Results from three comparative carbon footprint studies (AM vs. conventional)

Presented: Wednesday the 10th of February 2021

Corrected: Monday the 14th of March 2021

Dansk AM Hub

Project summary | Comparative carbon footprint assessment of three manufacturing cases

Purpose

The project aims to motivate Nordic manufacturing companies to using Additive Manufacturing (AM) as a tool in the green transition.

The goal of the project is to investigate **if** and **how** AM can be a tool to reduce the carbon footprint of products compared to conventional production methods.

This was done by assessing three manufacturing cases identified together with knowledge partners of Danish AM Hub.

The project originally set out to conduct comparative LCAs, but due to lacking data availability, this was changed to high-level carbon footprint assessments.

Methodology

Scope: The project has assessed the carbon footprint of components from cradle-to-grave, considering following steps of the life cycle from: (1) materials, (2) manufacturing, (3) transportation, (4) packaging, and (5) end-of-life. Use phase has been excluded from the scope as none of the components have direct energy consumption in use. However, the scope can in future be expanded to include indirect energy consumption as all components are installed on transportation means.

Included greenhouse gases (GHGs): The total carbon footprint is given in CO_2-equivalents and the different GHGs are weighted according to the GWP100 standard.

Data sources: Knowledge partners of Dansk AM Hub have together with case companies collected and estimated input data. The assessment is modelled using the ReCiPe hierarchist midpoint methodology with ecoinvent v.3.8 as primary background data.

Accounting approach: The consequential approach has been applied as results are to be used for guiding future decision-making of manufacturing companies in applying AM. Here, the system is expanded to estimate how climate change is affected by choice of production method – hence, the consequences of a decision.

Outcome

It has not been possible to identify three cases, where data exists for both an AM produced component and an exact comparable conventionally produced, and so hypotheses of the conventional components have been made. Furthermore, lack of data availability has left results with various degrees of uncertainty.
Of the selected three cases, one shows a lower carbon footprint of component in AM compared conventional production without high uncertainty.
Thus, AM will not necessarily result in a lower carbon footprint when compared to conventional production. However, in certain cases, it can be utilized as a tool to reduce carbon footprint compared to conventional production methods.

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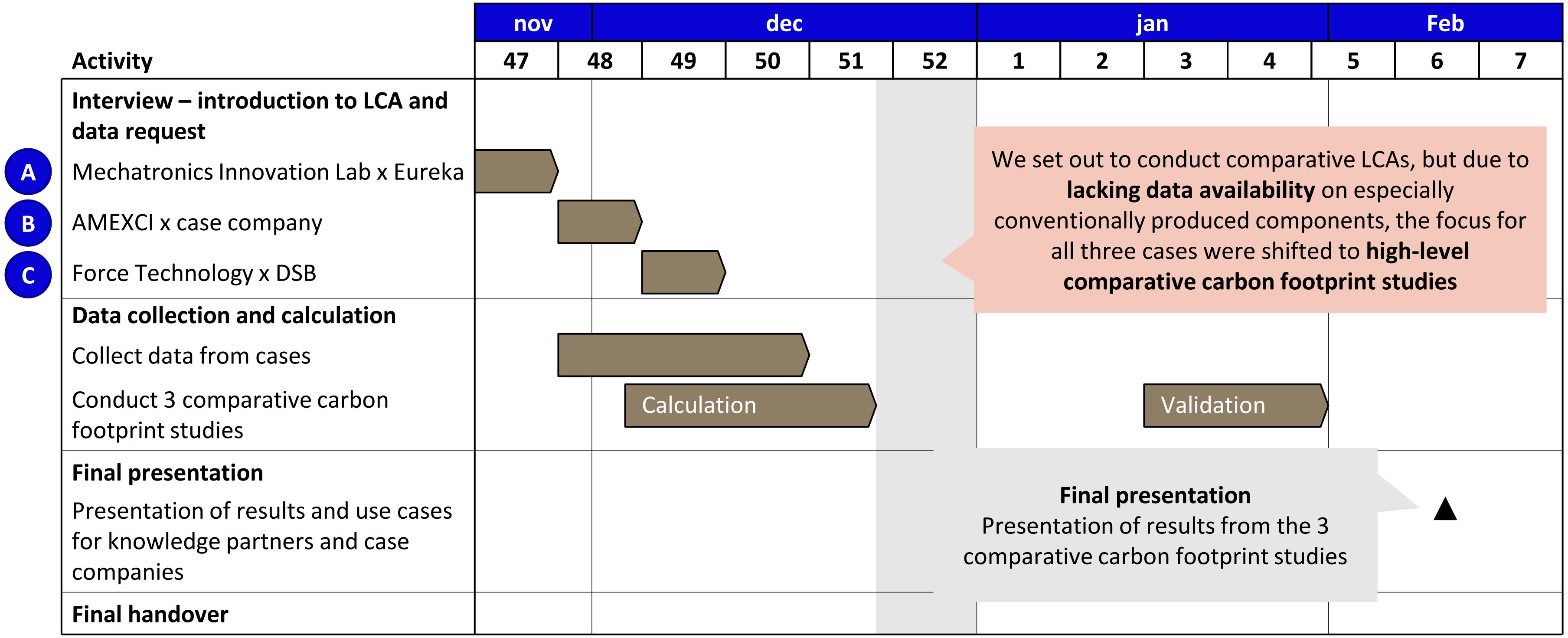
The project has been run in close engagement with knowledge partners and case companies



Expected project outcome

- Insights to **why** and **how** to use Life Cycle Assessments (LCAs)
- The **carbon footprint** of the components selected for the project
- Likely, a quantification of the **avoided CO_2e of using AM technology** across three cases
- An overview of **hotspots** to focus further reduction efforts

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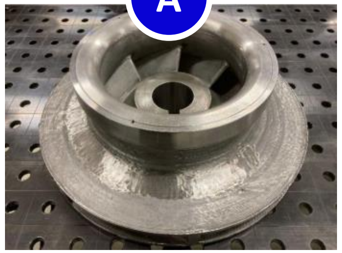
The project has assessed the carbon footprint on a total of 6 components **across 3 studies**

Overview of the three manufacturing cases being assessed

A



B

C

	A	B	C
Component description	*Impeller for ballast water pump installed on vessels*	*Bracket holding sensor for trucks driving long-haul distances*	*Pin bolts and bearings to connect trainsets*
Knowledge partner	MIL Mechatronics Innovation Lab	AMEXCI	FORCE TECHNOLOGY
Case company	EUREKA	*Confidential*	DSB

The carbon footprint studies quantify CO_2e-emissions in a **lifecycle perspective**

Overview of lifecycle stages from cradle-to-grave

NOT EXHAUSTIVE

Included in scope *Not included in scope*

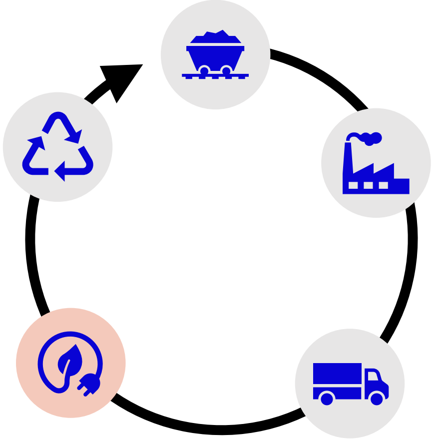
Raw material extraction
Materials have different carbon footprint – also dependent on source of origin.

Manufacturing and processing
This stage includes energy consumption and waste. Some processes are more energy-intensive than others

Transportation and distribution
Distance, weight and by what means of transport influences emissions in this stage

Use
Electricity and water consumption from using product

End-of-life
Products can be disposed at landfills, be incinerated, recycled, etc.



As all three components being assessed is installed on transportation means, they will all have an indirect energy consumption during use from the end-product. This will be the same for AM and conventional if the component has the exact same design and weight. If AM enables lightweight design, this phase will be important to include in the future. However, the scope of this study is focused on the production and disposal of the components.

