Sustainability in Additive Manufacturing

WITH OUR SUSTAINABLE AM ROADMAP P.6

Current status and roadmap to transparent AM

A fair comparison of AM vs. conventional manufacturing

In brief

How green is Additive Manufacturing?

FIND 7 SUSTAINABLE AM USE CASES ON P.8

Everyone thinks that additive manufacturing (AM) avoids waste and is kind to the environment. But what about the waste incurred when preparing powders, filaments and resins for use in AM processes? Not to mention the energy consumed and the further (in)efficiencies in the process? A new Roland Berger report scratches below the surface and shows that, for all its ability to go where conventional manufacturing has never gone before, additive manufacturing has the potential to get greener – and a lot more transparent. AM part production often has a larger carbon dioxide footprint than conventionally manufactured processes, though this unbalance can be richly offset during the downstream use phase – even more so if AM further improves its green credentials. All this, however, must be communicated to (potential) users, so the industry must first take the trouble to produce accurate life cycle analyses. Only then can customers know how climate-friendly AM really is and what value it genuinely adds. And only then will doors open to new areas of application that currently remain firmly closed. Roland Berger's four-step roadmap shows the way.

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Cover: timandtim/Getty Images

How sustainable is AM today?

All industries and technologies face a rising need to mitigate environmental impact and reduce CO_2 emissions. As an increasing number of companies across almost every sector commit to carbon neutrality or net-zero CO_2 emissions in the decade(s) ahead, additive manufacturing (AM) too must play its part in ensuring a more sustainable future. Sustainability is not only about reducing CO_2 emissions: recycling, renewable raw materials and waste mitigation are other important issues, along with all other aspects of the environmental, social and governance dimensions. Throughout this article, the reduction of CO_2 emissions therefore serves merely as an example to showcase AM's contribution to the environment going forward and developing AM further as ***Next Generation Manufacturing*** technology.

At first glance, AM seems to be the perfect technology for responsible manufacturing, with a minimal impact on the environment. Building parts additively and therefore using only the material genuinely required for each part, with no waste, seems an ideal way to save resources. The reality, however, perhaps falls short of this lofty ambition. Almost all AM technologies require materials that have already undergone an additional processing step *(see figure 1)*. The most relevant AM polymer material classes – polymer powders, filaments and resins – have previously been converted thermally or chemically, which requires energy and therefore adds a debit entry to their CO_2 emissions ledger. Similarly, metal AM materials such as metal powders and wires must first be atomized into particle-shaped powders or drawn into wires. The gas atomization of powders in particular consumes large amounts of energy before the material can be used in an AM machine. Metal ingots are melted and dispersed by a hot, high-speed inert gas stream to form spherical powders of a certain particle size. These particles then need to be sieved to retain an optimal particle size distribution – producing large amounts of scrap powder in the process. Moreover, additive manufacturing requires long processing times, normally in the range of a couple of hours for polymers, though metal powder bed fusion parts can take up to a week. Processing also presupposes an inert gas atmosphere, electricity to heat the build room and machine operation during printing. The process gases themselves are obtained via gas separation, which is itself very energy-intensive. In addition, AM fabrication is always followed by one or more post-processing steps that further enlarge the environmental footprint of the AM part.

> "Currently, we do not have sufficient transparency to make a blanket statement about the climate-friendliness of AM."
>
> BERNHARD LANGEFELD
> SENIOR PARTNER, ROLAND BERGER

