM repair vs. conventional 1:1 replacement. The study is based on actual experimental tests of the additive remanufacturing of said parts vs. traditional, formative manufacturing of a new spare part.

The presented results indicate, that one should be vary of “greenwashing” in assuming that additive manufacturing always presents a lesser environmental footprint, and further that comparative analyses can be highly sensitive to their boundary conditions: inflicting even a minor change at any stage in the modelled product lifecycle can tip the carbon balance entirely.

1.1. Conventional replacement vs. AM-based re-manufacturing of train components

The study is based on a replacement of a commercial component-set used in joining train sets of passenger trains, consisting of a pin bolt and bearing bridge.

In the comparison, a worn component set is either replaced by an identical, conventionally produced spare part or remanufactured using an additive method: Directed Energy Deposition. DED allows for a new surface to be applied on any worn area of the component set, restoring or improving the properties of the components.

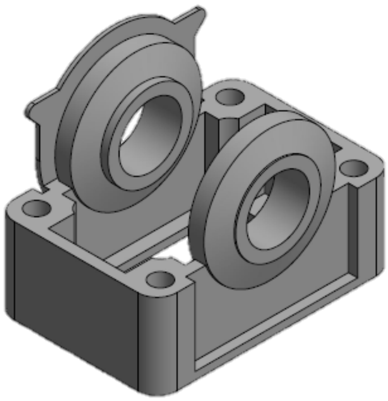

Fig. 1. Simplified CAD-model of the bearing bridge subject to the carbon footprint study (pin bolt not shown).

The study attempts a one-to-one comparison, including all relevant parameters in the carbon footprint associated within the cradle-to-grave lifecycle of the components.

The conventional manufacturing in the present case is based on conventional molding of the component set: 37.54 kg of cast iron. The repair method is based on DED and uses 1.9 kg of Stellite^{TM} SF21 powder to remanufacture only the worn surfaces of the component. Both methods include a series of additional processes and consumables, such as CNC machining, lubricating oils, protective gasses and electricity, all of which are taken into account in the study.

One important deviation from one-to-one comparison is made in the attempt to enhance the properties of the AM-remanufactured component via optimizing the choice of alloy to achieve an improved component lifetime.

Stellite™ 21 alloy is used in the AM repair, to take advantage of the option to enhance the component lifetime. Stellite™ 21 is cobalt-based, which proves to be quite determining for the outcome of the carbon footprint analysis.

Table 1. Stellite™21 composition [1]

Co	Cr	Ni	Fe	Mo	Others
Base	27	2.5	1.5	5.5	C, B, Si, Mn

2. Framework of the comparative study

The framework of the comparative study is to assess the carbon footprint of the components considering the following steps:

- Materials
- Manufacturing
- Transportation
- Packaging
- End-of-life

The total carbon footprint is given in CO_2-equivalents, CO_2e, and the modelling is based on collected and estimated input, modelled using ReCiPe hierachist midpoint methodology with *ecoinvent 3.8* as primary background data.

2.1. Boundary conditions for comparison of the carbon footprint of conventional- vs. additive remanufacturing

The comparative study includes production of a single initial component, plus remanufacturing of one (1) AM repair or production of one (1) conventional replacement spare part component set, and disposal of the component set. The assessment off the conventionally produced component includes the disposal of the worn-out initial component.

Main assumptions:

- Emissions from cradle-to-gate for initial component is based on conventional replacement
- 100 % recycling of metal waste from production and at end-of-life
- Exact same lifetime of AM repair and conventional replacement
- Production of mold is not included in assessment of conventional replacement.

The overall system boundaries are illustrated in fig. 2.

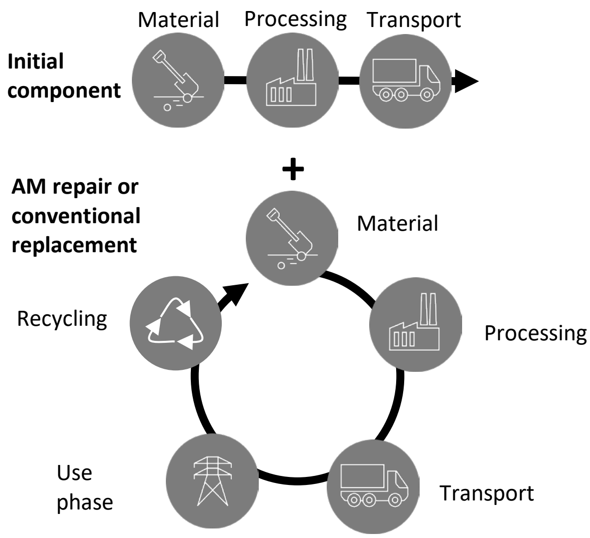

Fig. 2. System boundary of the CO2e assessment: Two stages. 1st, upper: Initial component. 2nd, lower: Replacement component. The second stage can be either conventional 1-to-1 replacement or AM-repair.