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Emissions are calculated using the global database **ecoinvent** to find emission factors

Overview of calculation method applied in assessments

Quantity of emitting activity

(e.g. 1000 kg iron, 3000 kWh electricity in DK)

×

CO_2e

Emission factor

(e.g. 24 kgCO_2e/kg iron, 0,101 kgCO_2e/kWh in DK)

=

CO_2e emissions per activity

About ecoinvent

- Paid database
- Updated annually
- Life cycle inventory database, containing environmental assessment of products, materials and processes

Source: https://ecoinvent.org/

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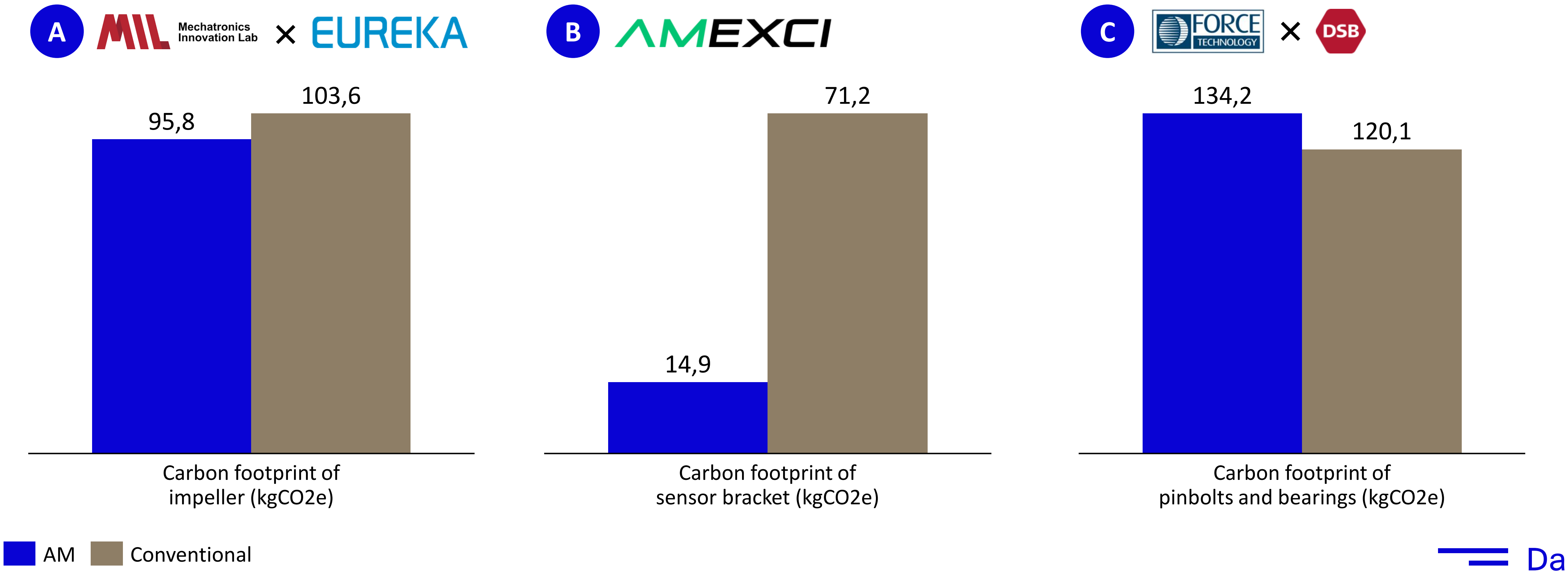
Of the **3 analysed cases**, 1 has a **lower** carbon footprint of AM compared to conventional

Overview of results cross the three comparative carbon footprint studies[1]



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Source: Analysis by The Footprint Firm.

Note: 1) Case study A and B show a lower carbon footprint of AM compared to conventional manufacturing, but only case study B shows a lower carbon footprint without high uncertainty.

A Case overview | The component assessed is an **impeller** for a ballast water pump

NOT EXHAUSTIVE

Overview of AM- and conventionally produced component being assessed

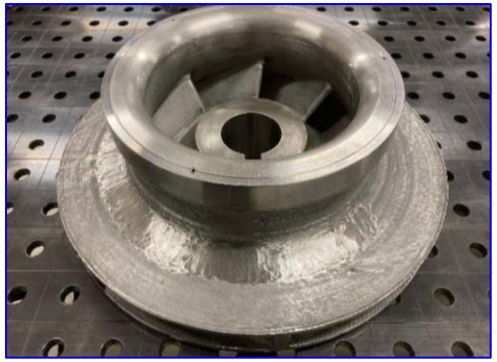
MIL Mechatronics Innovation Lab × EUREKA

Description of component:
The impeller is a component within a ballast water pump to support pumping of 200 m^3 water per hour for 24 hours/a day for 10 years

Description of comparative analysis:
Each carbon footprint assessment includes production and disposal of 1 impeller

Main assumptions:

- Exact same design compared for AM- and conventionally produced component
- Exact same material composition of the stainless steel
- Exact same lifetime of 10 years for 1 component
- Impeller is produced as part of a modification project, thus, mould is assumed applied 2 times in casting



	AM	Conventional
Raw material extraction	Duplex stainless steel powder	Duplex stainless steel
Manufacturing and processing	LMD[1]	Casting
Transportation	Lorry truck	Lorry truck
Use	Not included	
End-of-life	Global split assumed (15% landfill, 85% recycling[2])	

Included in scope *Not included in scope*

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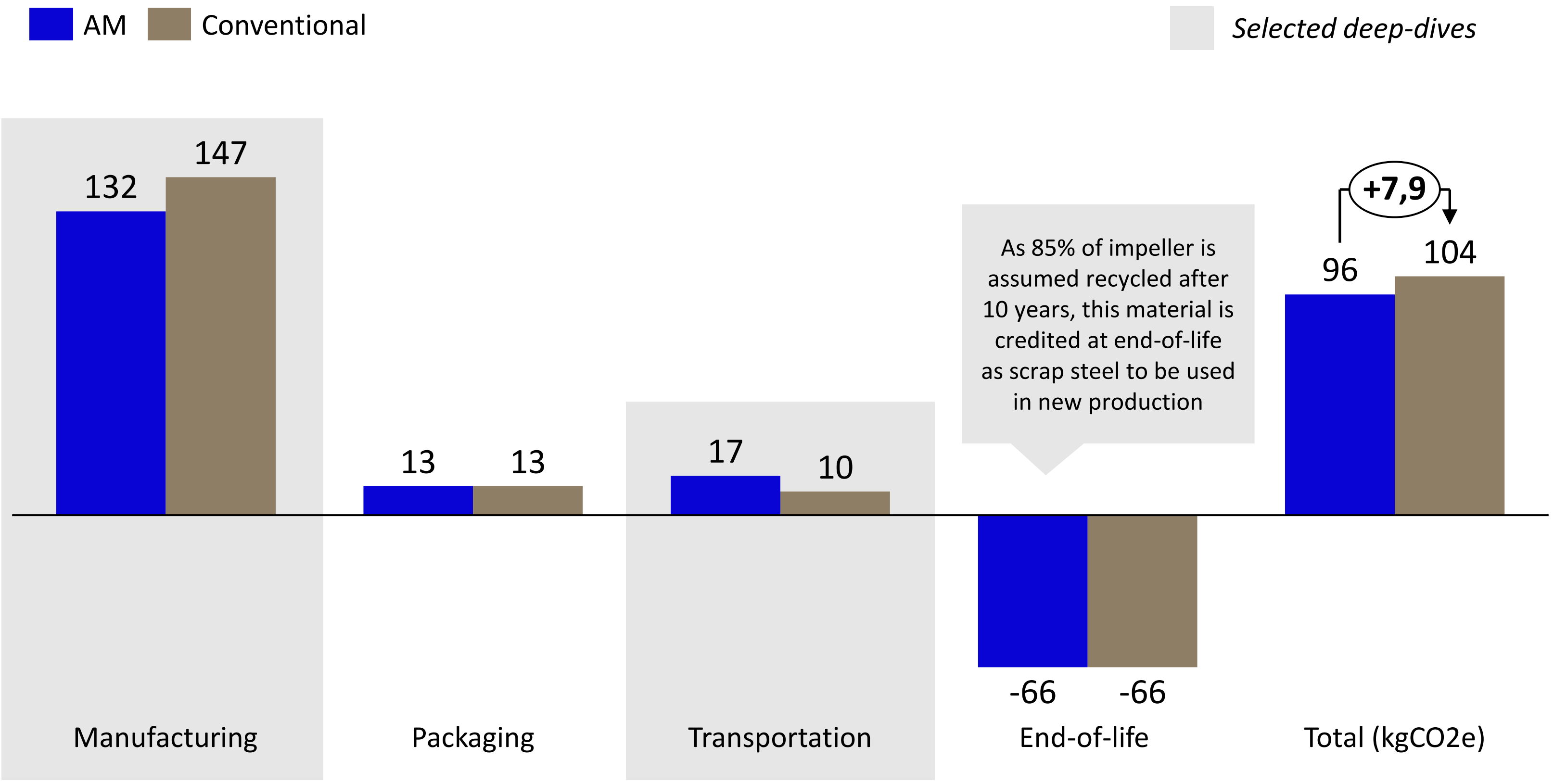
Note: 1) Laser Metal Deposition
Source: 2) Comprehensive Multilevel Cycle of Stainless Steel (Barbara Reck); ISSF - The Global Life Cycle of Stainless Steels.

A Results | The AM-produced impeller emits **7,9 $kgCO_2e$ less** than conventionally produced

Comparative carbon footprint of AM- and conventionally produced component

Mechatronics Innovation Lab × EUREKA



Key take-aways

- AM-produced impeller has a carbon footprint of **95,8 $kgCO_2e$** from cradle-to-grave (excl. use phase)
- AM-produced impeller have lower carbon footprint when compared to the conventionally produced component
- The main difference lies in the **manufacturing** lifecycle stage, but also in transportation life cycle stage

Source: Analysis by The Footprint Firm.