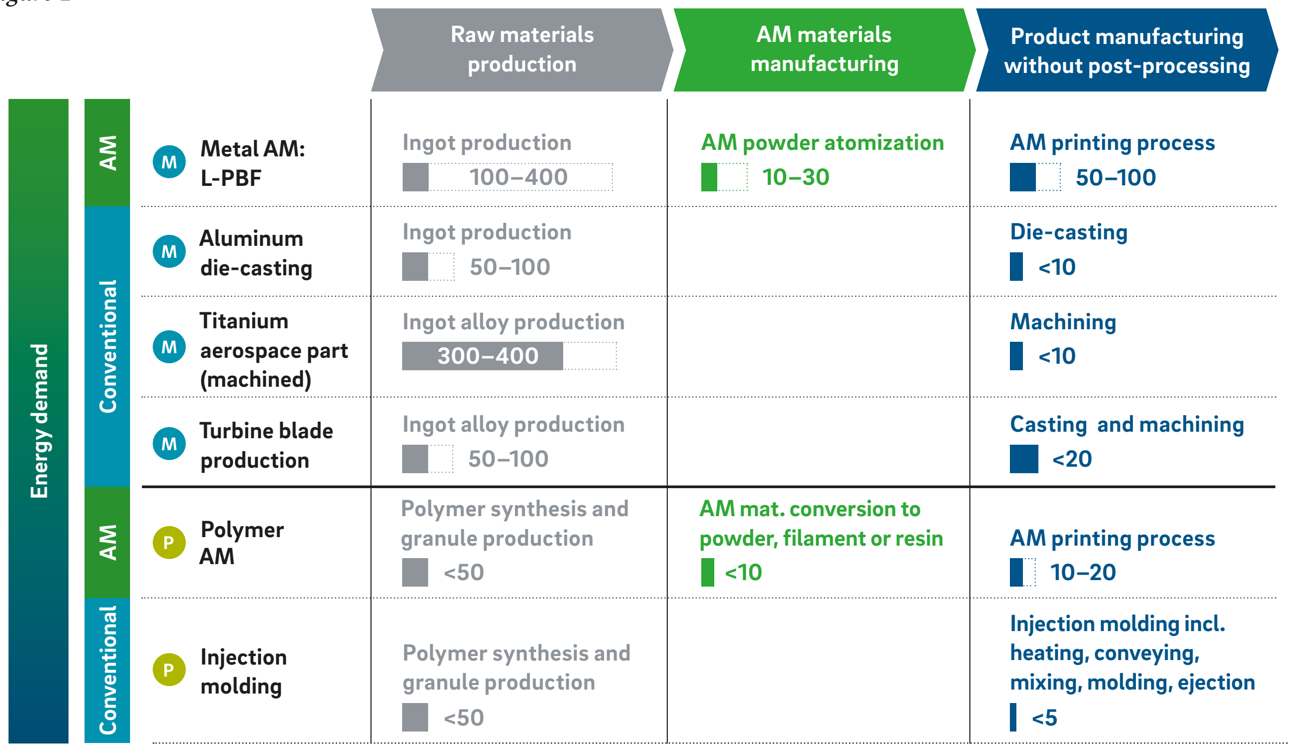
AM vs. conventional

M Metal   P Polymer

Energy demand on a kilogram-by-kilogram comparison in each manufacturing step

Per-kilogram process energy demand [kWh/kg]

