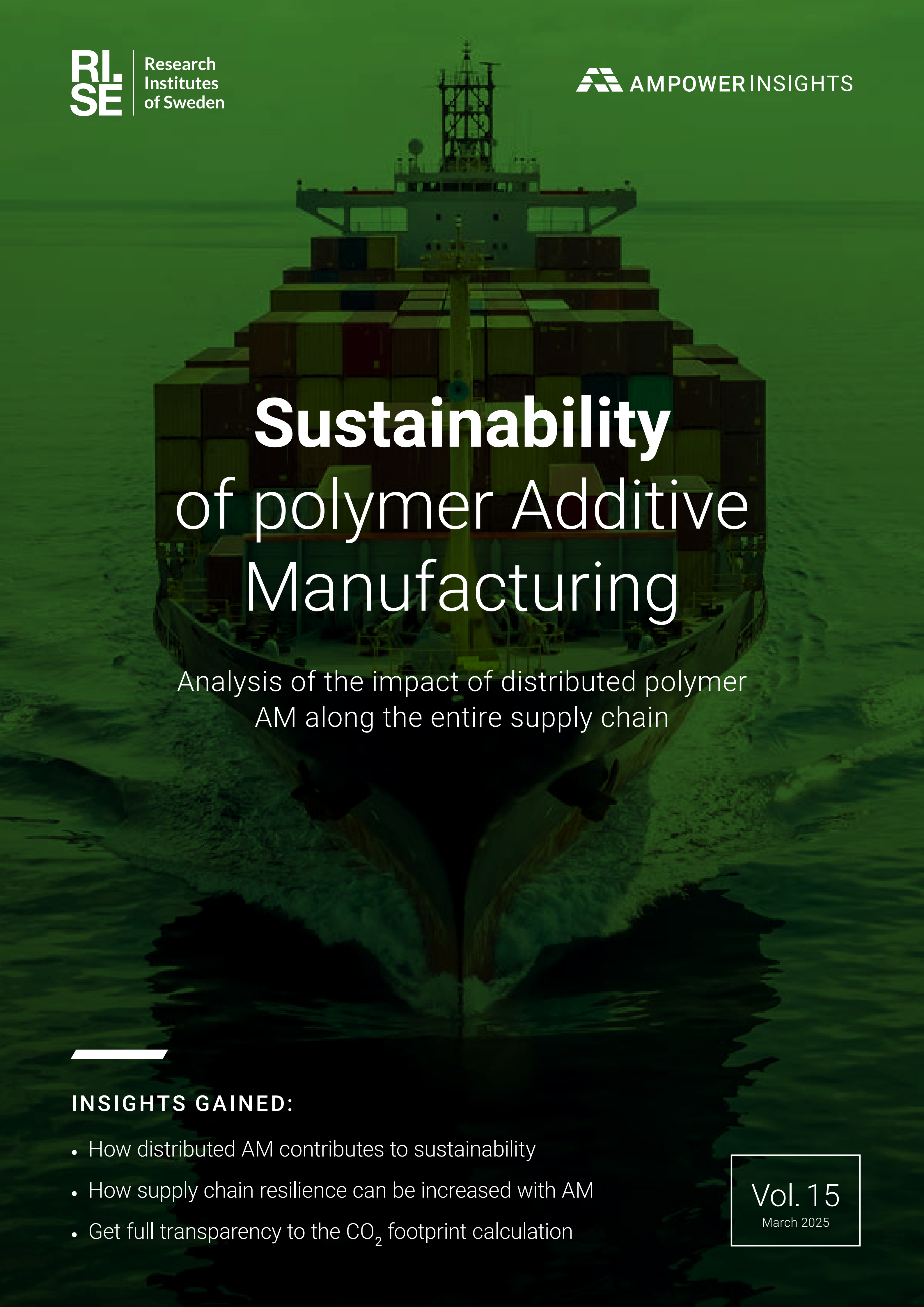

RISE Research Institutes of Sweden

AMPOWER INSIGHTS

Sustainability of polymer Additive Manufacturing

Analysis of the impact of distributed polymer AM along the entire supply chain

INSIGHTS GAINED:

- How distributed AM contributes to sustainability
- How supply chain resilience can be increased with AM
- Get full transparency to the CO_2 footprint calculation

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COURTESY OF DRÄGER

Insights gained

How distributed AM contributes to sustainability

How supply chain resilience can be increased with AM

Get full transparency to the CO_2 footprint calculation

Management summary

In today's rapidly evolving business landscape, companies must reduce costs, shorten lead times, and strengthen supply chains. Additive Manufacturing (AM) provides a powerful solution—enabling distributed production, minimizing waste, lowering emissions, and increasing flexibility. By leveraging the energy mix of local production sites, AM can further enhance sustainability, particularly in regions like Europe with low carbon energy sources.

Initially targeting prototyping, AM is now transforming to end-use production, driven by technological advancements, improved quality, and sustainability goals. By localizing production, AM reduces lead times, inventory costs, and CO_2 emissions while improving supply chain resilience. Unlike traditional manufacturing, it also enables part consolidation, material substitution, and lightweighting for greater efficiency.

A structured business case is essential to quantify AM's impact. In this paper AMPOWER and RISE analyze supply chain scenarios, comparing centralized production in China with regional AM in Europe where key findings are:

- Lead Time Reduction: 90% decrease
- CO_2 Reduction: 98% in transportation, 69.5% in production
- Inventory Optimization: 70% decrease in safety stock and tied-up capital

AM's strengths in low-volume production and distributed manufacturing enhance parts availability, reduce environmental impact, and generate cost savings. Companies that adopt AM can build more sustainable, agile, and competitive supply chains.

Download this paper at www.ampower.eu/insights

About AMPOWER

AMPOWER is the leading consultancy in the field of industrial Additive Manufacturing. AMPOWER advises their clients on strategic decisions by developing and analyzing market scenarios as well as compiling technology studies. On operational level, AMPOWER supports the introduction of Additive Manufacturing through targeted training programs as well as identification and development of components suitable for production. Further services include the setup of quality management and support in qualification of internal and external machine capacity. The company was founded in 2017 is based in Hamburg, Germany.

About RISE

RISE (Research Institutes of Sweden) is an independent research institute, owned by the Swedish state, that works closely with industry, academia, and the public sector to promote sustainable growth, drive innovation, and strengthen business competitiveness. With unique expertise and more than 130 test and demonstration environments, RISE is committed to developing future-ready technologies, products, and services. The Application Center for Additive Manufacturing at RISE specialises in advancing and optimising additive manufacturing for industrial applications. It supports clients throughout the entire process – from business models, product development, and hands-on training, to material and technology selection, production, testing, verification, and industrialisation.

Content

Introduction

Additive Manufacturing as key enabler to build a sustainable business case

In the rapidly evolving business landscape, companies are under a constant pressure to cut costs, reduce lead times, and create more sustainable and resilient supply chains. Global disruptions, such as conflicts and pandemics, have highlighted the vulnerabilities of traditional supply chains were AM presents an opportunity to address these challenges. By enabling cost reductions, decreasing lead times, and bolstering supply chain resilience, AM not only helps companies stay competitive but also supports long-term sustainability goals.

Today, the use of Additive Manufacturing in many industrial companies is shifting from being a tool for visualization, prototyping, and manufacturing support to industrial manufacturing of end-user components, such as spare parts. This shift is driven by the increasing maturity of the technology, advancements in design and preparation for AM, improved quality assurance, heightened global competition, and the push toward sustainability targets. This evolution in the usage of AM paves the way for the implementation of distributed production. For decades, companies have relied on centralized production. This approach offers economies of scale, efficient use of the production resources, and consistent product quality, leading to lower costs and higher output but also results in inefficiencies from long transports, surplus inventory, scrapping and challenges to adapt to fluctuations in demand.

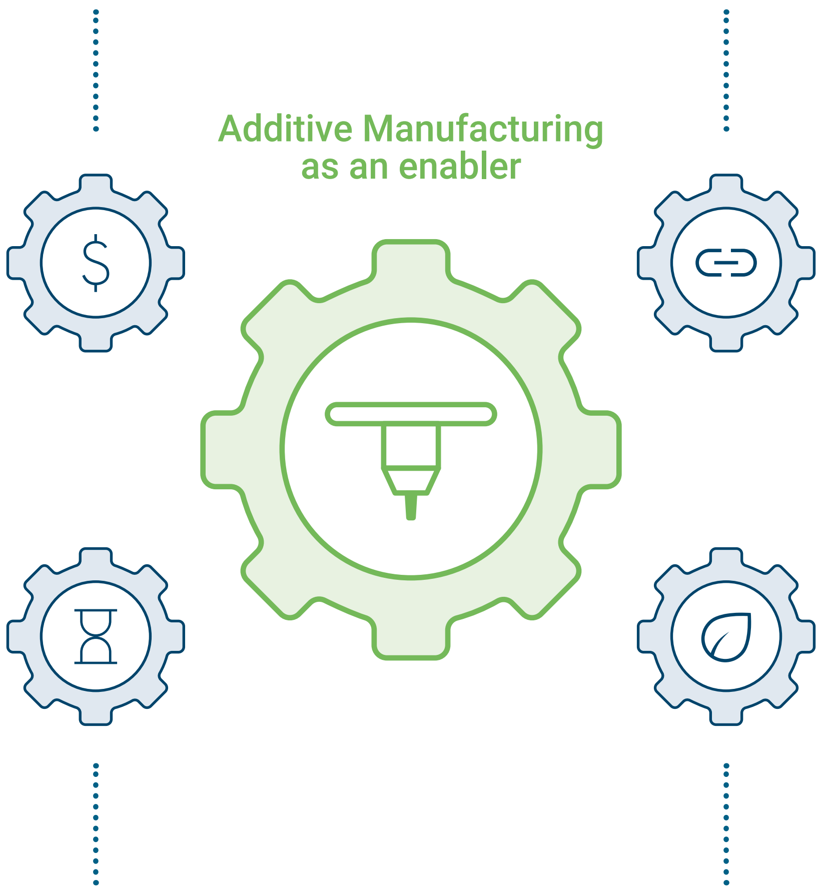
This is where AM becomes a key enabler. By localizing production, AM reduces the need for extensive storage space and minimizes the shipping of parts, directly contributing to cost savings and reduced carbon footprint.