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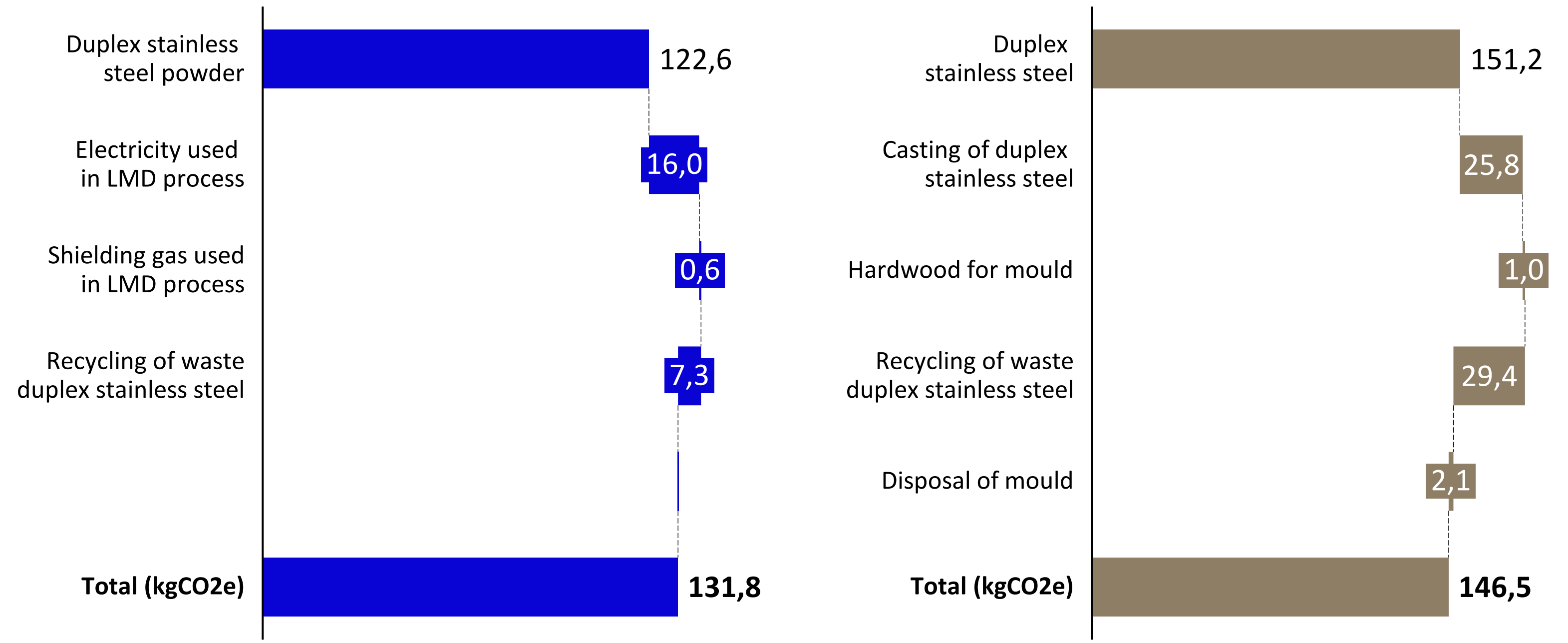
A Deep dive | **Less material use** in AM-produced impeller results in lower carbon footprint

Carbon footprint of manufacturing activities in AM- and conventionally produced component

MIL Mechatronics Innovation Lab × EUREKA

AM | **Conventional**



Key take-aways

- Overall, AM emits 14,7 kgCO_2e less than conventional manufacturing activities
- Material use in conventional is **9 kg higher**[1] than AM leading to more CO_2e emissions
- Duplex stainless steel powder emits more per kg due to **additional atomization process** of powder manufacturing
- LMD process emits **8,1 kgCO_2e** less than casting process

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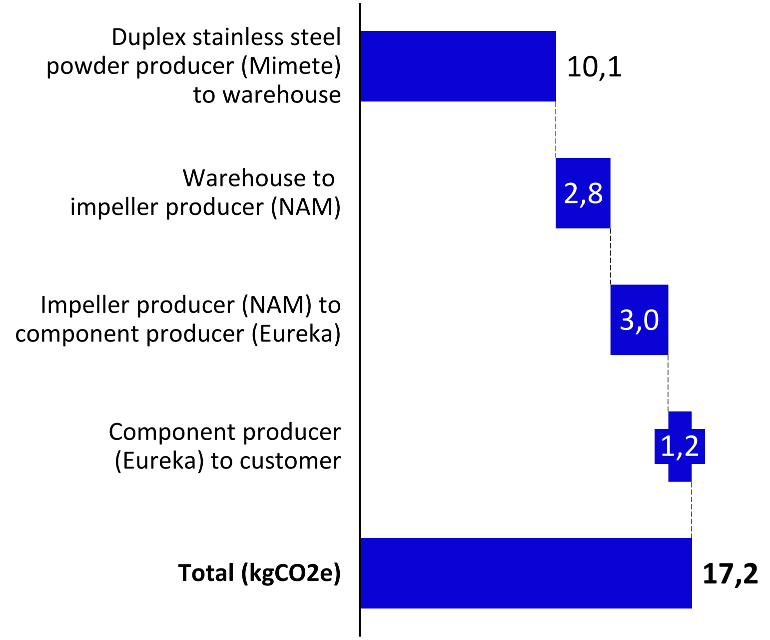
Note: 1) Assumption of total material use in conventional manufacturing of 45 kg by Eureka compared to use of 36 kg for AM manufacturing.
Source: Analysis by The Footprint Firm.

A Deep dive | **Longer distance** in AM-produced impeller results in higher carbon footprint

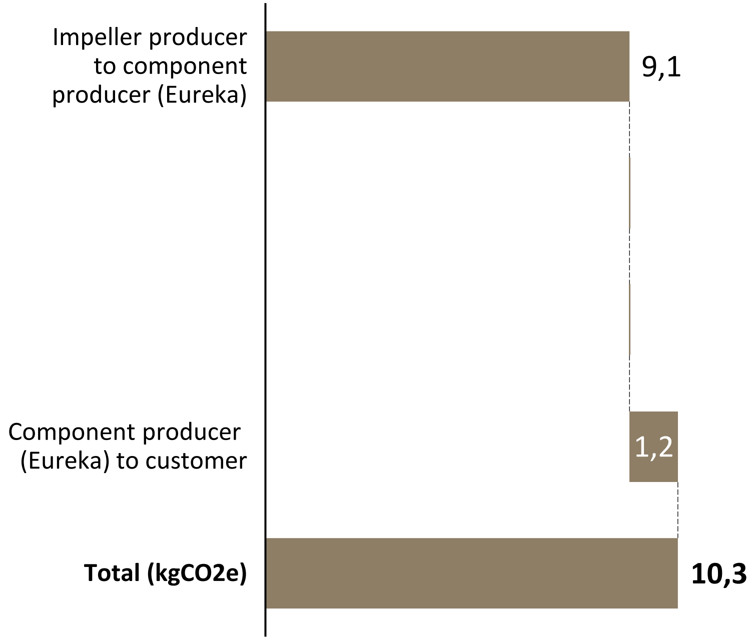
Carbon footprint of transportation activities in AM- and conventionally produced component

Mechatronics Innovation Lab × EUREKA

AM



Conventional



Key take-aways

- Higher carbon footprint of distribution lies in **additional transportation of AM powder** to a warehouse in Sweden before reaching impeller producer
- Producer of conventional impeller is **assumed** to be located near sourcing of materials[1], why freight distance is shorter and thus emits less

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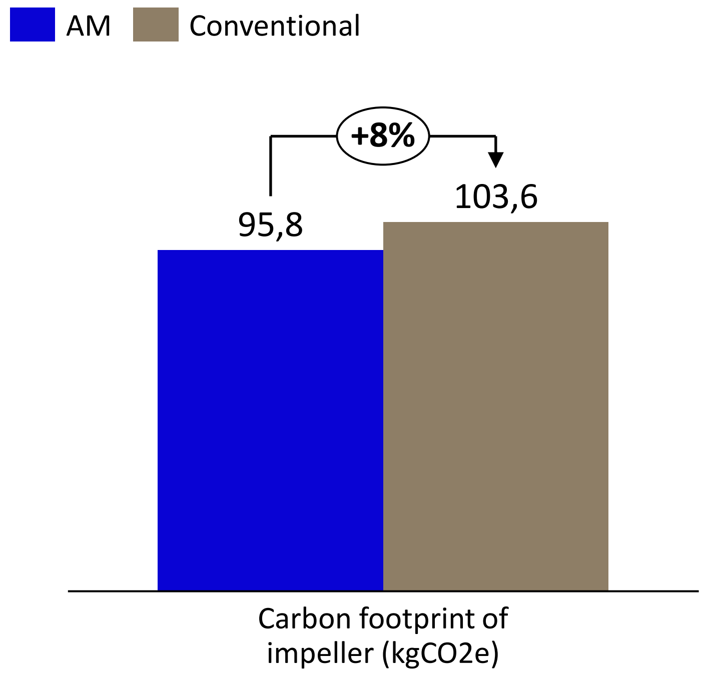
Note: 1) Material is assumed to be locally sourced by Eureka and thus transportation of this is not included.
Source: Analysis by The Footprint Firm.