figure 1

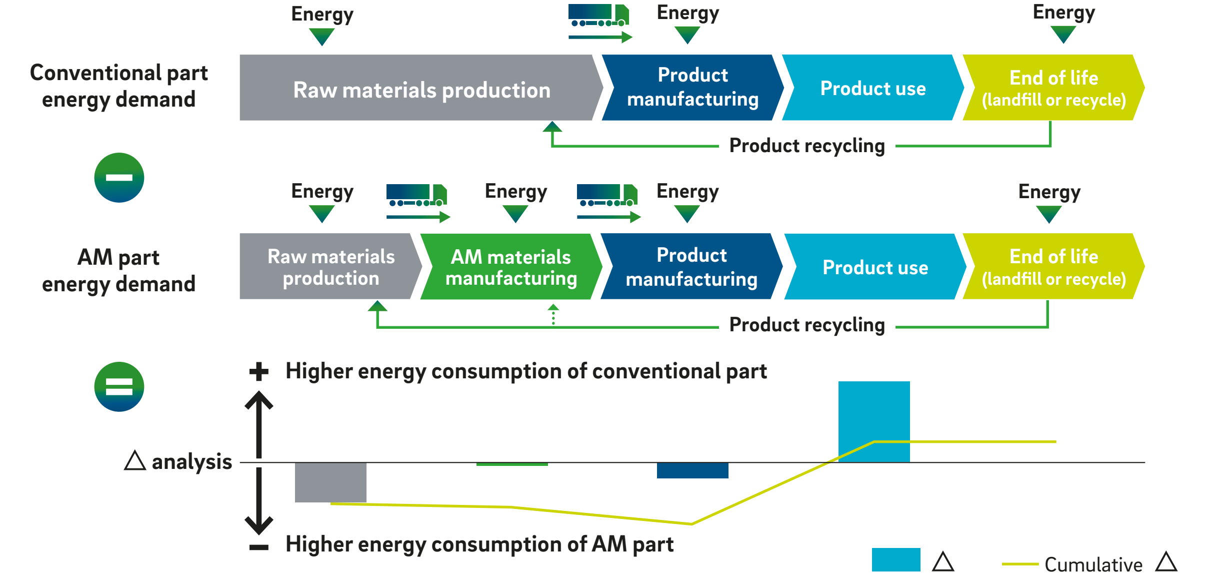


Energy demand			Raw materials production	AM materials manufacturing	Product manufacturing without post-processing
	AM	M Metal AM: L-PBF	Ingot production 100–400	AM powder atomization 10–30	AM printing process 50–100
	Conventional	M Aluminum die-casting	Ingot production 50–100		Die-casting <10
		M Titanium aerospace part (machined)	Ingot alloy production 300–400		Machining <10
		M Turbine blade production	Ingot alloy production 50–100		Casting and machining <20
	AM	P Polymer AM	Polymer synthesis and granule production <50	AM mat. conversion to powder, filament or resin <10	AM printing process 10–20
	Conventional	P Injection molding	Polymer synthesis and granule production <50		Injection molding incl. heating, conveying, mixing, molding, ejection <5

Life cycle analysis

AM parts need to offset larger energy consumption until product use phase

figure 2



Source: Journal of Manufacturing Systems, Journal of Cleaner Production, Additive Manufacturing Journal, Proceedings of the IEEE International Symposium on Sustainable Systems and Technology, Roland Berger

> **"While most AM manufacturing techniques require additional energy during the material and production phase, the significant benefits of AM in the use phase result in improved overall energy consumption."**
>
> TIM FEMMER
> PROJECT MANAGER, ROLAND BERGER

Given this situation, a part produced using AM starts its life – i.e. before entering the usage and recycling phases – with a larger environmental footprint than a part manufactured conventionally on a per-kilogram and per-process-step basis. To date, the AM industry has seldom published entire life cycle analyses (LCAs) for AM parts or compared them with the conventional manufacturing route *(see figure 2)*. Yet a fair LCA is vital to prove whether AM genuinely has a lower environmental impact than a conventional part. There is a problem, however: how do you compare the two manufacturing trajectories when AM can create parts that are impossible to produce with conventional techniques? Indeed, these "impossible" areas are where AM is making the fastest advances. Processing AM parts yields an energy disadvantage when comparing 1 kg of material in each process step of the production chain *(see figures 1 and 2)*. However, the ratio changes for the example of a titanium aerospace bracket. This part showcases the fact that, thanks to limited waste material compared with milling processes *(see figure 3)*, the reduction in material needed by AM (indicated by the lower buy-to-fly-ratio of 1.5, against 8) more than makes up for the energy-intensive AM material and AM production steps even before design is optimized. Parts can then be optimized by admitting more complex designs that reduce weight by only placing solid materials where they are needed most to guarantee mechanical properties and ensure the functionality of parts. Today's titanium aerospace brackets are typically machined. However, if this production process is swapped for metal AM laser powder bed fusion (L-PBF), the part's total energy consumption throughout the raw material production, manufacturing and end-of-life phases is slashed by about 75%. If the geometry of the same bracket is then optimized to reduce its mass by 65% (from 0.9 kg to 0.3 kg), an additional 65% energy savings can be realized across the raw material production and manufacturing phases. Most importantly, however, decreasing the bracket's mass can lead to significant energy (and hence fuel) savings of about 24 MWh during the flight operation in the product use phase. This example illustrates that the intelligent use of AM capabilities can decrease a part's environmental footprint not just in the early life cycle phases, but also during the downstream product use phase.

Additive manufacturing is expected to deliver similar energy reduction effects in areas such as advanced cooling for vanes in gas turbines, which makes the gas turbines more effective and therefore again saves fuel. It is this "going beyond" the realms of the conventional that also justifies the additional cost that AM usually incurs compared with conventionally manufactured parts *(see figure 4)*. Many industries are already benefiting from AM fabrication features and the capabilities of the technology to produce more advanced products. It follows that the AM industry and its customers must produce more-transparent LCAs that fairly compare AM use cases with conventional ones. To this end, Roland Berger has developed a four-step roadmap for AM as a sustainable manufacturing technology.