Furthermore, AM's design flexibility offers a significant advantage over traditional manufacturing methods like injection molding. Unlike conventional techniques that impose strict design limitations, AM enables the consolidation of parts, material substitution (e.g., from metal to polymer), and lightweighting. These design enhancements lead to reduced material usage, minimized shipping volumes, and lower transportation footprint—all contributing to a more sustainable supply chain. Additionally, on-demand, localized printing of spare parts reduces downtime, accelerates production, and decreases CO_2 emissions, reinforcing the business case for AM. Throughout the supply chain, AM presents opportunities to drive cost reductions, accelerate lead times, and enhance resilience, making it an important tool for companies aiming to build a more sustainable and competitive future.

However, to fully realize these benefits, it is essential to quantify the business values to motivate the investments through a well-structured business case.

Cost
- **Part Consolidation**
  less manual labor
- **On Demand Manufacturing**
  less waste & less storage cost!

Supply Chain Resilience
- **Local Manufacturing**
  independence of global supply chains and disruptions



Lead Time
- **Distributed Manufacturing**
  faster lead time – no shipping needed
- **Toolless Manufacturing**
  Faster product development
- **Local Spare Part Manufacturing**
  fast reaction time to keep production running

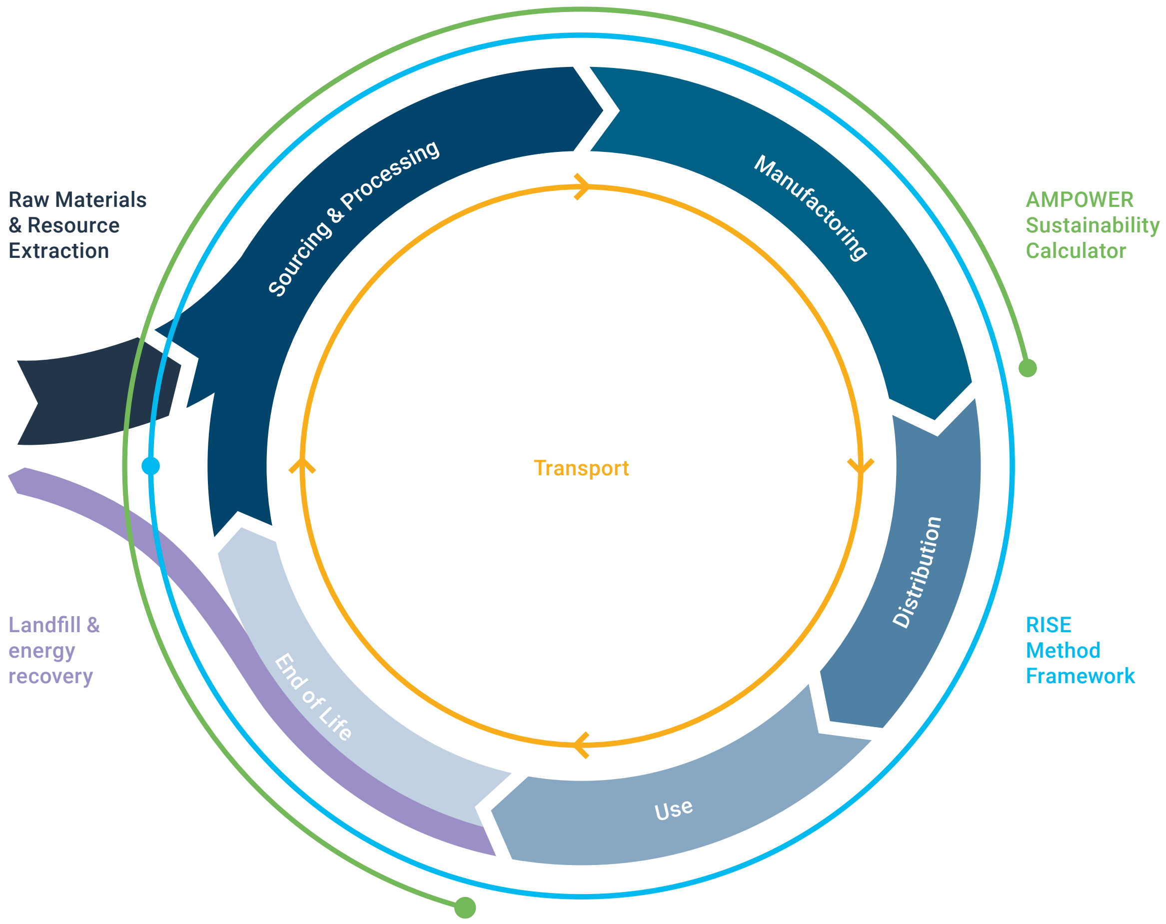
Sustainability
- **Local Manufacturing**
  No shipping and distribution
- **On Demand Manufacturing**
  Less storage needed – over production reduced
- **Toolless Manufacturing**
  Saving of high energy intensive tools

Business and sustainability potential of additive manufacturing over the product lifecycle

The supply chain is the critical link between Earth's natural resources and human consumption. However, its reliance on raw materials, energy, and transportation significantly impacts the environment and sustainability efforts. Key challenges include inefficiencies, material waste, pollution, and negative effects on ecosystems. Additionally, supply chain complexities often lead to disruptions, increased costs, inventory shortages, and lost sales, which strain production schedules and supplier relationships.

Additive Manufacturing offers a transformative solution to many of these challenges. By reducing material waste, lowering transportation emissions, and enabling localized production, AM supports a more sustainable industrial model. The ability to manufacture parts on demand reduces overproduction and excess inventory, while the use of optimized geometries and lightweight designs minimizes resource consumption. Furthermore, AM facilitates the transition to more sustainable materials, reducing reliance on resourceintensive processes.

As industries continue to focus on reducing their environmental impact, AM emerges as a powerful tool in the tool-box for creating more efficient, flexible, and environmental production. By leveraging AM's capabilities, companies can take significant strides toward achieving sustainability goals while maintaining a competitive edge.



Product Lifecycle

Sourcing & Processing

- **Reduced Material Sourcing**
  The freedom of design enables the creation of weight-optimized parts, ultimately reducing raw material consumption.

- **Sourcing & Processing**
  AM Part consolidation design reduce number of suppliers, transports and assembly efforts.

Manufactoring

- **Tool-free Manufacturing**
  Energy intensive steel and aluminum tools for injection molding are not needed in the AM process chain.

- **On demand Manufacturing**
  On-demand production ensures that parts are manufactured to meet actual demand, minimizing inventory, reducing emergency air transport and overproduction.

Distribution

- **Localized Manufacturing**
  Additive manufacturing enables production closer to the point of need, reducing lead times, transportation costs, and supply chain disruptions. However the local energy mix is one of the major drivers of the CO_2 footprint.

- **Reduced Warehousing**
  Shorter lead times reduces the safety stock levels, freeing up capital and storage space and minimize the risk of stock becoming outdated, unsellable and scraped.

Use

- **Improved Parts Availability**
  AM ensures parts are available on demand, reducing air shipments compensating for stockouts and backorders.

- **Increased Product Efficiency**
  Weight and performance optimized designs, unique to AM, allow for an efficiency increase during the usage phase.factured to meet actual demand, minimizing inventory, reducing emergency air transport and overproduction.

Distributed Production with Additive Manufacturing

Scenarios for integration of Additive Manufacturing into the supply chain

AM's original value, as a prototyping technology, is relevant for many businesses. But the shift from prototyping towards production does not only pave the way for product innovation but also for business process innovation such as distributed production and enabling a transformation of the supply chains.

Global companies typically structure their operations based on market proximity, operational efficiency, and cultural and regulatory similarities. This structure varies by company size, industry, and strategic objectives. AM can be strategically deployed across different geographical locations, offering diverse business values, opportunities, and challenges.

Key benefits include reduced inventory, increased parts availability, decreased transportation distances, improved lead times, and enhanced environmental sustainability through reduced material usage and minimized production waste, ultimately lowering CO_2 emissions and energy consumption.

To fully realize these benefits, there is a need for methods to assess AM's impact on supply chains and to calculate and analyze its potential for decentralizing production across a broad array of business values. In collaboration with multiple global OEMs, RISE has identified four distinct scenarios for AM-driven supply chains, each with specific characteristics and impacts. These scenarios provide a structured approach to comparing and optimizing AM implementation within supply chains.

Each scenario presents unique business values and challenges, offering various degrees of decentralization to optimize efficiency, responsiveness, and sustainability in the supply chain.

Scenario A. Conventional Manufacturing (as-is):

This scenario represents the conventional approach, where mass production is conducted in a central factory, and products are distributed globally. This approach offers economies of scale, efficient resource use, and consistent product quality, leading to lower costs and higher output but also results in inefficiencies from long transports, surplus inventory, scrapping and challenges to adapt to fluctuations in demand.

Scenario B. Central AM Production:

In this scenario AM is introduced in the supply chain at a single central location serving the global market. This reduces lead times for complex parts and lowers inventory costs through on-demand production, though transportation and safety stock costs remain. The central scenario leverages the benefits of AM while maintaining a centralized production model.

Scenario C. Regional AM Production:

AM production is distributed to multiple regional centers, reducing transportation distances and lead times as products are produced closer to the point of use. This approach balances centralization and decentralization. By having multiple AM facilities spread across different regions, companies can better serve local markets while still benefiting from the efficiencies of AM. The regional scenario offers a practical middle ground, combining the benefits of both centralized and distributed production.

Scenario D. District AM Production:

Further decentralization to smaller areas like countries or municipalities within a country. This model benefits industries requiring proximity to the customer, high customization and quick turnaround times, significantly reducing lead times and transportation costs. The district scenario takes decentralization a step further by bringing production closer to the end-users but requires production volumes to become a viable option.