A Scenario analysis | If AM design could enable a material reduction compared conventional design

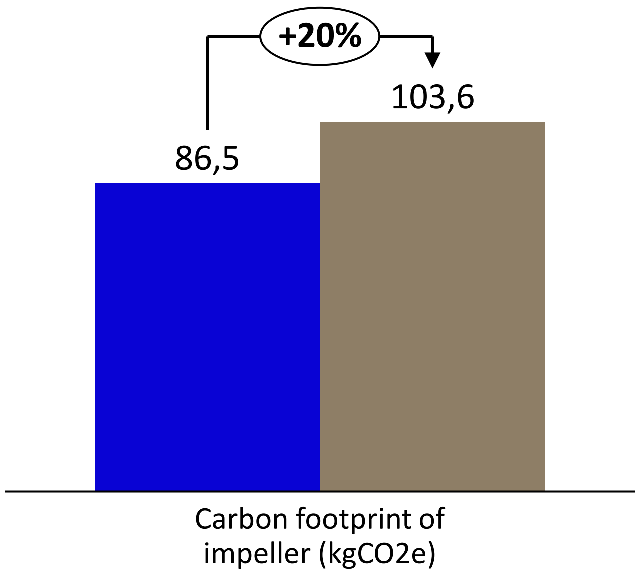
Scenario analysis of comparative carbon footprint study

Mechatronics Innovation Lab × EUREKA

Original results (36 kg duplex stainless steel powder)



Alternative results (~31 kg duplex stainless steel powder)



Scenario analysis

- The original study assumed exact same design of AM- and conventionally produced component
- In this scenario analysis, AM-design has assumed to enable reduced material used for impeller with 15% to **31,05 kg** through complex design shapes
- Waste in production, electricity and shielding gas consumption has not been changed
- 15% less material **reduces carbon footprint** of AM-produced impeller **with 9,3 kgCO_2e** compared to the complex design-optimized

Source: Analysis by The Footprint Firm.

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B Case overview | The component assessed is a **sensor bracket** used on trucks

NOT EXHAUSTIVE

Overview of AM- and conventionally produced component being assessed

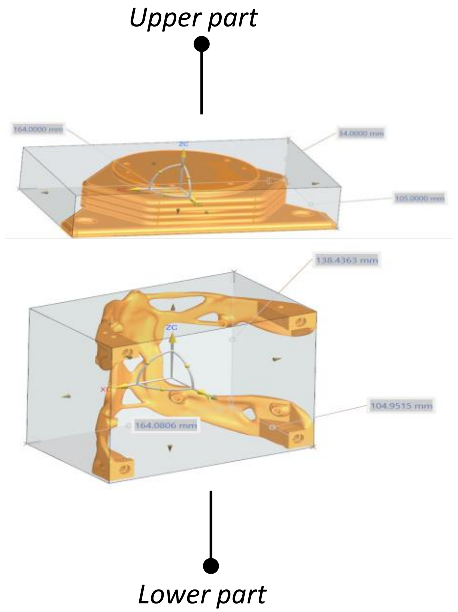
AMEXCI

Description of component:
The bracket will be holding a sensor to be installed on a truck driving long-haul distances

Description of comparative analysis:
Each carbon footprint assessment will include production and disposal of 1 sensor bracket consisting of 1 lower part and 1 upper part

Main assumptions:

- The design of the conventionally produced sensor bracket will have 40% more material on the upper part due to non-AM design
- Exact same material composition of the AlSi10Mg material
- Exact same lifetime of 20 years for 1 component



	AM	Conventional
Raw material extraction	AlSi10Mg powder	AlSi10Mg block
Manufacturing and processing	SLM[1]	CNC machining
Transportation	Lorry truck	Lorry truck
Use	Not included	
End-of-life	Global split assumed (24% landfill, 76% recycling[2])	

Included in scope *Not included in scope*

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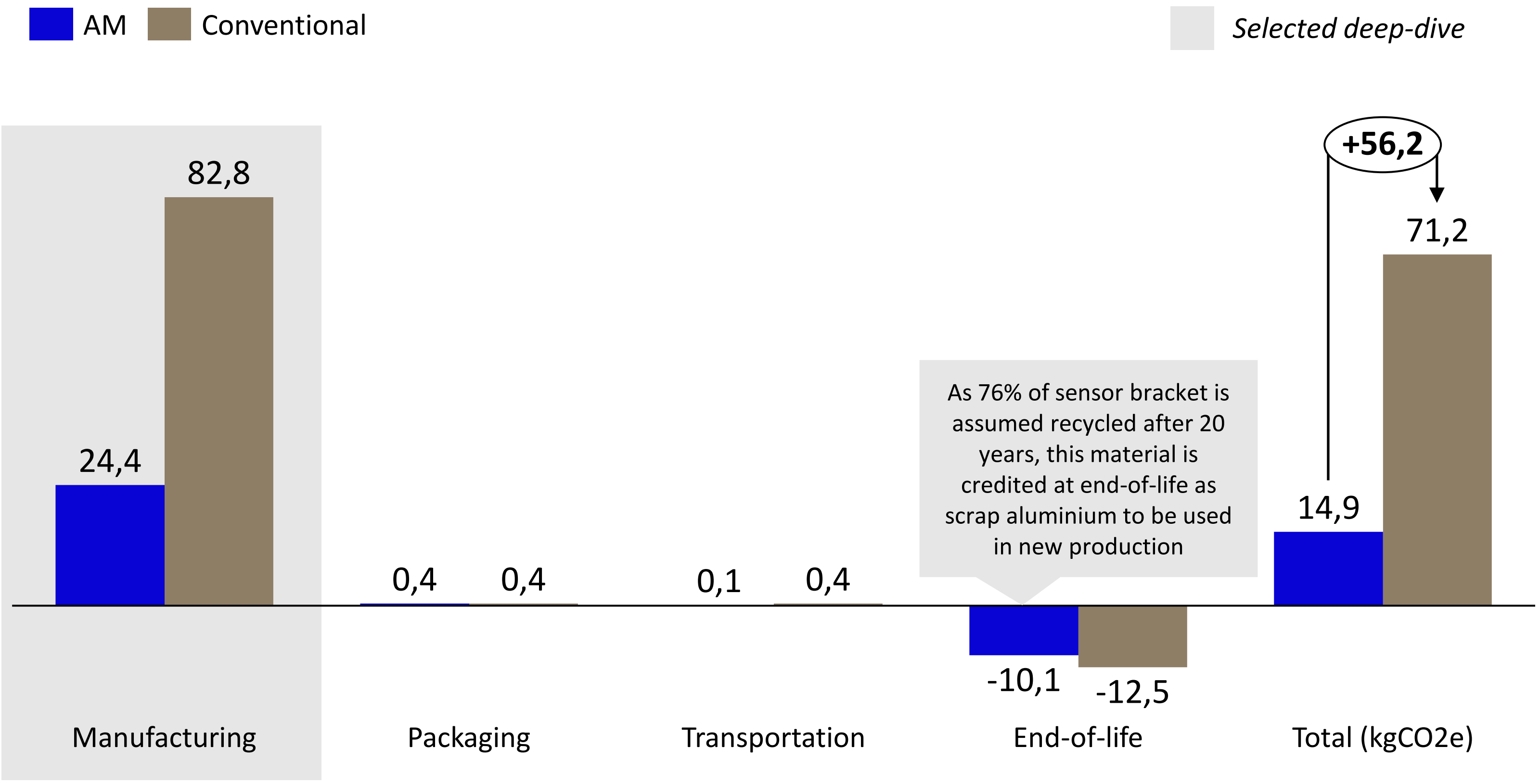
Note: 1) Selective Laser Melting
Source: 2) Aluminium Recycling; The International Aluminium Institute.

B Results | The AM-produced sensor bracket emits **56,2 kg CO_2e less** than conventionally produced

Comparative carbon footprint of AM- and conventionally produced component

AMEXCI



Key take-aways

- AM-produced sensor bracket has a carbon footprint of **14,9 kgCO_2e** from cradle-to-grave (excl. use phase)
- AM-produced sensor bracket have lower carbon footprint when compared to a conventionally produced component
- The largest difference between the two is found in the life cycle stage **manufacturing**, due to large difference in amount of used materials

Source: Analysis by The Footprint Firm.