The four steps are:

1. **Make the environmental footprint impact of AM materials, machines and processes more transparent;**
2. **Develop an LCA database especially for the usage and recycling phases;**
3. **Predict environmental impact before printing;**
4. **Take action to reduce the environmental footprint of AM *(see figure 5).***

Our roadmap toward greener AM

1

Make the environmental footprint of materials and processes more transparent

Existing AM users receive no information about how large the environmental footprint of their AM part could eventually be. Little information is provided about the AM materials that are printed. We investigated and found that only one supplier disclosed the CO_2 intensity for polyamide 12, whose fabrication generates approximately 7.8 kg of CO_2 per kilogram of AM powder. But apart from this, little detailed analysis is available about the environmental impact of the AM process – in particular about the post-processing chain (heat treatment, build platform separation, support removal, hot isostatic pressing, surface modification treatment, etc.). To increase the level of transparency, AM material manufacturers should estimate the amount of CO_2 emitted during AM material production and include it as one of the technical parameters in their product datasheets. AM machine manufacturers should follow suit, indicating the hourly environmental cost of operating their equipment for predefined process parameters. Additionally, stakeholders in the AM value chain should jointly develop a standard method to report the energy and CO_2 intensity of each link in the production and post-processing chains. This will give AM users visibility about the environmental implications of choosing different AM materials and items of equipment. It will also give them basic data with which to estimate the energy and CO_2 footprint of their AM part. Complementary information about possible recycling and zero-waste options would further enhance a sustainable customer experience.

2

Develop a suitable life cycle analysis database

Whether it is manufactured conventionally or using AM, the material production phase is the main driver of the CO_2 emissions of any part. On the other hand, it is the end-of-life phase – and especially the product use phase – that determine whether an AM part can reduce its overall CO_2 emissions compared with a conventional part. The requisite LCAs are published only sporadically, however, because of the level of detail that must be compared and the time and resources needed to produce them. In the future, comprehensive LCA databases should be available to verify energy consumption and CO_2 emissions throughout a product's life cycle. Fair comparisons of the value added by AM are also needed. While there is a direct correlation between weight reduction in AM parts and fuel savings for moving parts (in the air or on the ground), it is less clear whether a similar relationship exists between the value added by AM and the LCA benefits. This notional correlation must be fleshed out on a case-by-case basis.

3

Predict environmental impact before printing

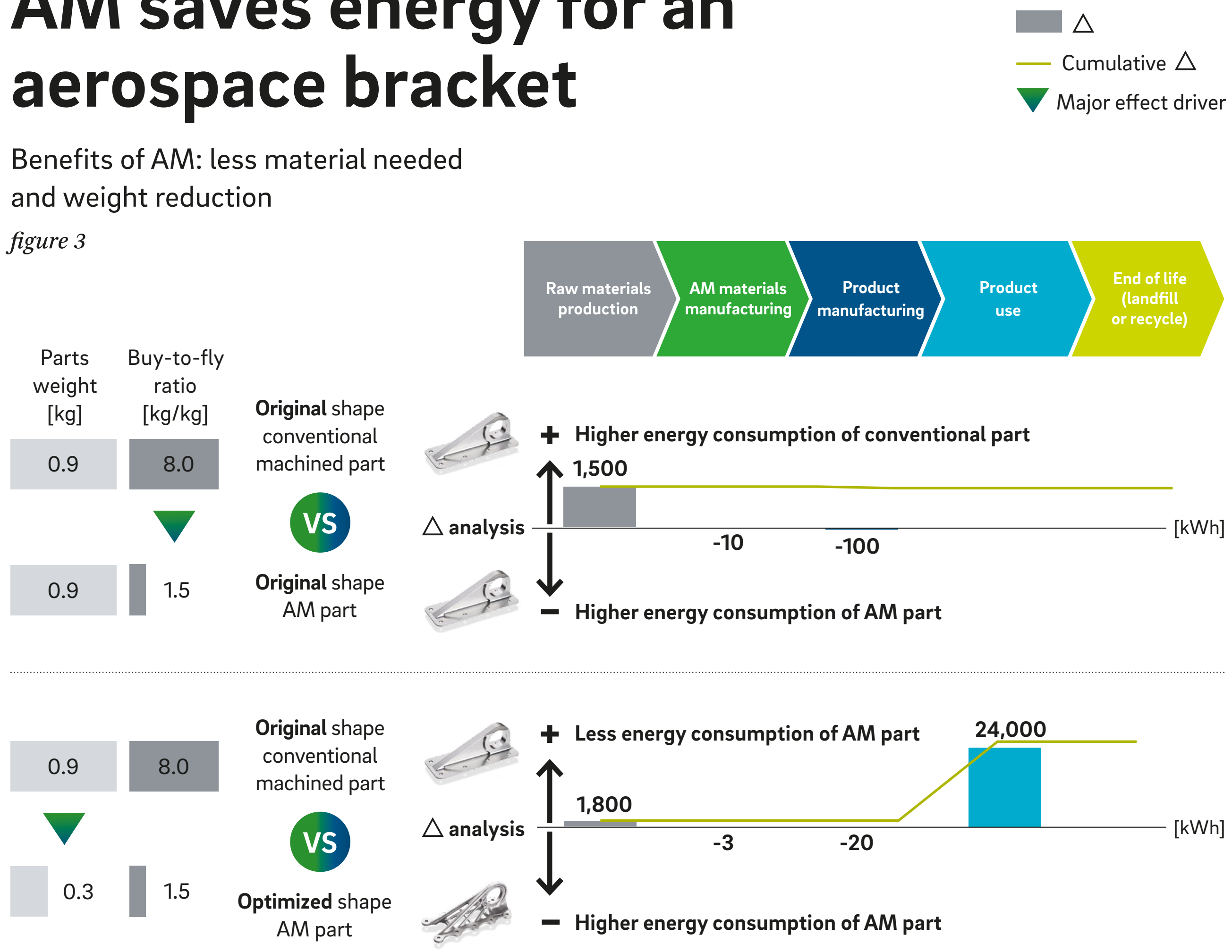
To really push AM in the right direction, reduce its overall environmental footprint and confirm AM as a sustainable production technology, the decision-makers behind the fabrication method need to know in advance whether AM has the potential to reduce CO_2 emissions. A quick and easy tool or software program to predict the difference between an AM part and a conventional one with a high degree of certainty is essential. Based on the producer's CO_2 reduction goals, the price of CO_2 certificates and prevailing political and public opinion, such a tool could boost the application of AM in areas where it is currently considered too expensive. However, it has to be based on solid LCAs and should serve as guidance only. This is because there may be process, material or part-specific issues that require adaptation by people with adequate experience and expertise in AM.