Scenario E. Onsite AM Production:

The most distributed manufacturing model, where AM production occurs directly at the point of use, such as in a store, a hospital or a workshop. This minimizes transportation needs and allows for immediate customization and production. The onsite scenario represents the ultimate level of decentralization, where production occurs exactly where the product is needed. This model offers unparalleled flexibility and responsiveness, as items can be produced in real-time based on immediate demand. The onsite scenario might sound visionary, but for the AM usage within R&D and manufacturing support this is one of the most common used scenarios, where low volumes and high mix is often the case.

Scenario A – Conventional manufacturing with a global supply chain

Scenario A represents the current state, where conventional production is concentrated to a central factory and products are distributed globally.

•••• Point of Production

Scenario A offers economies of scale, efficient use of the production resources, and consistent product quality, leading to lower costs and higher output but also results in inefficiencies and challenges that drives the need for more efficient and resilient supply chains.

High Energy and Material Consumption

Current supply chains often rely on energy-intensive production processes and long-distance transportation, leading to significant energy use and greenhouse gas emissions. Inefficiencies in the supply chain, such as overproduction or lack of optimization in transportation routes, further increase energy demands and air shipments. Additionally, the use of non-renewable materials and inefficient recycling practices contribute to high material consumption and waste generation.
Impact: These challenges result in a larger carbon footprint, depletion of natural resources, and increased operational costs.

Complexity and Lack of Visibility

The supply chains of today are typically global and complex, involving numerous suppliers, manufacturers, and logistics providers.
Impact: A lack of visibility into each segment of the supply chain results in inefficiencies, increased risk of errors, and difficulties in identifying and addressing issues.

Transports, Waiting and Lead Times

Waiting and prolonged lead times in a supply chain can be caused by production delays, bottlenecks in manufacturing, transportation slowdowns, customs clearance issues, inventory shortages, equipment breakdowns, supplier inconsistencies, and unexpected demand fluctuations.
Impact: These factors collectively impact the efficiency and timeliness of product delivery and parts availability.

Disruptions and Delivery Variation

Disruptions and delivery variations can result from external factors such as transport delays, production disruptions, or other unforeseen events within the supply chain. Disruptions may also arise from natural disasters, geopolitical events, pandemics, and logistical failures.
Impact: These factors can halt production, delay shipments, and increase costs, ultimately affecting the reliability and efficiency of the entire supply chain. Additionally, they can impact stock levels and tie up capital, leading to further financial strain on businesses.

Demand Volatility

Fluctuations in customer demand can be unpredictable and difficult to forecast accurately, especially with long lead times which increases the risks of forecast errors and changes in the market.
Impact: This can lead to issues such as overstocking or stockouts, inefficiencies in production, and difficulties in meeting customer expectations resulting in air shipments with increased costs and CO_2 emissions.

Maintaining Part Availability and Service Level

Maintaining part availability and high service levels requires balancing demand fluctuations, lead times, delivery variations, inventory levels, and safety stock. Companies must ensure sufficient inventory combined with delivery precision to meet customer demand while minimizing excess stock that ties up capital.
Impact: Stockouts lead to immediate lost sales and can damage customer loyalty. Additionally, excess inventory, due to higher safety stocks, incurs costs for storage, obsolescence, and binds capital, eroding profit margins.

Scenario B - Introducing AM at a central production site

In the central additive manufacturing scenario, AM is integrated in the supply chain at a single central location that serves the global market. This could involve a central production unit or a warehouse with nearby outsourced AM supplier.

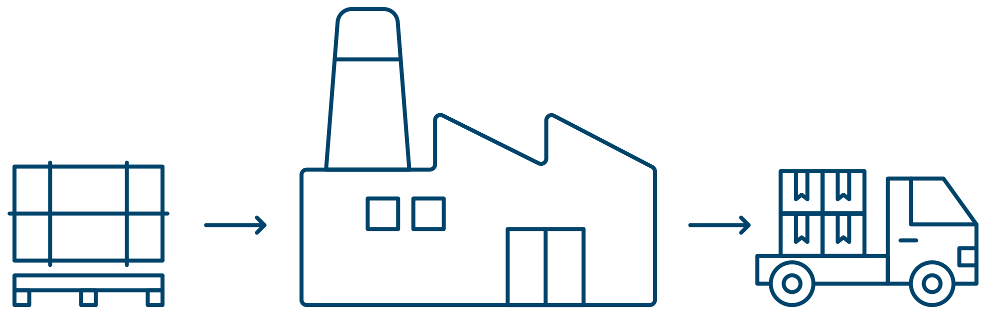
Point of Use

Implementing additive manufacturing at a single, centralized location for the production of end-user parts serving the global market is a common approach, especially within metal printing due to the high investment costs and the specialized expertise required to operate these technologies.

By concentrating production to one location, companies can develop and retain the required specialized expertise, enhancing technical proficiency and reducing production costs.

Centralizing AM production enables companies to fully utilize the technology's key strengths, such as on-demand and produce complex geometries by consolidating multiple components into a single unit. This consolidation significantly reduces the number of parts needed and minimizes assembly steps.

Part consolidation eliminates the need to source multiple components from various suppliers. This is particularly beneficial when parts have long lead times. By streamlining the inbound logistics, companies can shorten production cycles and increase their flexibility in responding to market changes and demand fluctuations.



Inbound complexity reduction
AM can reduce the need for multiple materials and components, simplifying supplier networks and decreasing logistics complexity and risks.

Internal complexity reduction
AM enables more flexible, on-demand production with fewer assembly steps, reducing internal lead times and material waste.

Outbound complexity reduction
The outbound stage remains largely unchanged, as finished products are transported to customers through conventional distribution channels.

Key benefits of centralized AM :

1 Economies of Scale

Centralized production allows for higher volumes, leading to cost savings through economies of scale. Bulk purchasing of materials and streamlined production processes can reduce per-unit costs. Setting up a single AM facility requires a lower initial investment compared to establishing multiple distributed sites.

2 Consistent Quality Control

Maintaining high-quality standards is easier with a single production site. Centralized AM ensures uniformity in production practices, leading to consistent product quality and reduced defects.

3 Resource Optimization

Centralization allows for optimal use of specialized equipment and skilled labor. High-cost AM machines and expert personnel can be concentrated in one location, maximizing their utilization and efficiency.

4 Simplified Supply Chain Management

Managing logistics, inventory, and supplier relationships is more straightforward with a single production site. This reduces complexity and administrative overhead, improving overall supply chain efficiency.

Scenario C/D - Distributing AM to regions and districts

While centralized manufacturing offers advantages, it falls short reducing the outbound complexity. In the regional AM scenario, additive manufacturing is distributed across multiple regional production centers.

Scenario C.

•••• Point of Use

Scenario D.

In the Regional AM scenario, additive manufacturing is distributed across multiple regional production centers, typically serving broad geographical areas such as continents or large groups of countries. This approach significantly reduces the supply chain complexity by reducing transportation distances, leading to shorter lead times and lower logistics costs. Regional AM production allows companies to balance the benefits of centralization with the flexibility of localized manufacturing, optimizing production efficiency while meeting regional market demands more effectively.

Taking decentralization further, the District AM scenario localizes production even more by establishing AM facilities at a district or municipal level. This structure enables companies to respond rapidly to local market needs, making real-time adjustments in production based on specific regional preferences.

By placing manufacturing closer to the point of consumption, companies benefit from increased flexibility, improved service delivery, and a reduction in both transportation costs and environmental impact. District AM fosters stronger connections with local markets, offering a highly adaptable solution to fluctuating demands.

Key benefits of regional and district AM :

1

Reduced Transportation Costs and Emissions

Producing goods closer to the point of consumption reduces the need for long-distance transportation. This lowers transportation costs and significantly cuts down on greenhouse gas emissions, contributing to a more sustainable supply chain.

2

Reduced Lead Times

Decentralized production can respond more quickly to local demand fluctuations. This agility reduces lead times, ensuring that products are delivered faster and more efficiently to customers. Leadtime reduction.

3

Match Fluctuations in Demand

With shorter lead times and production spread to multiple regions, companies can maintain lower inventory levels and reduce the risk of overstocking or stockouts. This improves inventory turnover and reduces inventory costs.

4

Improved Supply Chain Resilience

Distributed manufacturing mitigates the risk of supply chain disruptions caused by geopolitical events, natural disasters, or other unforeseen circumstances. Regional facilities provide redundancy and flexibility, enhancing overall supply chain resilience.

Scenario E - Onsite AM

The onsite AM scenario represents the most distributed approach, where production takes place directly at or near the point of use. This could be in a workshop, a store, a hospital, a dental office, or within a mobile container.

While the onsite AM scenario may seem visionary, it is actually a common practice in applications like research and development (R&D) and manufacturing support. In these contexts, manufacturing aids and prototypes are often produced on-site for internal use. The main driver of this approach is the facilitation of real-time production based on immediate demand, which offers unparalleled flexibility and responsiveness. The success of onsite AM in these applications is further enhanced by localized manufacturing, which encourages innovation and customization. Companies can experiment with new products and processes without the significant overhead typically associated with traditional manufacturing setups. This agility fosters a culture of creativity and rapid iteration.

One advantage of onsite AM is its ability to efficiently produce small batches and one-offs on demand. Onsite AM systems enable companies to match production to demand and with minimal disruption. This adaptability shortens production cycles and allows for more effective responses to shifting needs, consumer preferences, and customization. Moreover, Onsite AM enhances supply chain resilience by distributing manufacturing capabilities across multiple locations, which is particularly advantageous in military applications. Each site can operate independently, fulfilling localized demand and ensuring continuity of supply.

However, it is essential to acknowledge that while onsite AM offers significant flexibility and reduced logistics costs, it usually require higher investments and entail operational complexities compared to centralized AM manufacturing. Companies must ensure consistent quality across different sites and align processes to maintain efficiency and uniformity in product output. These mentioned challenges all lead to a currently low use of onsite production capacities for end user parts.

Key benefits of Onsite Manufacturing:

1 Flexibility and Real-Time Production

Onsite AM facilitates real-time manufacturing, allowing products to be produced immediately based on actual demand. This flexibility ensures that companies can respond quickly to market changes and customer needs, reducing the reliance on large inventories and minimizing lead times.