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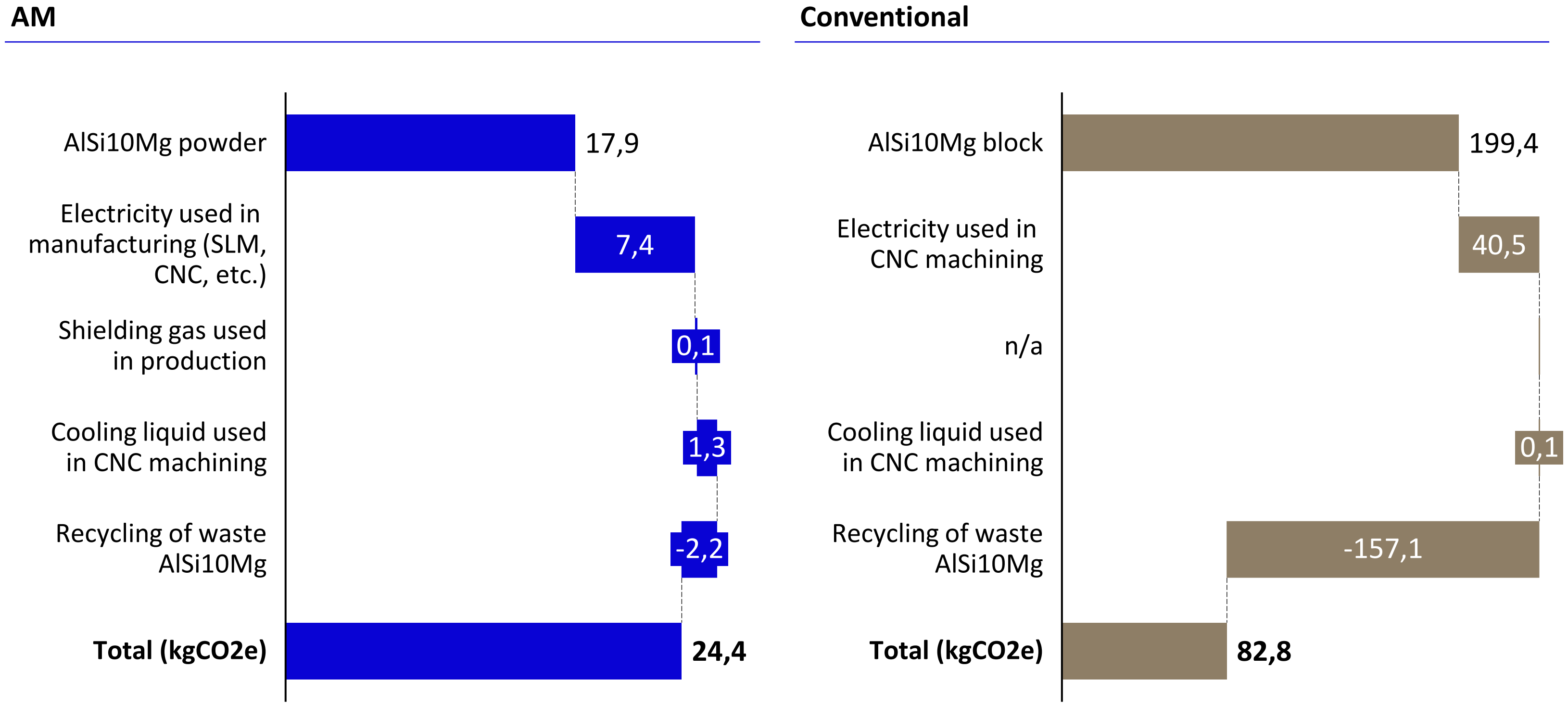
B Deep dive | **Less material use** in AM-produced sensor bracket results in lower carbon footprint

Carbon footprint of manufacturing activities in AM- and conventionally produced component

AMEXCI



Key take-aways

- Only 0,96 kg AlSi10Mg is used in AM-production compared to 10,9 kg in conventional, why the use of material emits **26,6 kgCO_2e less in AM** (incl. recycling crediting)
- Due to less material, AM-production require less CNC machining leading to decreased consumption of electricity – emitting **33,1 kgCO_2e less in AM**
- Use of AlSi10Mg is most CO_2e-intensive activity in both AM and conventional production

Source: Analysis by The Footprint Firm.

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C Case overview | The component assessed is **pin bolts and bearings** used in trains

NOT EXHAUSTIVE

FORCE TECHNOLOGY × DSB

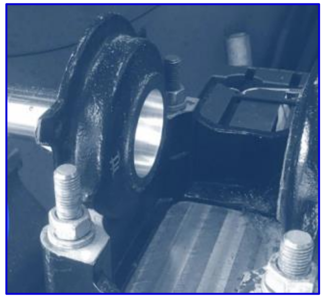
Overview of AM- and conventionally produced component being assessed

Description of component:
1 set of bearing and pin bolt. The bearings and pin bolts are used on DSB's IC3 trains for connecting trainsets

Description of comparative analysis:
The carbon footprint assessment will include production of initial component, production of 1 AM repair or 1 conventional replacement, and disposal of component. Assessment of conventionally-produced replacement will include 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 both metal waste from production and the component at end-of-life
- Exact same lifetime of AM repair and conventional replacement
- Production of mould is not included in assessment of conventional replacement



	AM	Conventional
Raw material extraction	Stellite SF21	Iron
Manufacturing and processing	DED[1]	Casting
Transportation	Lorry truck	Lorry truck
Use	Not included	
End-of-life	Recycling of iron	Recycling of iron

Included in scope *Not included in scope*

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Note: 1) Directed energy deposition

C Case overview | The carbon footprint assessment includes initial component produced for both studies

System boundary of AM- and conventionally produced component

FORCE TECHNOLOGY × DSB

AM

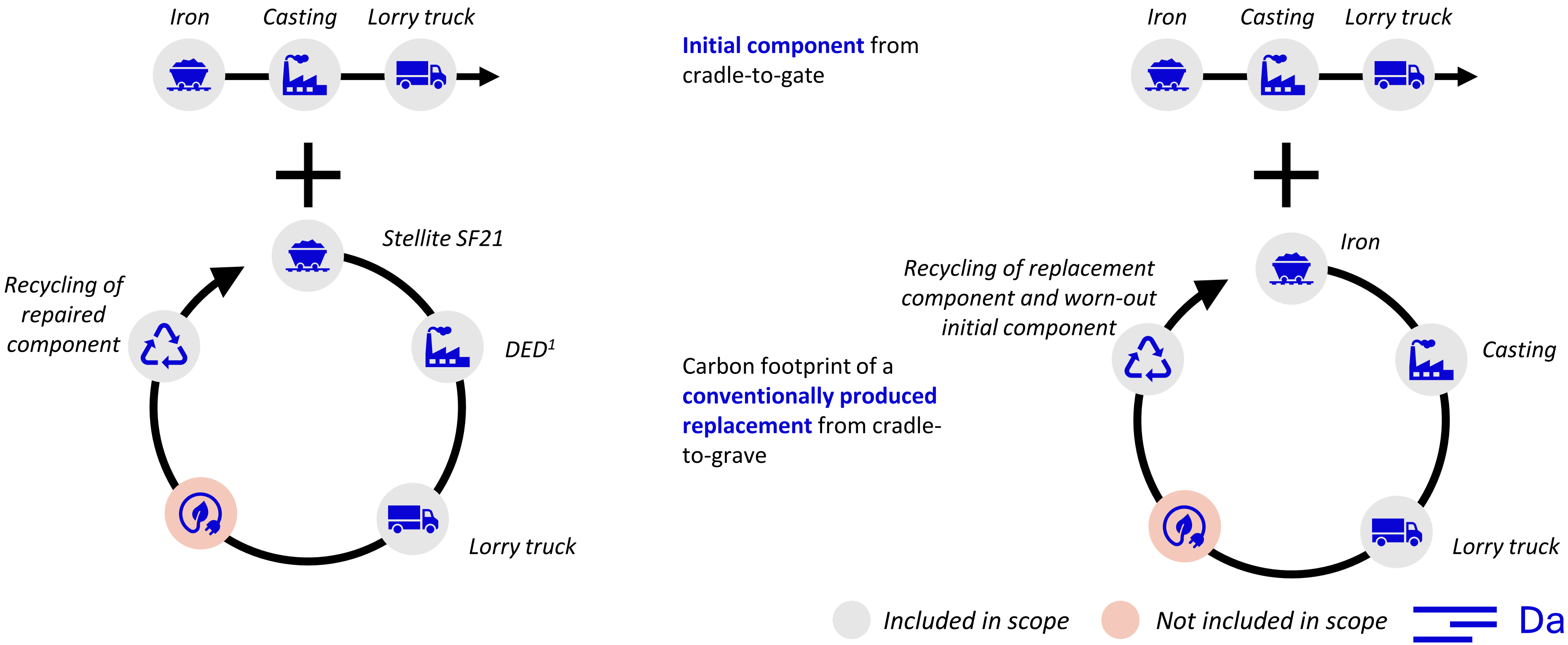
Initial component from cradle-to-gate

Carbon footprint of AM produced repair of initial component from cradle-to-grave

Conventional

Initial component from cradle-to-gate

Carbon footprint of a **conventionally produced replacement** from cradle-to-grave