> "AM can produce parts that conventional techniques often cannot. This must be accounted for in any comparison."
>
> MAX SCHAUKELLIS
> SENIOR CONSULTANT, ROLAND BERGER

AM saves energy for an aerospace bracket

Benefits of AM: less material needed and weight reduction

figure 3



Source: Journal of Manufacturing Systems, Journal of Cleaner Production, Additive Manufacturing Journal, Proceedings of the IEEE International Symposium on Sustainable Systems and Technology, Roland Berger

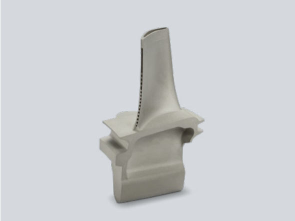
Image Credits: Courtesy of GE Additive

AM use cases for sustainability

figure 4

Seven AM use cases showing the added value of AM for an LCA

M Metal P Polymer

	I Weight reduction	II Material recycling	III Over-production	IV Fuel efficiency	V Reactor efficiency	VI Parts integration	VII Digital inventory/ localized product.
							
Description	**Aerospace bracket** Conventional design (upper) and AM lightweight designed bracket for commercial aircraft from titanium	**Recycled material AM** Parts printed with 100% recycled PA12 polymer powder, recycling source is the unsintered AM powder	**Custom eyeware** Frames produced additively via powder SLS from PA and subsequent coloring customized to user	**Gas turbine parts** Gas turbine blade made from nickel chrome superalloys with internal cooling channels	**Reactor autoclave** High-pressure reactor for autoclaving made from 316L stainless steel for applications up to 225 bar	**Door shaft** Latch shaft made from titanium via L-PBF for door of A350 XWB commercial aircraft	**Bus spare parts** Visible polymer PA parts for premium buses stored digitally and produced based on demand
AM technology	M L-PBF	P SLS	P SLS	M L-PBF	M L-PBF	M L-PBF	P SLS
Addressed LCA step	Product use	Product manufacturing	Product manuf. End of life	Product use	Product use	AM mat. manuf. Product manuf.	Product manufacturing
Benefits of AM vs. conventional	**Weight and material** ▶ 1 kg in weight reduction of a parts saves about 90K–120K k liters of fuel p.a. ▶ AM parts reduced buy-to-fly ratio of about 10:1 to 1:1	**Material efficiency** ▶ With all subtractive manufacturing techniques in general there is more excess material needed compared with additive technologies	**Material waste** ▶ AM eyewear shows up to 58% lower CO_2 ▶ Only 20% of the raw material ends up in the final frames of (sun)glasses, rest is wasted ▶ Demo glasses in stores are discarded after a season	**Fuel efficiency** ▶ Vanes and fuel burner tips can be optimized via AM ▶ Fuel can be burned better; 1% efficiency increase saves >4,000 MWh p.a. for a midsize turbine	**Fewer reactants needed** ▶ Freedom of design enables better chemical reaction control leading to fewer reactants ▶ Less energy is consumed by, e.g., enhanced cooling channel integration	**Parts integration** ▶ 10 conventionally made parts could be integrated in 1 single AM part ▶ Improvement of costs by 25% and additional weight reduction by 45%	**On-demand production** ▶ Digital spare parts warehouses in combination with decentralized on-demand production decrease transport/ warehouse needs significantly