2 Customization and Innovation

The decentralized nature of onsite AM supports localized manufacturing, encouraging innovation by allowing companies to customize products easily. Without the high overhead costs typically associated with centralized manufacturing setups, companies can prototype and iterate on new designs rapidly, fostering a culture of creativity and agility. This approach is e. g. already heavily used by dental laboratories for customized retainers.

3 Supply Chain Resilience

By distributing manufacturing capabilities across multiple locations, onsite AM reduces the risk of supply chain disruptions. Still the material needs to be provided unless a closed loop material circle has been established. Each production site operates independently, ensuring that localized demand is met and continuity of supply is maintained, which is particularly beneficial in critical applications like military logistics.

Tools and methods to calculate business value and sustainability of AM cost drivers

A detailed look at the complete process chain

The AMPOWER Sustainability Calculator enables the calculation of various material and technology combinations while allowing customization of manufacturing processes. To ensure a comprehensive analysis, the entire process chain, from material manufacturing to post-processing, is considered and incorporated.

The AMPOWER Polymer Sustainability Calculator enables users to calculate and compare all established AM technologies, including SLS, MJF, SLA, DLP, and FDM, against injection molding as a traditional manufacturing method.

Each AM process is analyzed in detail and broken down into granular process steps. The tool includes both mandatory and optional steps, such as chemical polishing and coloring, providing a comprehensive presentation of the production workflow. For each process step, a detailed model, incorporating all input and output parameters is used. Based on this model, the Sustainability Calculator determines energy and material consumption and converts it into CO_2 emissions.

Additionally, users can seamlessly integrate their specific raw material data, whether pellets, powder, or filament, using data provided by their material supplier.

1:1 comparison
Adopting identical part properties for an early-stage evaluation or if no further part optimization has been done.

Process specific part geometry
Detailing part properties for each manufacturing technology increases calculation accuracy and allows for a "fair" comparison between technologies.

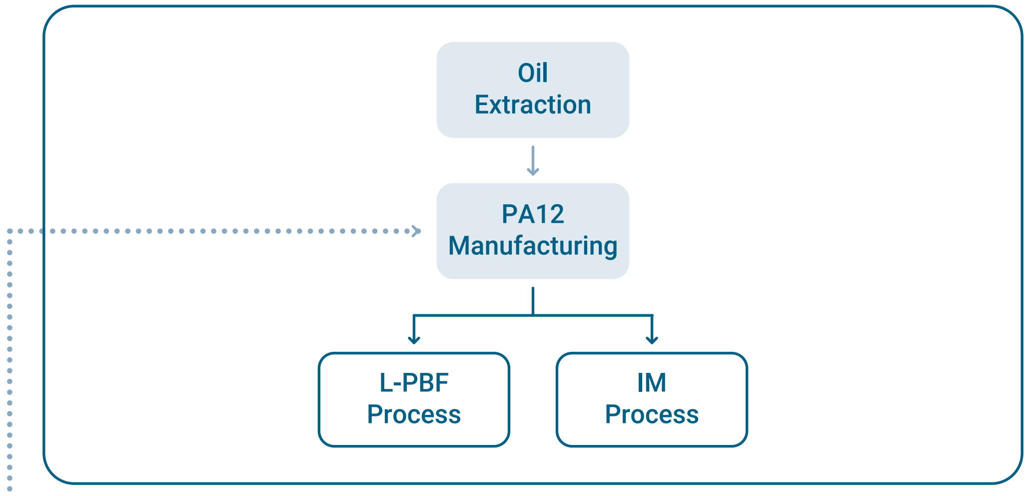
Part

		SLS	MJF	SLA	DLP	FDM	Injection Molding	
Volume								
- final part	65							cm³
- support	10							cm³
- % infill								%
Dimension X	57							mm
Dimension Y	95							mm
Dimension Z	100							mm
Material (-Process)	PA12			Resin	Resin	PA6	PA6	
Quantity	250							parts
Parts per buildjob (optional)								parts
Build times per buildjob (optional)								
- Recoating								h
- Deposition								h
Process								
- Refresh rate ?		50	30					%

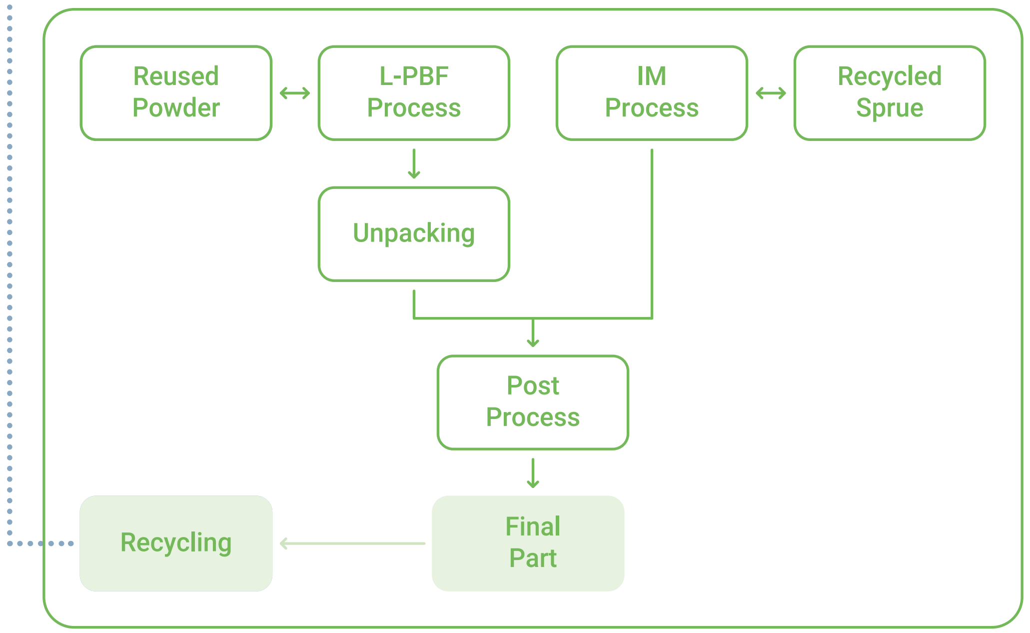
Material choice
The choice of material group influences the resulting CO_2 footprint significantly. The drop-down menu allows the selection of powder, resin filament and pellet material.

Process Optimization
All processes can be tuned towards the specific parameters of the user. More adoptions can be made in the backend.

Calculation based on CO_2 emissions per kg of produced material



Calculation based on energy consupmtion in kWh/kg



During the early stages of development and design, many details required for a comprehensive Life Cycle Assessment (LCA) are not yet available. However, estimating and comparing the CO_2 footprint of different design alternatives and manufacturing technologies can serve as a valuable decision-making parameter.

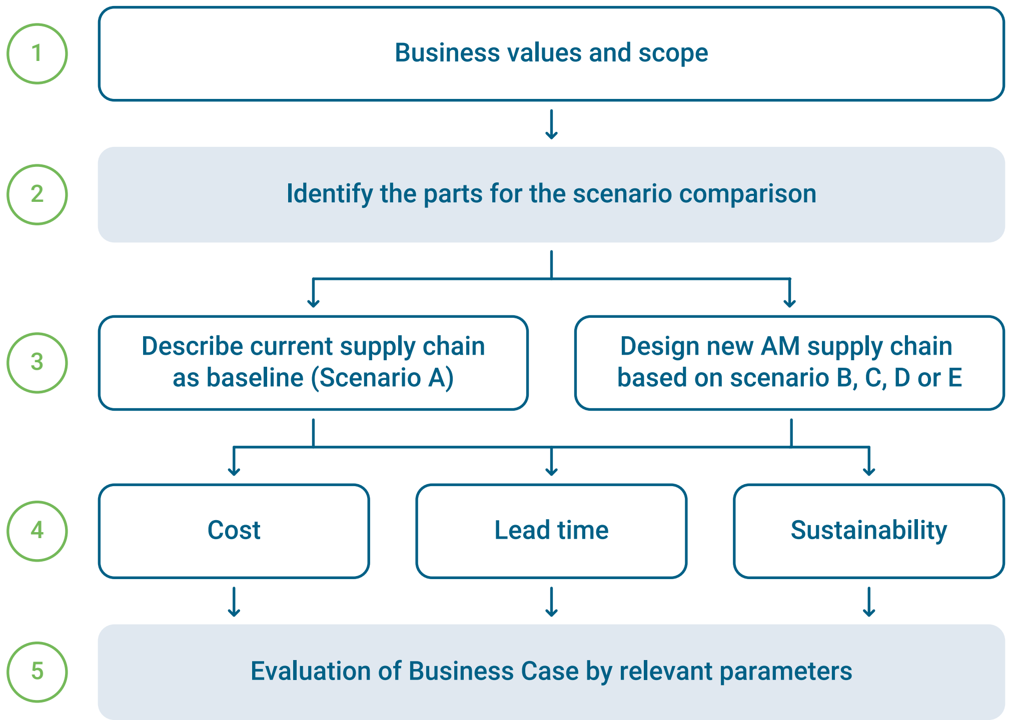
AMPOWER's Sustainability Calculator provides a fast and easy way to evaluate and compare these footprints.

Using a generic approach, the tool requires only minimal input parameters to calculate the CO_2 footprint across various manufacturing technologies. Additionally, if alternative or optimized part designs are available, the tool enables a direct comparison between conventional and optimized designs. This ensures the highest result accuracy and enables a fair comparison between different manufacturing methods.

Calculating the business value of Additive Manufacturing

Traditional methods for assessing the business value of AM often focus on cost. However, AM impacts multiple aspects of the supply chain, including lead times, inventory levels, and sustainability.
To build a strong business case, companies need a comprehensive view of the business values.

Life Cycle Assessment (LCA) is essential for analyzing environmental impact, but a comprehensive business case for AM must also integrate lead times and costs. In collaboration with industry partners, RISE, Research Institutes of Sweden, has developed a structured framework to analyze AM's impact on the supply chain. This framework enables businesses to compare traditional centralized manufacturing with four AM scenarios, evaluating key parameters such as cost, lead time, and environmental impact (CO_2e, material consumption, and energy usage) to support a well-founded business case.