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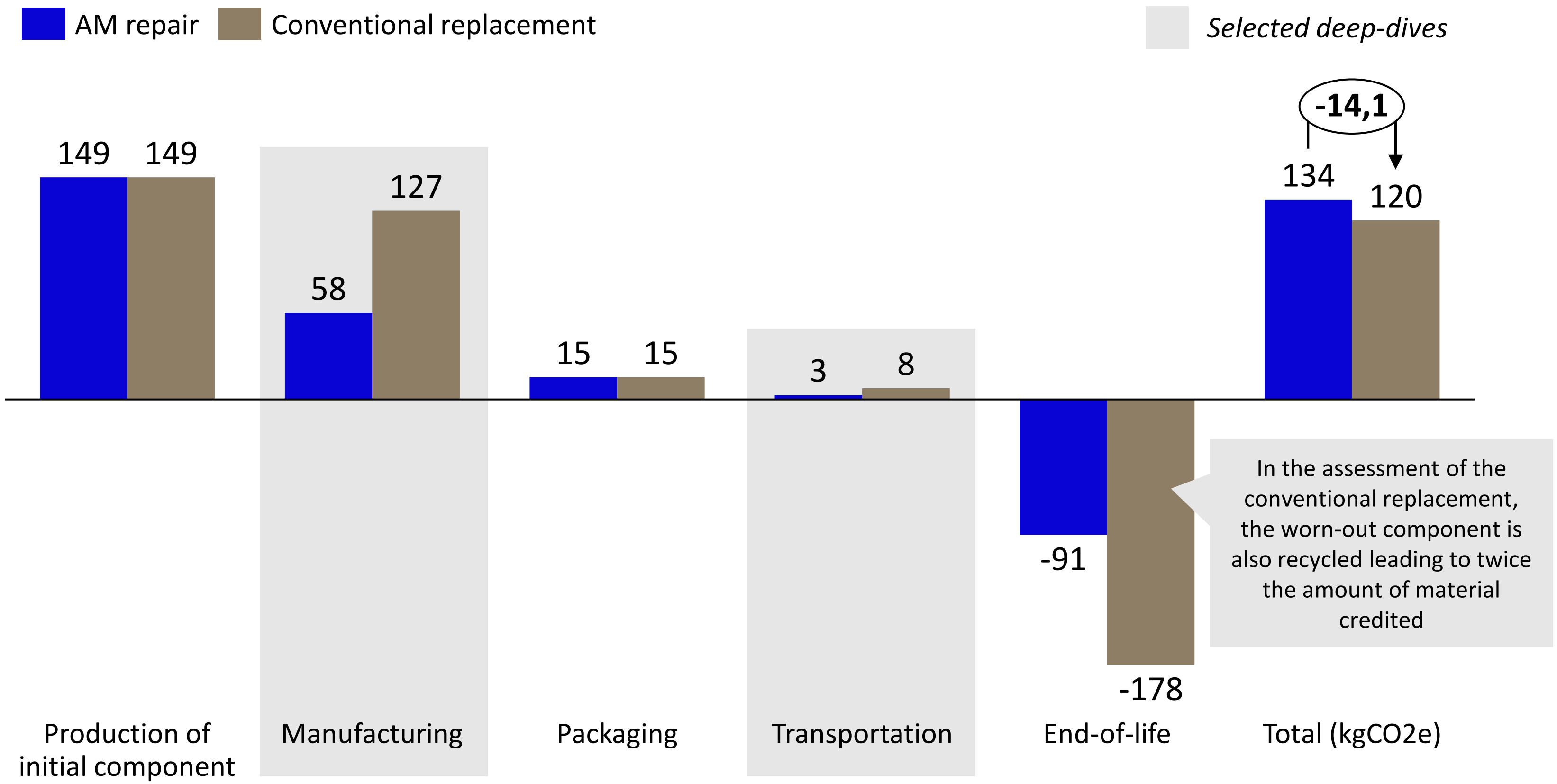
Note: 1) Directed energy deposition

C Results | The AM repaired pin bolts and bearings emits **14,1 kg CO_2e more** than replacement

Comparative carbon footprint of AM- and conventionally produced component



Key take-aways

- The **AM repair** from cradle-to-grave including production of initial component has a carbon footprint of **134 kgCO_2e**
- The **conventional replacement emits 14,1 kg CO_2e** (11%) **less** than the AM repair
- The lifecycle stages manufacturing, transportation and end-of-life drives this difference

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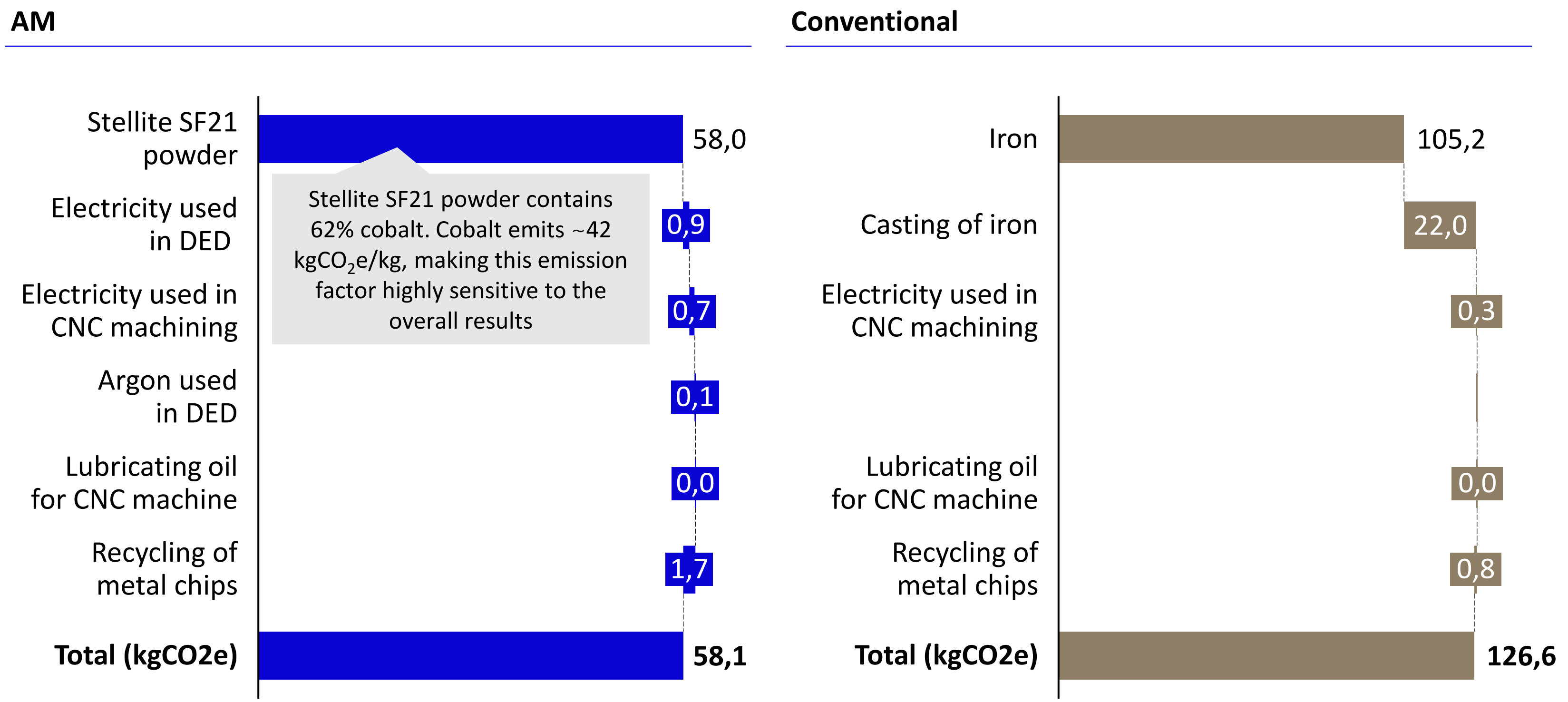
C Results | High CO_2e-intensity of AM material contributes to relatively high carbon footprint

Carbon footprint of manufacturing activities in AM- and conventionally produced component