Photos (left to right): Courtesy of GE Additive, Materialise Bluesint PA 12, YOU MAWO, EOS GmbH, Siemens Energy, © BASF SE, Airbus, EOS GmbH

Source: Roland Berger

Once transparency has been established, the real work begins

4

Reduce AM's environmental footprint

Additive manufacturing was not initially conceived of as a "green" technology. When the first AM machine was commercialized in 1986, the intent was to build parts and geometries that were impossible with subtractive techniques, not a manufacturing solution to reduce CO_2 emissions. And in the three and a half decades that followed, AM has seen rapid development and progress. Emissions have not been optimized, of course, but initial steps toward this goal can be prioritized even without in-depth LCAs. The AM-specific energy and emission contributors are AM material production and AM part production, while the benefits of AM are seen in the product use phase.

The producers of AM materials – powders, filaments, resins and wires, for example – need to identify and address their main sources of emissions. One immediate step would be to replace the fossil fuel energy inputs in their processes with renewable alternatives, as this would cut emissions directly. Another would be to implement measures to increase energy efficiency in the process (such as by recovering heat wherever possible). A longer-term initiative would involve R&D around AM materials derived from alternative raw materials (e.g. plant-based fibers as reinforcements instead of glass and carbon fiber) and/or around chemical methods that generate less pollution.

To reduce emissions during the production of AM parts, AM machine manufacturers can achieve a lot by optimizing the rate of powder recycling, reducing inert gas consumption and optimizing the build-job preparation software that, together with other parameters, defines the necessary support structures. Furthermore, more-stable AM processes would diminish the need for testing and inspection. Upgrades such as in-process, layer-by-layer monitoring could prove the absence of porosity and – using X-rays and CT scans, for example – avoid extensive and expensive non-destructive testing, which also comes with its own environmental cost. Finer build jobs that result in nearer net-shape parts can also shorten post-processing steps if the overall AM process time is not extended. In this way, post-processing steps such as chemical surface modification and machining could be reduced, leading to lower costs and emissions.

"AM parts must be designed and engineered with a specific 3D-printing value-add in mind so that their energy consumption and embodied CO_2 are minimized and their business case is optimized."

MIGUEL LÓPEZ
CONSULTANT, ROLAND BERGER

EXPERT TALK

Is Additive Manufacturing a green manufacturing technology?

BERNHARD LANGEFELD
Senior Partner

TIM FEMMER
Project Manager

Why is sustainability in Additive Manufacturing so important?

Bernhard Langefeld: Sustainability is a top priority for companies today with focus on (total) CO_2 emissions, with regard to bio-compatibility but as well recycling and zero waste. We see more and more companies from the consumer goods industry addressing these questions systematically when selecting a production technology and associated supply chain. Sustainability is therefore also a critical part of our Next Generation Manufacturing framework. Additive Manufacturing can have a huge impact on Scope 1 emissions (material usage) and Scope 3 (use phase) as explained in this study.

How can Additive Manufacturing improve the ESG rating of a company?

Bernhard Langefeld: Every time a manufacturing technology is chosen to produce a part and Additive Manufacturing is on the list of possible choices, the overall emissions should be taken into account. Here a fair life cycle analysis of the part made with conventional technologies or Additive Manufacturing reveals the impact to especially the E of the ESG rating. Critical here is to look at the entire part's life from raw material to recycling. As well 3D printing often is a key enabler for local production, adressing short transport ways and fast delivery, which positively impacts transport emissions.

Additive Manufacturing is still expensive, will sustainability make it even more costly compared with conventional techniques?

Tim Femmer: Our research shows that this is very unlikely. Two aspects are critical here, first of all, if less raw material from AM directly reduces material costs and emissions are reduced simultaneously. Second, during the use phase of the part, the advantages of Additive Manufacturing usually make the difference. When the AM part performs better than a conventional one, it is most likely also better from an emissions point of view, especially when it is a moving component in the air or on land. The drivers for the AM business case and the AM emissions case follow the same logic.

"When the business case improves, the emissions will likely improve as well."