The two cases differ only in the repair/replacement stage of their lifecycle in the materials and processing phases:

The analysis takes into account the different origins and the transportation of materials and parts for various sub-routines in the manufacturing process, e.g. mining and machining.

Any CO_2-emissions originating from the use phase are not included in the study, as the components are assumed to be one-to-one comparable with zero direct impact on emissions during use. This implies an assumption, that the AM-repaired component will have the exact same product life-time as the conventional component.

Table 2. Input data for the CO2e comparison

Case	Material	Process	Transport	Use phase	Re-cycling
AM Repair	Stellite SF21	DED	Lorry (913 km)	N/A	100 %
Conventional replacement	Cast iron	Casting	Lorry (1571 km)	N/A	100 %

3. Comparative carbon footprint study – Initial results

Under the above assumptions, the result of the carbon footprint for the AM-remanufactured component set is 134 kg CO_2e, whereas the conventionally manufactured (cast) component set results in a mere 121 kg CO_2e, i.e. at first glance a counter-intuitive green advantage of the conventional replacement of 13 kg CO_2e.

The AM repair is performed in Denmark in relatively proximity to the user of the parts, and the AM powder is sourced from Sweden, resulting in a total distance travelled by the raw materials of 913 km. The conventional replacement components are manufactured in Italy, with a total distance travelled of 1571 km. The total impact of transportation in the analysis is 4.5 kgCO_2e for the AM remanufactured components.

The AM repair uses a mere 1.9 kg of Stellite 21 for the repair process, compared to the 37.5 kg of cast iron required for the conventional component. The AM-process uses Stellite 21 powder, which contains 62 % Co, an alloying element which is very CO_2-intensive in terms of mining and production at 30.6 kgCO_2e/kg compared to a mere 2.8 kgCO_2e/kg for the iron used in casting. Consequently, the choice of material significantly impacts the carbon footprint study.

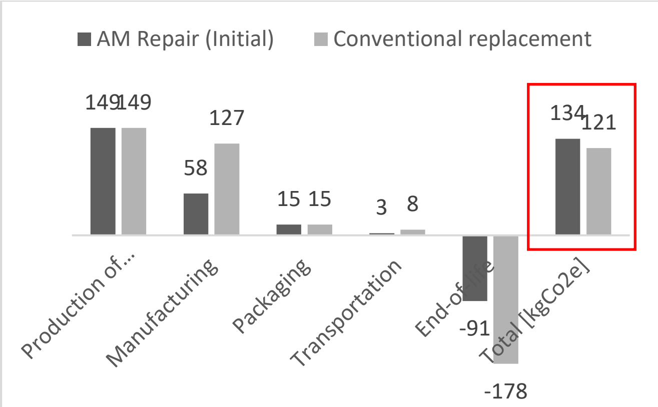

Fig. 3. Initial results of the comparative study of CO_2e: The conventional replacement emits 13 kgCO_2e less than the AM-repair.

4. Sensitivity of the analysis

The main drivers for the observed difference in CO_2e are the lifecycle stages: manufacturing, transportation and particularly end-of-life, where the conventional method cashes in on two recycled parts rather than the one remanufactured part of the AM-approach. In addition, the choice of a CO_2e-intense cobalt-based alloy for the AM-repair, significantly impacts the results of the analysis.

Assessing the impact of a change in the boundary conditions of either of the significant stages in the component lifecycle may thus be relevant.

4.1. Assessing the impact of a lack of recycling

The initial results of the study assumes 100 % recovery of all raw materials at end-of-life, and thus their carbon footprint is subtracted from the final carbon footprint when recycled.

In a real world, not all components are recycled. Assuming that all components are scrapped but not recycled, results in the AM remanufactured component set emitting 74 kgCO_2e less than the conventional part.

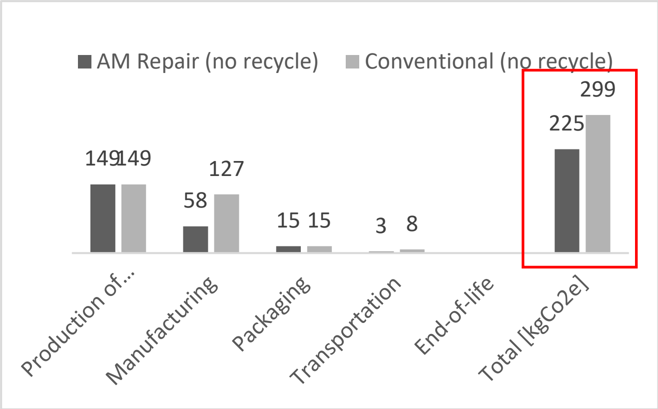

Fig. 4. Assuming no recycling at the end-of-life results in 74 $kgCO_2e$ less for the AM remanufactured component set.