FORCE TECHNOLOGY × DSB



Key take-aways

- The AM repair use 1,9 kg material compared to the 37,54 kg needed to replace through conventional production method (i.e. ~**20 times more material** is used for a **replacement)**
- However, emissions derived solely from the **AM powder** is only **half** of the iron for casting
- This is driven by the CO_2e-intensity of **Stellite SF21 powder** of **30,6 kgCO_2e/kg**, while iron has CO_2e-intensity of 2,8 kgCO_2e/kg

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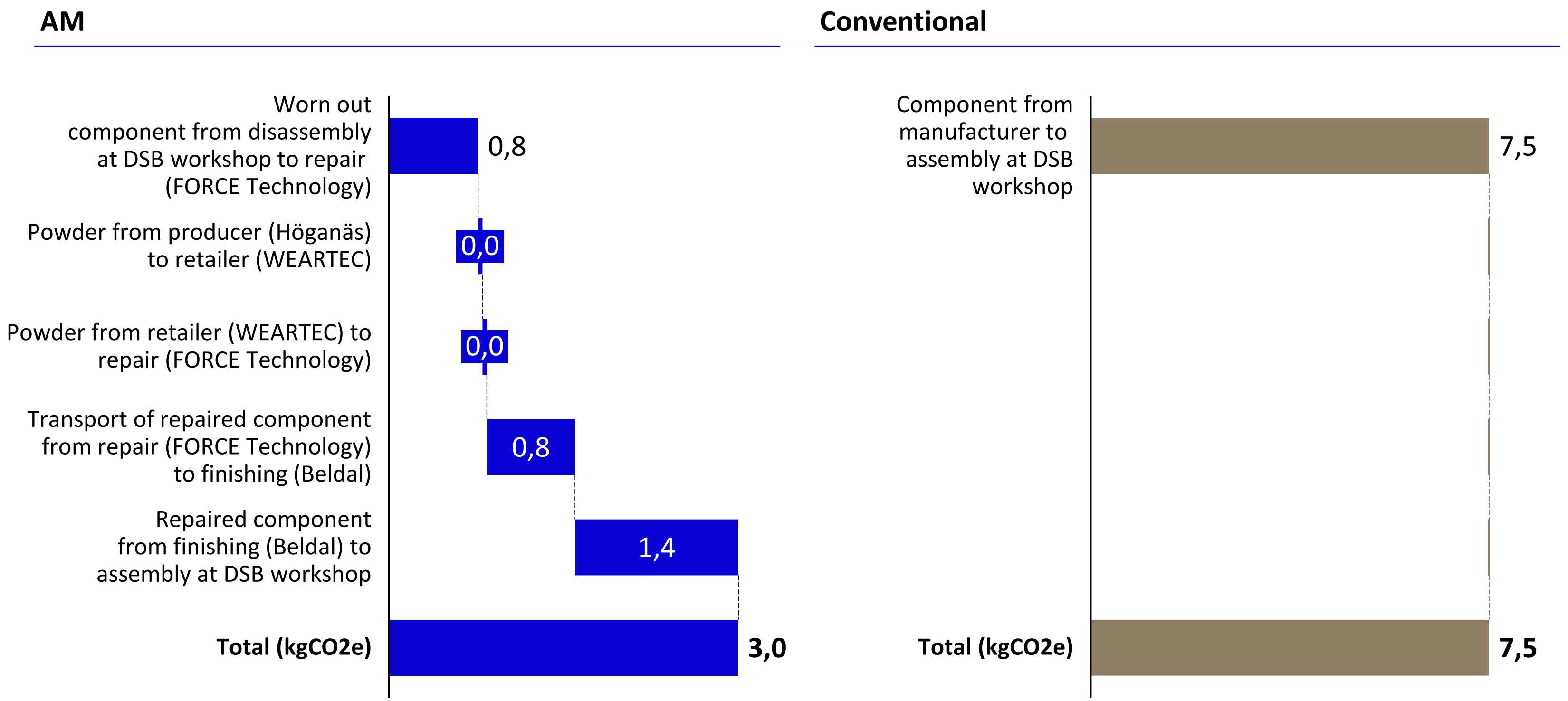
C Deep dive | **Shorter distance** in AM-produced component results in lower carbon footprint

Carbon footprint of distribution activities in AM- and conventionally produced component

FORCE Technology × DSB



Key take-aways

- Since the AM repair is conducted in Denmark, and supplier of AM material is located nearby in Sweden, the total distance is 913 km during the repair
- Assuming that replacement component is produced in Italy, the total distance from production site to DSB workshop is 1571 km
- This difference results in **4,5 kgCO_2e less** from **transportation of AM repair**

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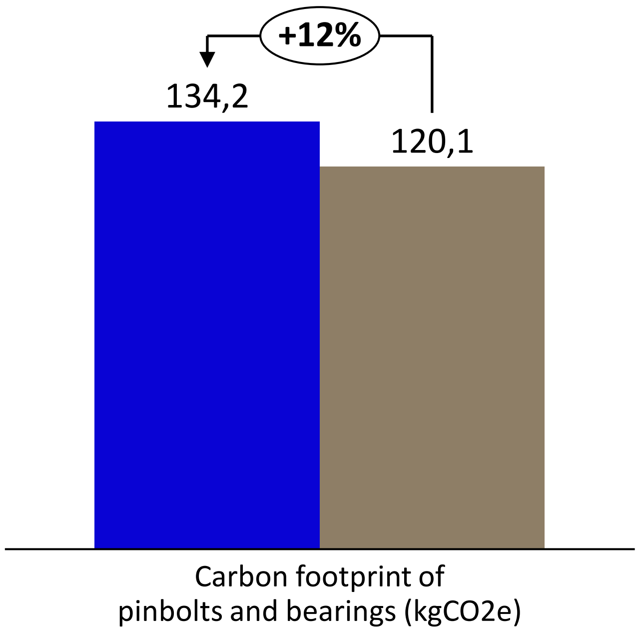
Ⓒ Sensitivity analysis | Emissions from cobalt is a **highly sensitive** parameter to results

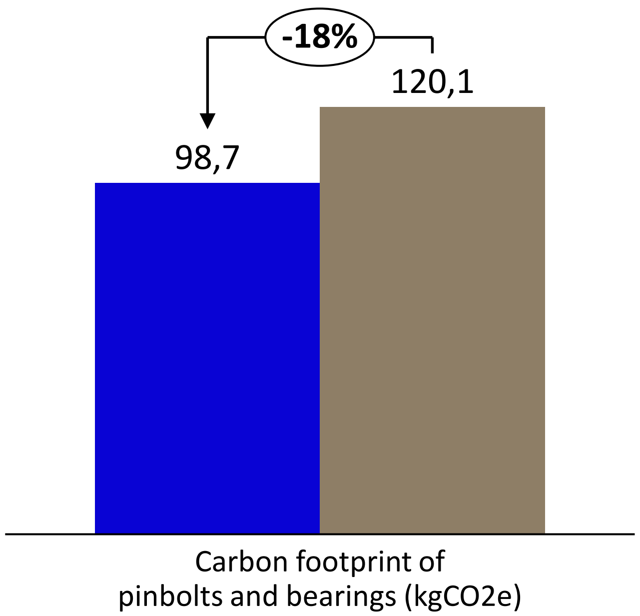
Sensitivity analysis of comparative carbon footprint study

FORCE TECHNOLOGY × DSB

Original results (EF for cobalt at ~42 kgCO_2e/kg)



Alternative results (EF for cobalt at ~12 kgCO_2e/kg)



AM Conventional

Description of sensitivity analysis

- The average-based emission factor applied for cobalt is ~42 kgCO_2e/kg, making this emission factor highly sensitive to the overall results
- Here, emission factor for cobalt has been changed to **11,73 kgCO_2e/kg**[1]

Results of sensitivity analysis

- Changing the emission factor of cobalt **decreases carbon footprint** of AM-produced pin bolts and bearings **with 35,5 kgCO_2e**

Source: 1) Farjana, S. H., Huda, N., & Mahmud, M. P. (2019). Life cycle assessment of cobalt extraction process. Journal of Sustainable Mining, 18(3), 150-161. Analysis by The Footprint Firm.