1 Define business values, scenarios and build your team

To identify the business value of AM within your company, a multidisciplinary team is typically required. The specific expertise needed depends on the business areas being explored, but often includes specialists from engineering, production, supply chain, procurement, sustainability, sales, and customers/suppliers. This ensures that the team has the right competencies to cover the entire value chain.

To calculate the business value of AM in your supply chain, you need to select the most relevant AM scenarios for comparison. The following steps can guide your selection:

1. Determine the product lifecycle phase – Identify whether AM will be applied to New product development, production or aftermarket (spare parts).

2. Define AM production characteristics – Assess whether the AM setup will focus on high-mix, low-volume production or low-mix, high-volume production.

3. Evaluate your company's AM maturity – Align the scenario selection with your organization's current experience and readiness in adopting AM.

By systematically selecting AM scenarios based on these factors, you can ensure a meaningful comparison that supports well-founded business decisions.

The purpose of the framework is to help companies to make informed decisions by providing a clear business case which motivates further steps and investments in the AM adoption.

2 Identify the parts for the scenario comparison

The selection of parts is driven by the specific business values being targeted. Parts can be chosen from existing spare parts catalogs or new development projects.

Common selection criteria are part size, safety criticality, material requirements, price, and production volume. For instance, large parts with strict safety requirements, or those made from materials not suited for current AM technologies are typically excluded. Low-volume parts are often prioritized, as AM provides cost advantages for small batch production. Mature companies often use dedicated screening tools to assess the technical feasibility of AM. These tools help identify which parts can be efficiently transitioned to AM, considering factors such as material compatibility and design constraints.

Based on these evaluations, usually 5–10% of parts from a spare part catalog are identified as suitable for AM (using current technologies).

3 Perform Supply Chain modelling

Modelling the supply chain for the selected parts enables an analysis of the key cost drivers, lead times, material and energy consumption, and CO_2 emissions throughout the supply chain. The supply chain modelling is carried out in a top-down approach to enable efficient analysis and different resolutions depending on which business values is the focus for the scenario comparison.

High-Level Modelling of the supply chains
The supply chain analysis begins with high-level modeling to identify key areas and hotspots where detailed modeling are needed. First step is to model the current supply chain (Scenario A) for the selected parts using key supply chain nodes such as:

- Supplier locations (tier 1–n)
- Production facilities
- Central warehouses
- Regional warehouses
- Logistical nodes (seaports, airports, train stations, cross-docking hubs)
- Customer sites (sales offices, repair workshops, etc.)
- Transport modes between the nodes in the supply chain

Once the current supply chain has been mapped, alternative AM scenarios (B-E) are developed and analyzed. Unlike the current state, the "To-Be" scenarios often require assumptions and estimations to enable meaningful comparisons. For instance, a make-or-buy analysis can help determine whether AM production should be in-sourced at an existing facility or outsourced to a service provider. High-level modeling also helps identify key hotspots that require further investigation with a detailed modelling.

Detailed Modelling of the supply chain
The purpose of the detailed modelling is to explore the identified hotspots with the required level of detail for deeper insights. The following tools can be effectively used to further refine the analysis and achieve the desired results:

SCOR - The Supply Chain Operations Reference (SCOR) model is a globally recognized framework for supply chain modelling. It provides generic activities, allowing different supply chains to be modelled and compared using standard set of activities.

Life Cycle Analysis (LCA) – Evaluates environmental impacts, such as CO_2 emissions and energy consumption.

Life Cycle Cost Analysis (LCC) – Assesses costs throughout the entire supply chain, from raw materials to disposal.

Value Stream Mapping (VSM) – Identifies inefficiencies by mapping material and information flows, helping to reduce waste and improve lead times.

4 Collect and generate data

Data for the calculations based on scenario 1 supply chain modelling can be collected from several databases available within your company. The following data sources can be used:

Data Sources

- Supply chain and transport data bases
- Warehouse and inventory management systems
- Supply and demand planning data bases
- Engineering and product data databases

To obtain future-state data is needs to be calculated, estimated or generated using tools such as AMPOWER Sustainability Calculator or the NTM calculator used in the illustrative case to calculate CO_2e emissions.

5 Create the business case and present

Depending on the business objectives identified in step 2, the final presentation of the comparison can have different formatting, as transport CO_2e and Lead Time (figure 6).

Reference:

Eriksson, M., Van Loon, P., Widfeldt, M. & Kurdve, M. (2024).
Framework for comparing business value of decentralized additive manufacturing with conventional manufacturing, Euroma Conference, Madrid, Spain, July 1-3 2024.

Building a business case on AM through sustainable production and logistics

COURTESY OF MATERIALISE

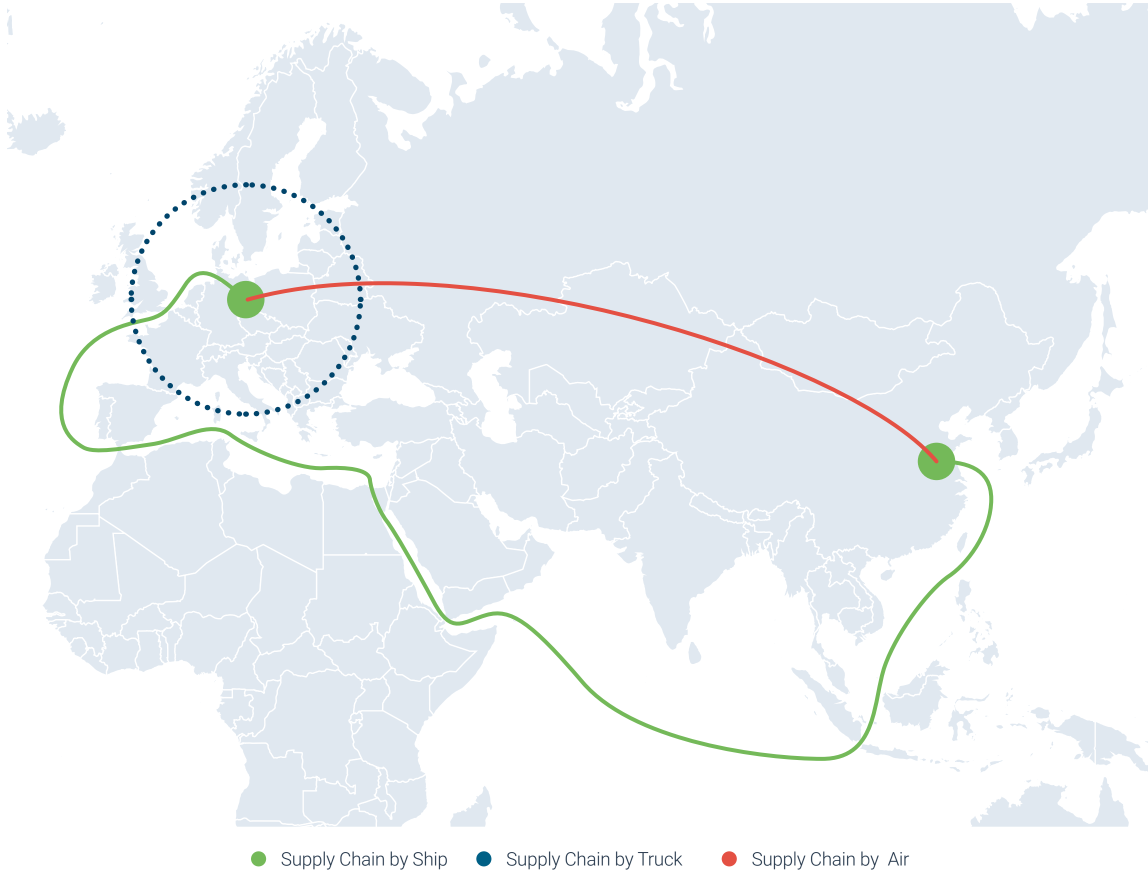
Illustrative case how to calculate the business values of distributed production in the automotive Industry

To illustrate how the tools and methodology presented in the previous chapters can be applied, we use a illustrative automotive supply chain scenario A for spare parts produced in China and distributed to Europe. We compare this with a distributed scenario C where production is moved to a central location in Europe. This comparison involves multiple processes and factors that impact the key parameters in this analysis: lead time and CO_2 emissions.

Selected parts for the case
To identify components suitable for AM from a technical perspective, several key criteria were applied, including part size, safety criticality, material properties, and production volume. Part screening tools specifically designed for the technical evaluation of parts' printability was used.

Production Method assumptions
Only polymers, injection molding, 5 different AM polymer technologies.

Additive Manufacturing production should be Insourced at an existing production facility or outsourced to a service partner. In this case it is assumed that the production is initially outscored to a service provider.



Supply Chain assumptions and scenario selection
The case study is based on the Yangtze River Delta region, including Shanghai, Jiangsu, and Zhejiang provinces—one of the world's largest hubs for automotive parts manufacturing and exports. This region has a dense network of automotive suppliers and proximity to major ports such as Shanghai Port and Ningbo-Zhoushan Port, facilitating exports to Europe.

Logistics and Transport Assumptions
80% of the parts are transported via sea freight, the most cost-effective mode.

20% are shipped by air, mainly for urgent orders or to handle demand fluctuations.

Parts shipped by sea arrive in Hamburg, a key European port, before being transported by truck to centralized distribution warehouses.

Parts shipped by air arrive Leipzig/Halle Airport (LEJ). This airport is a major logistics hub in Germany, often handling cargo flights from Asia. From here, parts can be distributed across Germany and to Hamburg by road.

Warehouse Assumptions
The major warehousing locations considered are:

A central logistics hub with warehouses situated near the port, allowing for fast unloading of sea freight and efficient redistribution.

Harburg and Maschen (South of Hamburg) was selected for their large-scale logistics infrastructure. Maschen is for example home to one of Europe's largest rail freight yards. The selected location also offers direct access to major highways (A1, A7), facilitating fast truck transport to central and regional warehouses.

The Inventory levels are balance availability demands and costs and the size of the levels are optimized for sea transport.

Safety stock policies are based on the replenishment lead times from sea transport and MOQ (Minimum Order Quantity).