TIM FEMMER
PROJECT MANAGER, ROLAND BERGER

figure 5

The roadmap toward AM as a sustainable manufacturing technology

A four-step approach

1

Gain transparency of materials and processes

- ▶ Understand energy demands end-to-end, from raw materials to final produced part, incl. recycling
- ▶ Indicate specifics for different materials, AM production processes and post-processing techniques used

2

Develop a suitable life cycle analysis database

- ▶ Develop fair benchmark of AM (incl. added value) vs. conventional manufacturing routes
- ▶ Based on (1), further consider parts/products use, recycling and disposal
- ▶ Also analyze further dimensions of environmental, social and governance impacts

3

Predict environmental impact before printing

- ▶ Based on (1) and (2) develop a predictive tool to estimate environmental impact of AM part/product before production, incl. estimated product use phase and end-of-life phase for carbon dioxide emissions and other environmental impacts

4

After gaining transparency, the real work starts – mitigate AM harm to the environment

- ▶ Address main drivers on carbon dioxide sources in the AM process value chain
- ▶ Further improve key AM aspects to realize AM benefits in product use phase
- ▶ Intensify the effort in recycling techniques for AM, both in-process (powder, inert gases) and at end of life

Source: Roland Berger

Save money and carbon dioxide

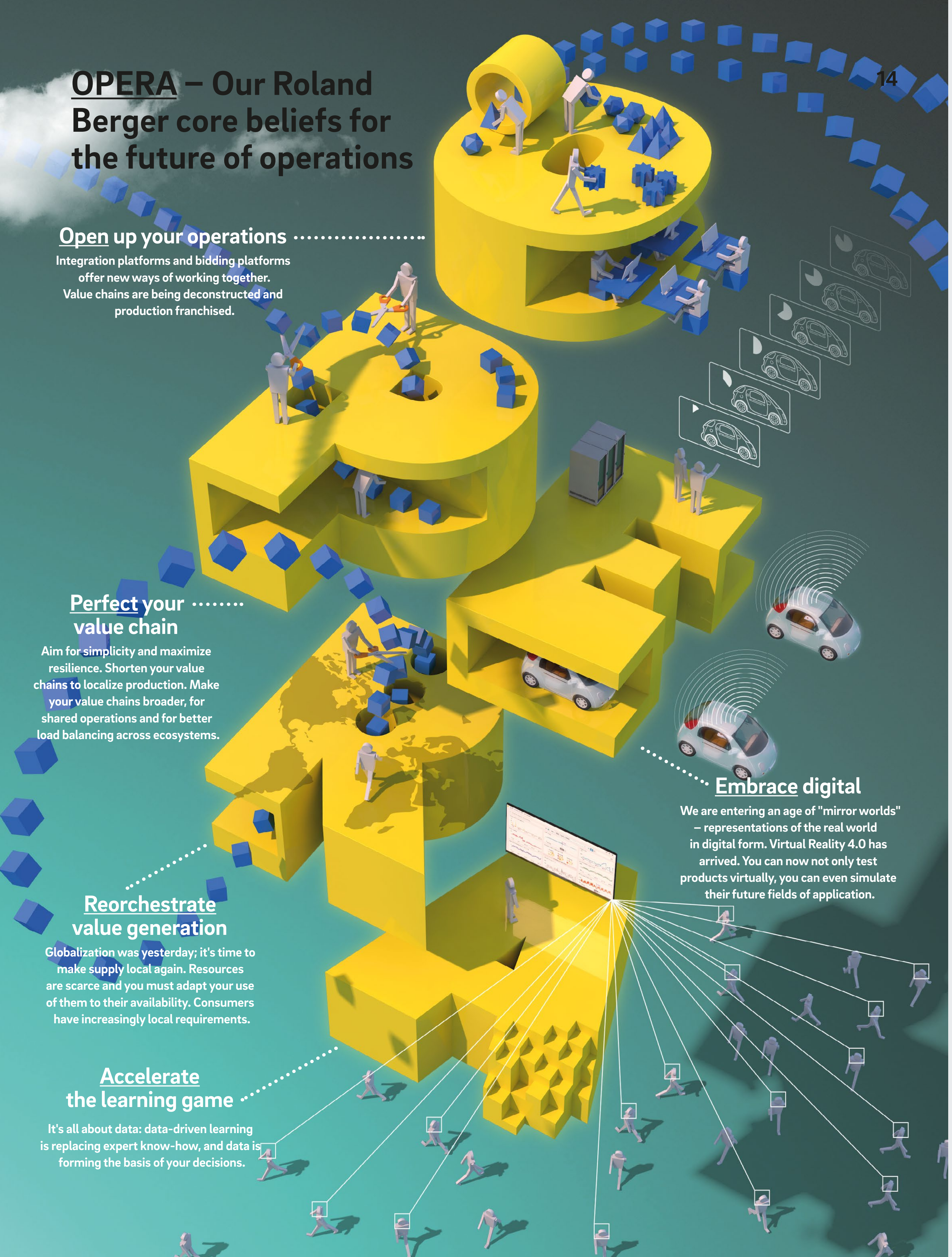
figure 6

Analogy between AM part business case and carbon dioxide emission

▲ Increased profitability
▼ Decreased footprint

		AM parts business case		AM parts carbon dioxide emission
AM materials manufacturing	▶ **AM material processing efficiency incl. powder recycling**	▲ **Lower material cost** Saved costs for, e.g., powder atomization, AM material production	▼ leads to ▶	▼ **Process CO_2 reduction** Less energy consumed in AM material production
Product manufacturing	▶ **High conversion rate from raw material to final part** (e.g., buy-to-fly ratio)	▲ **Less material purchased** Less material needed	▼ leads to ▶	▼ **Lower CO_2 for material production** Less energy and waste during production
	▶ **Parts integration, batch flexibility and mass customization**	▲ **Lower manufacturing cost** Fewer manufacturing and assembly steps		▼ **Process and usage CO_2 reduction** Fewer assembly steps
	▶ **AM printing process improvements** (e.g., faster build-speed, fewer supports/less inert gas)	▲ **Lower manufacturing cost** Increased productivity and material efficiency		▼ **Process CO_2 reduction** Less energy, material-induced emissions
Product use	▶ **Weight reduction of parts**	▲ **Lower material cost** Topology optimization as functional benefit	▼ leads to ▶	▼ **Usage CO_2 reduction** Lighter parts save, e.g., energy, fuel