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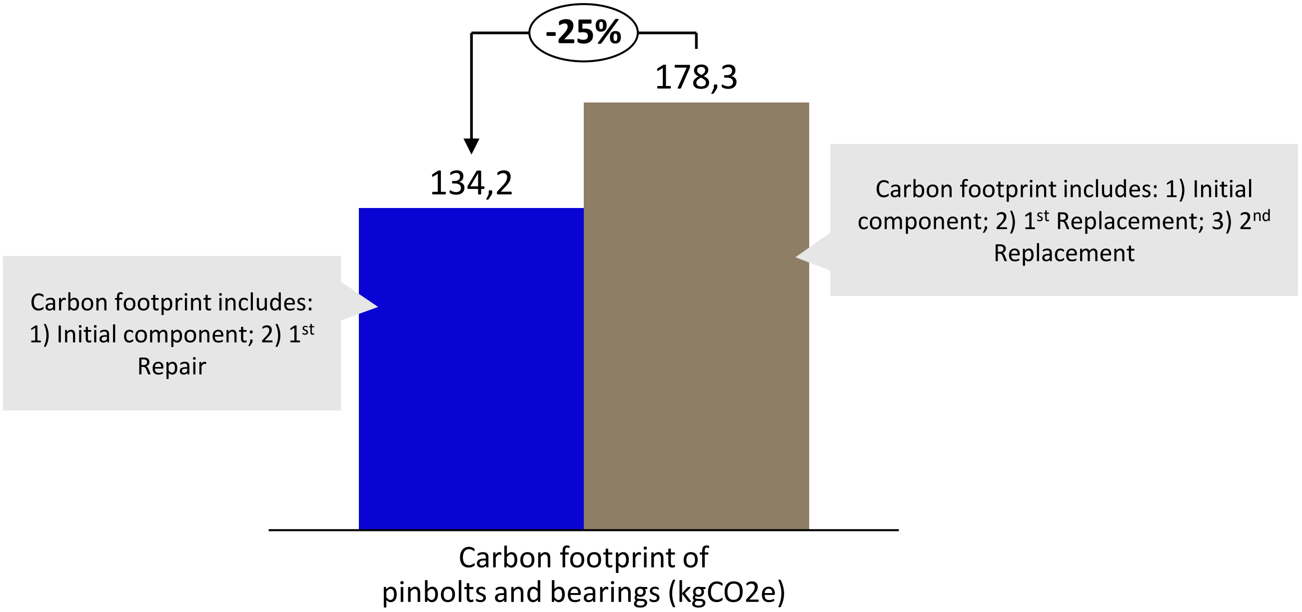
C Sensitivity analysis | Lifetime of AM repair is a **sensitive** parameter to results

Sensitivity analysis of comparative carbon footprint study

FORCE TECHNOLOGY × DSB

Alternative results (repair last twice as long as replacement)



Description of sensitivity analysis

- The AM powder applied for repair, Stellite SF21, is much more resistant than iron
- Thus, the AM repair may last longer than a conventionally-produced replacement
- Here, the repair is assumed to last **twice as long** as a conventionally produced replacement in cast iron

Results of sensitivity analysis

- The carbon footprint of AM-produced repair of pin bolts and bearings **emits 44 kg CO_2e less** than continuing with conventional replacements if lifetime of AM repair is twice of conventional replacement

Source: Analysis by The Footprint Firm.

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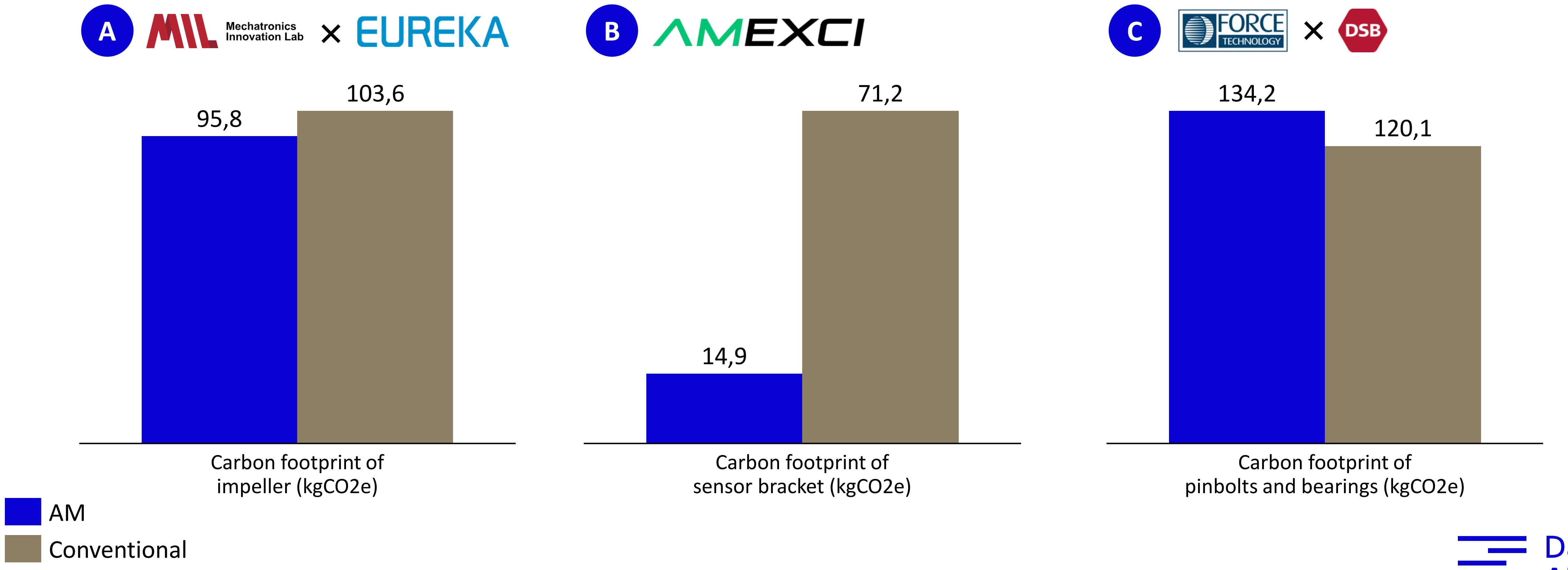
Summary | Of the **3 analysed cases**, 1 has a **lower** carbon footprint of AM compared to conventional

Overview of results cross the three comparative carbon footprint studies



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Source: Analysis by The Footprint Firm.

Note: 1) Case study A and B show a lower carbon footprint of AM compared to conventional manufacturing, but only case study B shows a lower carbon footprint without high uncertainty.

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The 3 carbon footprint studies show both advantages and disadvantages of using AM

Key take-aways from comparative carbon footprint studies from cradle-to-grave

AM material composition

AM materials can be more CO_2e intensive, making less material usage and increased lifetime crucial variables to enable CO_2e reductions compared to conventional production

Reference: Pin bolts and bearings (Force Technology x DSB) - AM powder for repair vs. iron for replacement

Material reduction in AM

AM can enable lower material usage in manufacturing, e.g. due to complex design possibilities compared to conventional production

Reference: Sensor bracket (AMEXCI) – 40% less material in AM-designed upper part

Energy consumption in manufacturing

AM can lead to lower energy consumption compared to conventional production methods if AM design has enabled less material to be processed

Reference: Sensor bracket (AMEXCI) – DED and post CNC machining vs. CNC machining

Local production

AM can enable local repair and production leading to decreased transportation compared to conventional production

Reference: Pin bolts and bearings (Force Technology x DSB) – repair in Denmark vs. replacement in Italy

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Especially **material reduction** would improve the carbon footprint of AM-produced components

Life cycle stages	Areas of improvement for AM-produced component		
	A MIL x Eureka	**B** AMEXCI	**C** FORCE Technology x DSB
Raw material Materials used in production of product	• Increase use of recycled metal • Reduce amount of material through design	• Increase use of recycled metal	• Increase use of recycled metal • Consider material composition in terms of CO_2e-intensity vs. lifetime
Manufacturing Energy consumption and waste	• AM production mostly run on electricity, why the energy sources of the grid determines the emissions from manufacturing. Choosing suppliers with higher share of renewable energy sources will influence emissions from AM		
Transportation Distance, weight and means of transport			
End-of-life Disposed at landfills, incinerated, recycled, etc.	• Ensuring that components are returned for recycling (or even better reused), and thus, used to produce new products will lower cradle-to-grave carbon footprint of component		

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Improving data quality of studies would increase robustness of results and support reduction efforts

Life cycle stages

Recommendations for next steps of improving data quality

A MIL x Eureka | **B** AMEXCI | **C** FORCE Technology x DSB

Raw material
Materials used in production of product

- Ratio of recycled and virgin material in the AM powders and conventional materials
- Collect supplier-specific energy consumption of AM powder production (e.g., atomization process)
- Collect supplier-specific origin countries for raw material in AM powders (e.g., aluminium extracted in Europe or China)

Manufacturing
Energy consumption and waste

- Measure actual energy consumption in AM production methods
- Collect supplier-specific data for argon
- Increase granularity of data for conventional production methods (e.g., type of casting method, energy source, etc.)

Transportation
Distance, weight and means of transport

- Increase granularity of data to specific means of transportation (e.g., van, 16-32 ton lorry truck, etc.)

End-of-life
Disposed at landfills, incinerated, recycled, etc.

- Investigate waste treatment processes and recycling rates for the end-product (either actual rates or average-based for industry, type of product, etc.)

Other recommendations

- Lifetime considerations for AM-design and repair compared to conventionally produced components
- Include indirect use phase emissions related to end-product by expanding the scope of the study
- Expand scope of assessment to include other impact categories than climate change, e.g., resource depletion or the natural environment on a higher level to create a more holistic assessment

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