From there, spare parts are distributed across Europe by truck, impacting carbon emissions and lead times based on distance to dealers.

High level modelling of the current supply chain (Scenario A)

Modelling the supply chain for the selected parts enables an analysis of the key cost drivers, lead times, material and energy consumption, and CO_2 emissions throughout the supply chain. The supply chain modelling is carried out in a top-down approach in steps to enable efficient analysis and facilitate the required resolution.

The high-level modeling of Scenario A begins with mapping the current supply chain for the selected components. During this modeling, key logistical nodes are identified, playing a central role in the flow, In the selected case the current supply chains are modeled using the following entities:

- Suppliers and production facilities
- Ports and airports
- Mode of transports
- Location of central and regional warehouses
- Location of customer

Data for the calculations based on scenario A supply chain modelling can be collected from several databases available within your company. The following data sources can be used.

- Supply chain and transport data bases
- Warehouse and inventory management systems
- Supply and demand planning data bases
- Engineering and product data databases

To calculate the transport related CO_2e emissions in the scenarios the Network for Transport Measures (NTM) tool were used. The NTM tools employ a calculation methodology consistent with the CEN standard EN 16258, which is designed for assessing greenhouse gas emissions and energy use across the different transport modes road, rail, sea, and air.

Regular Supply Chain - Sea Transport

Supply Chain (Sea)	Order Handling	Supplier Manufac-turing & Ware-house	Road Transport	Sea port/ Customs	Sea Trans-port	Sea port/ Customs	Road Trans-port	Regional Ware-house (SoD -> SIT)	Road Trans-port	Dealer/ Customer	
Lead Time											**86 days**
Order / Planning	1 day	2 day	–	–	–	–	–	1 day	–	–	4 day
Set-up and production	–	14 day	–	–	–	–	–	–	–	–	14 day
Transport (Truck)	–	–	1 day	–	–	–	1 day	–	1 day	–	3 day
Transport (Sea)	–	–	–	4 day	45 day	4 day	–	–	–	–	53 day
Wait	–	2 day	–	2 day	–	1 day	1 day	4 day	1 day	1 day	12 day
Environmental Sustainability (CO_2e per shipped kg)											**0.42 kg**
Manufacturing CO_2e	–	CO_2 Hotspot*	–	–	–	–	–	–	–	–	
Transport CO_2e Regular	–	–	0.03542 kg	–	0.3179 kg	–	0.001269 kg	–	0.06249 kg	–	
Warehouse Safty Stock level index											**1.0**

*high-level level modelling reveals a hotspot that requires a detailed analysis in the following pages

Express Supply Chain - Air Transport

Supply Chain (Air)	Order Handling	Supplier Manufac-turing & Ware-house	Road Transport	Air port/ Customs	Air Trans-port	Air port/ Customs	Road Trans-port	Regional Ware-house (SoD -> SIT)	Road Trans-port	Dealer/ Customer	
Lead Time											**39 days**
Order / Planning	1 day	2 day	–	–	–	–	–	1 day	–	–	4 day
Set-up and production	–	14 day	–	–	–	–	–	–	–	–	14 day
Transport (Truck)	–	–	1 day	–	–	–	1 day	–	1 day	–	3 day
Transport (Air)	–	–	–	2 day	2 day	2 day	–	–	–	–	6 day
Wait	–	2 day	–	2 day	–	1 day	1 day	4 day	1 day	1 day	12 day
Environmental Sustainability (CO_2e per shipped kg)											**4.95 kg**
Manufacturing CO_2e	–	CO_2 Hotspot*	–	–	–	–	–	–	–	–	
Transport CO_2e Express	–	–	0.03122 kg	–	4.850 kg	–	0.03002 kg	–	0.06249 kg	–	
Warehouse Safty Stock level index											**1.0**

*high-level level modelling reveals a hotspot that requires a detailed analysis in the following pages

High level modelling of regional AM production Supply chain (Scenario C)

To produce end-user spare parts Scenario C has been chosen in this illustrative case. Regional AM scenario, balances decentralization and efficiency, easily integrating into existing supply chain structures while reducing transportation costs and lead times across regions.

In Scenario C, where AM is distributed to a regional distribution center, three main strategies are typically considered for sourcing and locating the production:

- Locating AM production at the distribution center premises.
- Establishing AM at an existing production unit near the regional distribution center.
- Outsourcing AM production to a nearby service bureau.

Initially, many companies lean toward Strategy 3, despite the higher costs and lead times, because it offers strategic advantages such as flexibility and reduced capital investment. However, as AM production volumes grow over time, companies often shift toward Strategy 2, which provides benefits like cost savings, reduced lead times, improved operational control, and enhanced quality assurance.

To evaluate the impact of regional AM, the "To-Be" scenario is modeled according to scenario C which in our illustrative case, leads to the following high-level modeling of the supply chain.

As lead times are reduced through the introduction of AM, companies can realize significant savings in tied-up capital, particularly in terms of reduced safety stock levels. These savings can be calculated using various methods. In this illustrative case, we have applied the square root rule to estimate the reduction in tied-up capital. This method involves multiplying the old safety stock level (Index 1) by the square root of the ratio between the current and new lead times after implementing AM. The resulting ratio indicates by how much safety stock can be reduced, which is then expressed as a percentage reduction.

In this illustrative case the lead time of the sea route serves as the key dimensioning factor for the safety stock, as 80% of the volume is expected to be shipped via sea.

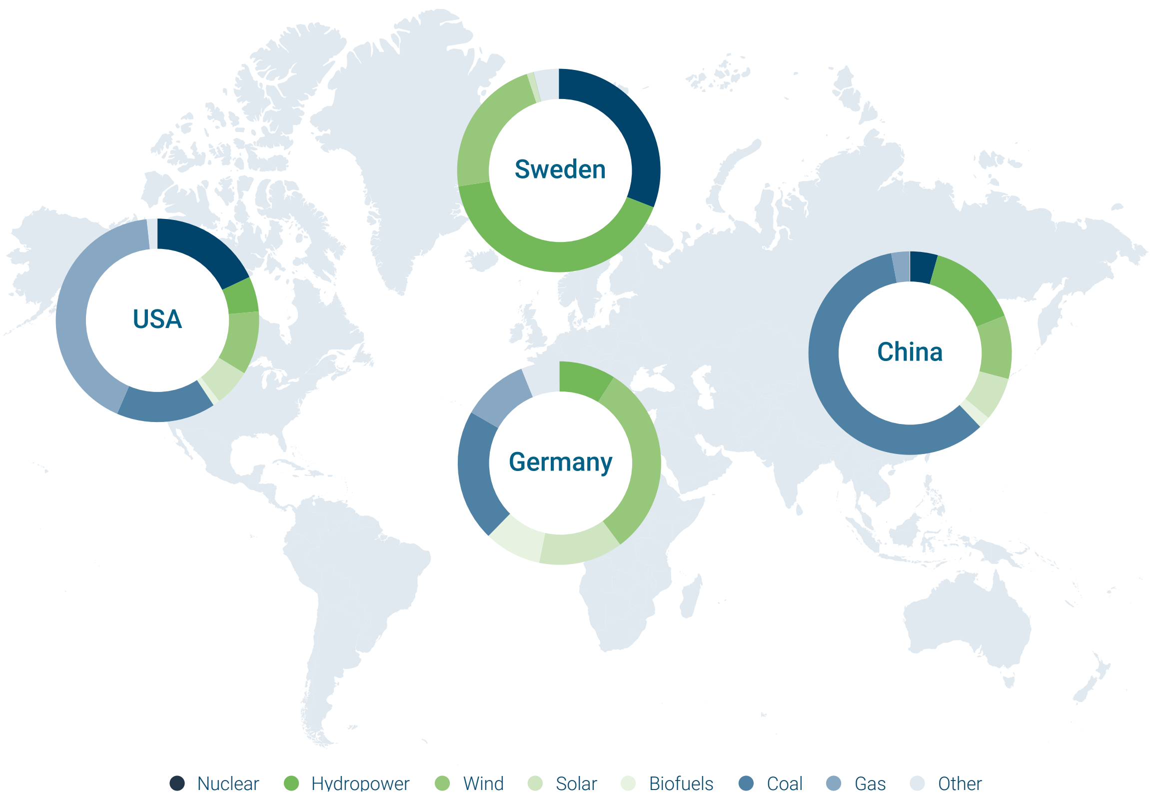
Regional AM Production

Regular flow (AM)	Order Handling	Supplier Manufacturing & Warehouse	Road Transport	Regional Warehouse (SoD -> SIT)	Road Transport	Dealer/Customer	
Lead Time							**9 days**
Order / Planning	1 day	1 day	–	–	–	–	2 day
Set-up and production	–	2 day	–	–	–	–	2 day
Transport (Truck)	–	–	1 day	–	1 day	–	2 day
Wait	–	–	–	2 day	–	1 day	3 day
Environmental Sustainability (CO_2e per shipped kg)							**0,063 kg**
Manufacturing CO_2e	–	CO_2 Hotspot*	–	–	–	–	
Transport CO_2e Regular	–	–	0.001269 kg	–	0.06249 kg	–	
Warehouse Safty Stock level index							**0.32**

*high-level level modelling reveals a hotspot that requires a detailed analysis in the following pages

Detailed modelling and calculation of how the local energy mix impact the environmental sustainability of manufacturing

The high level modelling indicate that both scenario A and C is highly dependent on the local energy mix used for production, which directly influences CO_2 emissions per part. While some countries still rely on fossil fuels such as coal and gas, others have already transitioned to renewable energy. This disparity can result in a tenfold or greater difference in CO_2 emissions during part production.