4.2. Assessing the impact of mining (Cobalt)

The initial analysis indicated a 13 $kgCO_2e$ advantage to the conventional replacement. A result significantly impacted by the relatively high carbon-impact of the AM-powder, mainly originating from the emissions associated with the mining of Co, of which the Stellite^{TM} 21 contains roughly 62 %. The average emission factor for cobalt is app. 42 $kgCO_2e/kg$, which has been applied in the initial study.

According to [3] mining of Cobalt can be performed with much lower resulting carbon emissions at 11.73 $kgCO_2e/kg$.

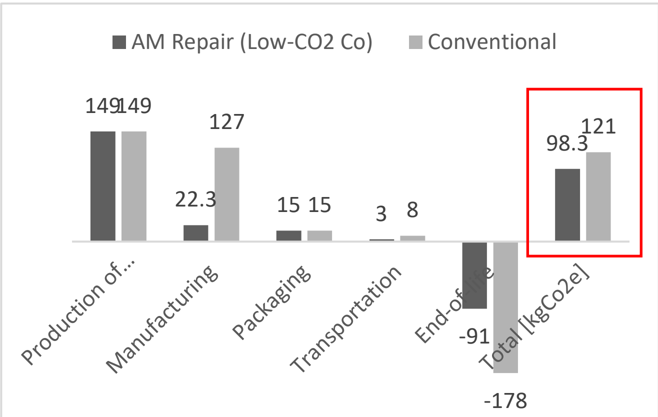

Fig. 5. Assuming "least-impact cobalt (Co) mining results in 23 less $kgCO_2e$ for the AM remanufacturing.

4.3. Assessing the impact of AM enhancing the lifetime

It is obvious from the above, that the choice of alloy for remanufacturing may significantly impact the carbon footprint. In the present case, a Co-based alloy was chosen for the remanufacturing process, in order to increase the service lifetime of the remanufactured component.

No data is available for the service life of the component in question before or after the repair process. If it can be assumed, that the lifetime of the AM-remanufactured component set is doubled in comparison to a conventional component set, the resulting CO_2e for the AM-remanufactured part is 134 $kgCO_2e$, whereas the conventional replacement would now require a total of three parts to achieve the same, total service life, leading to a carbon footprint of app. 182 $kgCO_2e$.

In the assumed case of the AM-remanufacturing being able to double the component service life, this leads to 48 $kgCO_2e$ less for an AM-remanufactured component set.

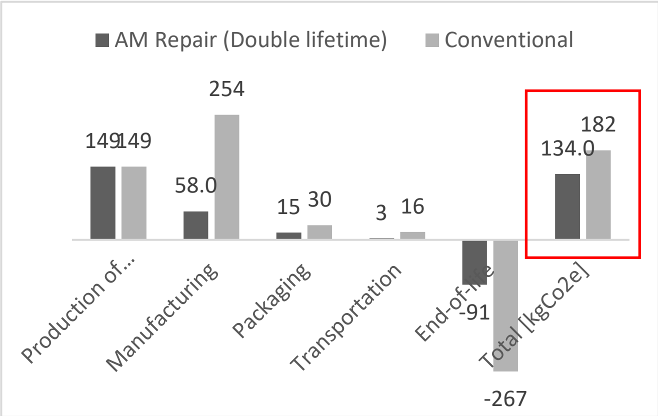

Fig. 6. Assuming the AM-remanufactured component set has double the lifetime of a conventional component set results in app. 48 less $kgCO_2e$ for the AM remanufacturing.

Table 3. Summary of Carbon footprints [$kgCO_2e$]

Comparison	Initial result	No recycling	Low-impact Co	2 x service-life
AM-repair	134	225	98	134
Conventional	121	299	121	182
AM vs. Conventional	+11 %	-25 %	-19 %	-26 %

The sensitivity of the comparative carbon footprint study is outlined in Table 3, indicating results ranging from 26 % advantage in CO2e for AM-remanufacturing to an 11 % disadvantage in terms of CO_2e.

This implies, that intricate knowledge of all phases of the product lifecycle are required, in order to be able to present a fair base for comparison of the repair- or replace-scenarios from a carbon footprint perspective.

5. Conclusions

A comparative study of the carbon footprint of AM-remanufacturing vs. conventional replacement of a component set for a passenger train is performed, cradle-to-grave. The initial conclusions of the comparative study indicates an advantage in terms of carbon footprint to the conventional replacement, resulting in 13 $kgCO_2e$ less for the conventional replacement (11 %).

The analysis proves to be highly sensitive to potential, realistic changes to the boundary conditions at several stages of the component life cycle, such as the origin of certain alloying elements (Co) in the AM powder, the resulting service lifetime of the repaired component set, and whether or not the components are recycled correctly.

A few select scenarios are presented, reversing the carbon footprint balance in favor of the additive remanufacturing, with an advantage to AM of up to 26 % in terms of CO_2e in the most favorable scenario.

6. Acknowledgements

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