	▶ **AM parts geometry optimization** (integrated cooling channels, etc.)	▲ **Higher parts efficiency and sales price** Better parts performance with added value		▼ **Usage CO_2 reduction** (e.g., higher efficiency)
	▶ **AM-enabled new part functionalities** (e.g., parts integration, chemical reaction enhancement)	▲ **Increased revenue** Broader application, improved performance, lower material costs		▼ **Part and usage CO_2 reduction** Longer usage phase, lower reaction consumption
End of life (landfill or recycle)	▶ **Prevention of overproduction** (e.g., digital warehousing, mass customization, etc.)	▲ **Lower warehousing/waste removal cost** Lower inventory levels, waste levels	▼ leads to ▶	▼ **Less wasted CO_2 in products/processes** Less waste, less storage/movement

Source: Roland Berger



OPERA – Our Roland Berger core beliefs for the future of operations

Open up your operations

Integration platforms and bidding platforms offer new ways of working together. Value chains are being deconstructed and production franchised.

Perfect your value chain

Aim for simplicity and maximize resilience. Shorten your value chains to localize production. Make your value chains broader, for shared operations and for better load balancing across ecosystems.

Embrace digital

We are entering an age of "mirror worlds" – representations of the real world in digital form. Virtual Reality 4.0 has arrived. You can now not only test products virtually, you can even simulate their future fields of application.

Reorchestrate value generation

Globalization was yesterday; it's time to make supply local again. Resources are scarce and you must adapt your use of them to their availability. Consumers have increasingly local requirements.

Accelerate the learning game

It's all about data: data-driven learning is replacing expert know-how, and data is forming the basis of your decisions.

Further readings

Next Generation Manufacturing

Next Generation Manufacturing gets ready to roll

After a long, slow ride, manufacturing is about to get exciting again

Additive Manufacturing

New business models and comprehensive product innovation

Polymer additive manufacturing

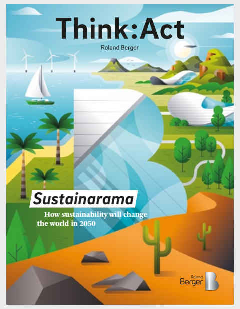
De-risking your supply chains

Taking metal 3D printing to the next level

Beyond powder bed – AM on the brink of industrialization

Sustainability

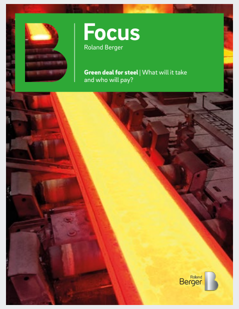
Climate Action
A new competitiveness paradigm



Sustainarama
How sustainability will change the world in 2050

Innovate and industrialize
Offshore wind energy

Hydrogen
Transporting the fuel of the future



Green steel
The race is on

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