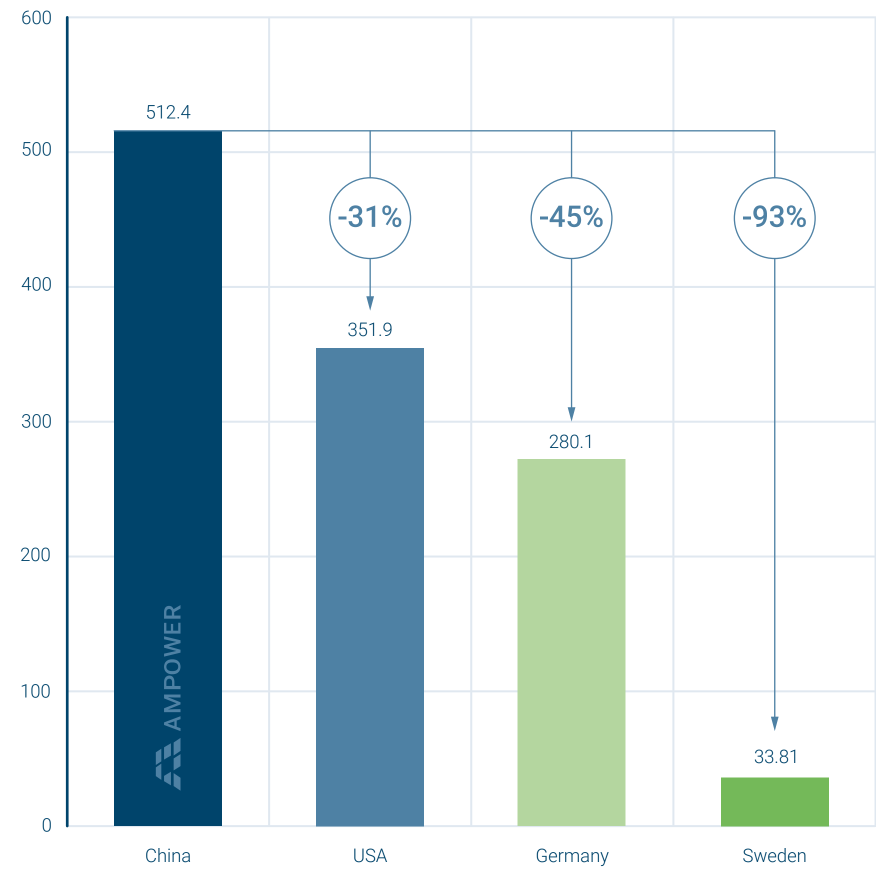


When comparing the energy mix across different regions worldwide, substantial variations become apparent, largely dictated by the energy sources available and utilized. Highly industrialized nations, such as Germany, the United States, and China, remain heavily reliant on fossil fuels like natural gas and coal. In contrast, other countries, such as Sweden, demonstrate a strong commitment to renewable energy, with a notable mix of hydropower and wind energy forming the backbone of their energy systems.

These differences in CO_2 emissions per kWh are particularly significant when analyzing energy-intensive manufacturing processes like injection molding and Additive Manufacturing. Since these technologies demand considerable energy inputs, their environmental impact is closely tied to the carbon intensity of the energy source.

Considering that China serves as the global hub for producing polymer parts through additive manufacturing, there exists a substantial opportunity to reduce CO_2 emissions. This can be achieved by optimizing the energy mix used in these production processes, effectively lowering emissions independently of the manufacturing technology itself.

Average CO_2 Emissions per kWh in different locations [gCO_2eq/kWh]



Source of local energy mix: https://lowcarbonpower.org/

Comparison of CO_2 Emissions of low volume production methods

Regional AM production adds significant value to low-volume manufacturing processes by enabling simple supply chains and distributed, on-demand production. In turn, this leads to lower energy consumption in production, influenced by the local energy mix and the advantages of additive manufacturing as a toolless manufacturing method.

As a basis for the following calculations, certain parameters had to be set. This includes the previously discussed values for the energy mix of different countries. Additionally, the AMPOWER Sustainability tool considers various parameters along the process chain, including the energy required for material production, the energy consumed during manufacturing, and post-processing steps. Details can be found in the introduction chapter of the calculator.

In addition to these parameters, a general framework was considered for this exemplary case, including the following conditions:

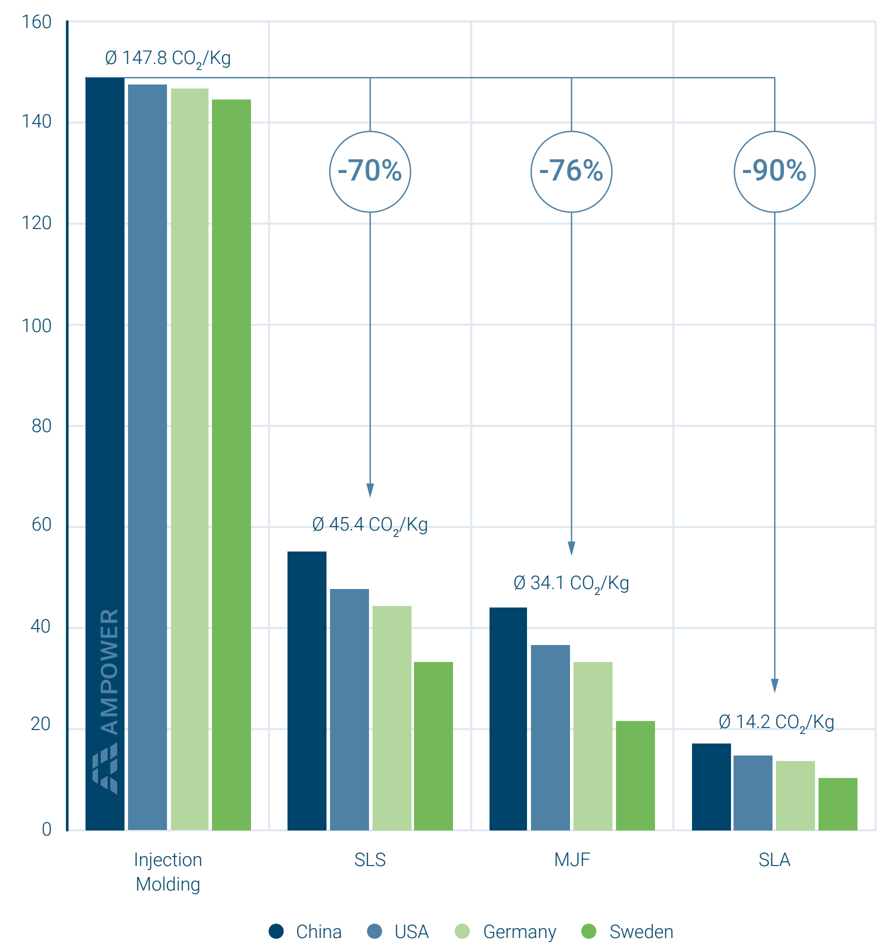
1. **Part Size:** up to 200 x 100 x 100 mm³
2. **Production Volume:** up to 5.000 Parts/Year
3. **Material:**
   - SLS: PA12
   - MJF: PA12
   - SLA: Tough Resin
   - Injection Molding: PA6
   - Injection Molding Tool: Steel

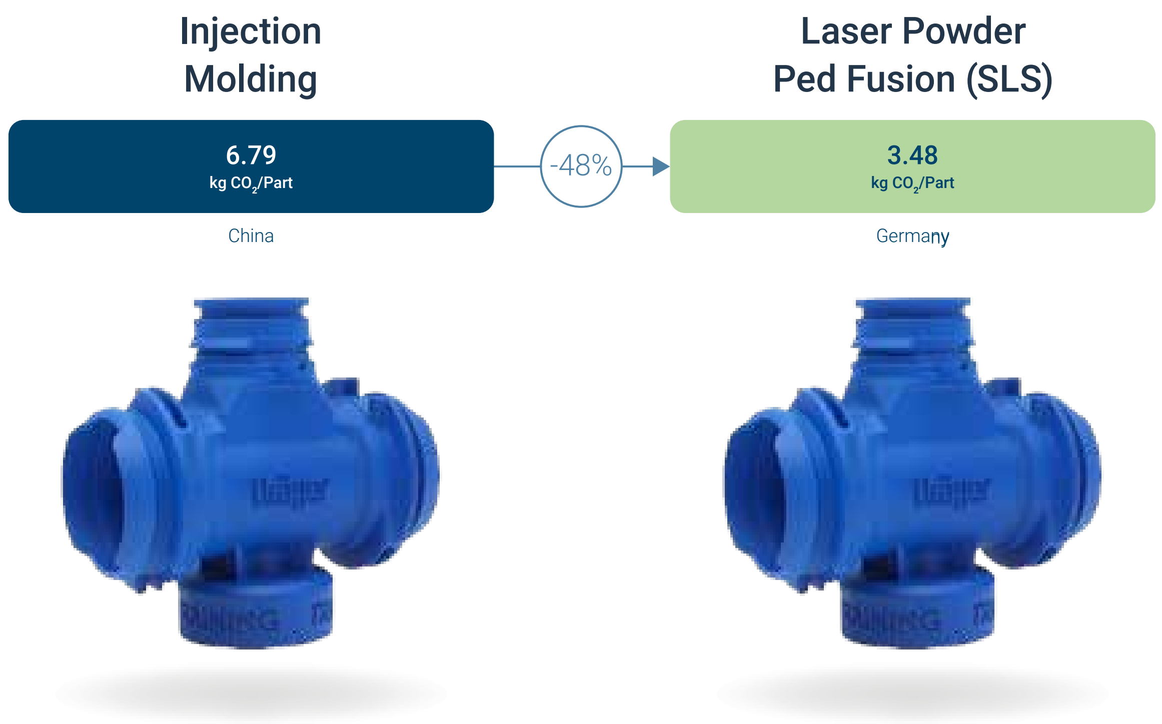
Taking these factors into consideration, we have calculated several parts to determine an average value for the CO_2 emissions caused by different manufacturing processes.

When analyzing the calculations, we see that additive manufacturing has significant potential to reduce CO_2 emissions for low-volume part production, considering only the manufacturing process itself. Comparing AM technologies such as SLS, MJF, or SLA with injection molding reveals a potential CO_2 emission reduction of up to 76% for powder-based processes and even 90% for resin-based processes like SLA. The high energy demand for low-volume injection molding is primarily driven by the production of complex steel tools, which are extremely energy-intensive to manufacture and source materials for. However, this factor diminishes with high-volume production.

If we also take the energy mix into account, the potential savings become even more significant. Relocating the production of low-volume products from China to countries like Sweden could enable users to achieve an 85% CO_2 reduction for thermoplastics such as PA12 and a 93% reduction for thermoset materials (resins). These figures do not yet account for additional benefits such as reduced transportation emissions, shorter lead times, and other contributing factors.

Average CO_2 Emissions per KG of produced material [Avg. Kg CO_2/Produced Part]





Courtesy of DRÄGER / Annual part volume: 250

Comparison of Scenarios – Regional AM Production has potential to decrease emissions by 70%

Regional AM production saves time and resources throughout the entire process chain. Scenario C, therefore, presents a valuable business case for the automotive industry and many others that rely on sourcing numerous parts from abroad, particularly for low-volume production.

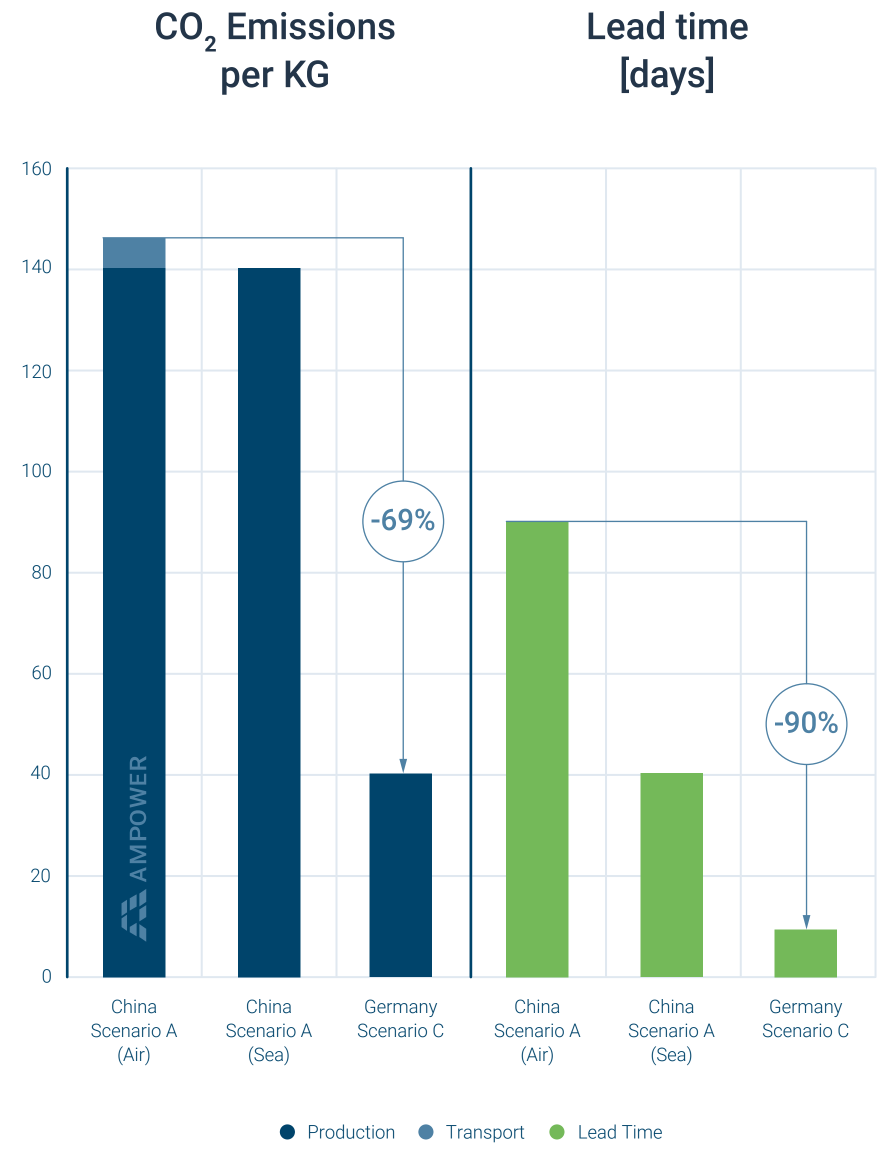
The global supply chain has traditionally relied on sourcing parts from abroad, with many Western companies outsourcing mass production to Asia for cost advantages. While this trend is likely to continue for high-volume production, additive manufacturing offers a compelling alternative for low-volume production—delivering significant savings in time, resources, and costs. Let's explore the key factors driving this shift.

Lead Time
Sourcing parts from China typically involves long lead times, primarily due to transportation, with delays further compounded by the need to manufacture injection molding tools. Regional AM production dramatically shortens lead times by eliminating the need for tooling and reducing transportation. Scenario C, for example, can reduce lead times by up to 80 days, streamlining supply chains and accelerating product availability.

Transportation
Scenario C also reduces transportation emissions by localizing production. Regional AM can lower CO_2 emissions from transportation by up to 98%, optimizing sustainability throughout the supply chain. When production is considered alongside transportation, the emissions from shipping become nearly negligible in comparison.

Production
Beyond logistics, Regional AM offers environmental benefits from the use of cleaner, localized energy mixes. While AM processes can be energy-intensive, regions like Germany or Sweden benefit from a cleaner energy mix compared to China. Shifting production from China to Germany could reduce manufacturing emissions by 70%, with even greater reductions achievable when renewable energy sources are utilized in regions with predominantly green energy.

By incorporating Regional AM into supply chain strategies, companies can achieve faster lead times, reduce transportation emissions, and enhance production sustainability—all while maintaining cost efficiency for low-volume manufacturing.



Around 70% CO_2 emission reduction by regional AM production!

Lead time of components is reduced to days instead of months!

Summary

Summary

Regional AM production reduces transportation-related emissions and enhances supply chain flexibility. The sustainability impact of AM is heavily influenced by the regional energy mix, highlighting the need to assess local energy sources. With its ability to achieve short lead times, AM remains a viable solution for mitigating supply chain disruptions while promoting a more sustainable and resilient future.

Distributed production is a key driver of sustainability and supply chain resilience for AM

Distributed production plays a crucial role in enhancing sustainability and supply chain resilience through additive manufacturing. By localizing production, AM reduces dependency on long-distance transportation, cutting carbon emissions and energy consumption associated with global logistics. It also boosts supply chain flexibility by enabling quicker response times, shortening lead times, and reducing inventory. Producing closer to the point of use helps mitigate risks from geopolitical instability, trade barriers, and global disruptions. Leveraging AM for Distributed production empowers companies to create a more sustainable, efficient, and resilient manufacturing ecosystem.

Major gains in lead time while transportation of small volumes has limited environmental impact

With distributed production transport-related CO_2 emissions can be reduced by up to 98% with AM. However, since transportation accounts for a small fraction of the total CO_2 emissions associated with producing and transporting a part, the overall environmental impact is limited for small volume production. The most substantial benefit of regional AM manufacturing lies in its effects on lead times and business agility. In the case presented, lead time was reduced from 84 days to just 9 days—an 90% improvement. This reduction has two key effects:

Local energy mix is a critical factor for AM sustainability

The sustainability impact of additive manufacturing is heavily influenced by the local energy mix used in production. While AM supports on-demand manufacturing, minimizing both overproduction and stock-outs as well as backorders, its energy consumption remains a key consideration In regions dependent on fossil fuels, AM's carbon footprint can be significantly higher compared to areas powered by renewable energy.

Challenges of Additive Manufacturing

1

Technology Maturity

Additive Manufacturing has matured for prototyping but faces challenges in large-scale production due to lower industrial maturity than injection molding. High material waste, limited automation, and workforce training gaps hinder its adoption and sustainability impact.

2

Industry Acceptance

Replacing conventional parts with AM parts comes with several challenges, including material availability, qualification regulations and design adoptions. AM is yet to overcome these challenges to be acceptant as an equivalent manufacturing method.

3

Globally accepted standards

Sourcing of AM components from different suppliers often comes with challenges in thermos of quality. Due to the complexity of the technology as well as the process chain, quality often differs from supply to supplier. This is a major challenge for AM users who are following the Scenario C approach.

About the authors

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DIRECTOR OF POLYMER AM AT AMPOWER

Timo holds a master's degree in Production Technology and Management and has been actively engaged in Additive Manufacturing since 2018. As Director of Polymer AM at AMPOWER, he has played a key role in establishing and expanding the Polymer AM business since 2020. Leveraging his extensive C-level network across the entire supply chain, he contributes to industry strategy development, drawing on his deep expertise in market intelligence and Polymer AM technologies.

Markus Eriksson

SENIOR RESEARCHER AT RISE

Markus is a senior researcher at RISE, Research Institutes of Sweden, specializing in the business potential of Additive Manufacturing within supply chain, logistics, and the industrial value chain. His research highlights the Just-in-Demand concept, which utilizes AM to match production with customer demands, effectively enhancing resilience and sustainability. Through close collaboration with industrial partners, Markus leverages his 15 years of experience from leading companies such as Scania and Sandvik.

Dr.-Ing. Eric Wycisk

MANAGING PARTNER AT AMPOWER

Since 2008 Eric successfully supports OEMs from aerospace, medical and automotive to identify Additive Manufacturing applications and implement production capacities in their regulated environments. With a background in topology optimization, titanium alloys and fatigue he is focused on achieving the maximum part performance with the right AM technology. As Managing Partner at AMPOWER, Eric focuses on technology evaluation and benchmarking, AM material and part properties as well as sustainability.

Detailing the energy consumption of each single process step enables an exact analysis which are the drivers of energy use and CO_2 emission along the process chain.

The Additive Manufacturing Sustainability Calculator for polymers encompasses both AM and conventional processing technologies. Each manufacturing process is meticulously detailed, breaking down all process steps to a granular level. The description covers mandatory and optional steps, such as powder production, allowing for customization of the process route.

Additionally, the calculator incorporates material recycling at all appropriate stages. The recycling rate can be individually adjusted for feedstock production and for the manufacturing process steps where excess material is produced.

For each process step, a comprehensive model is created, detailing all input and output parameters. Based on this model, the Polymer Additive Manufacturing Sustainability Calculator computes the consumption of energy and consumables and converts these into CO_2 emissions.

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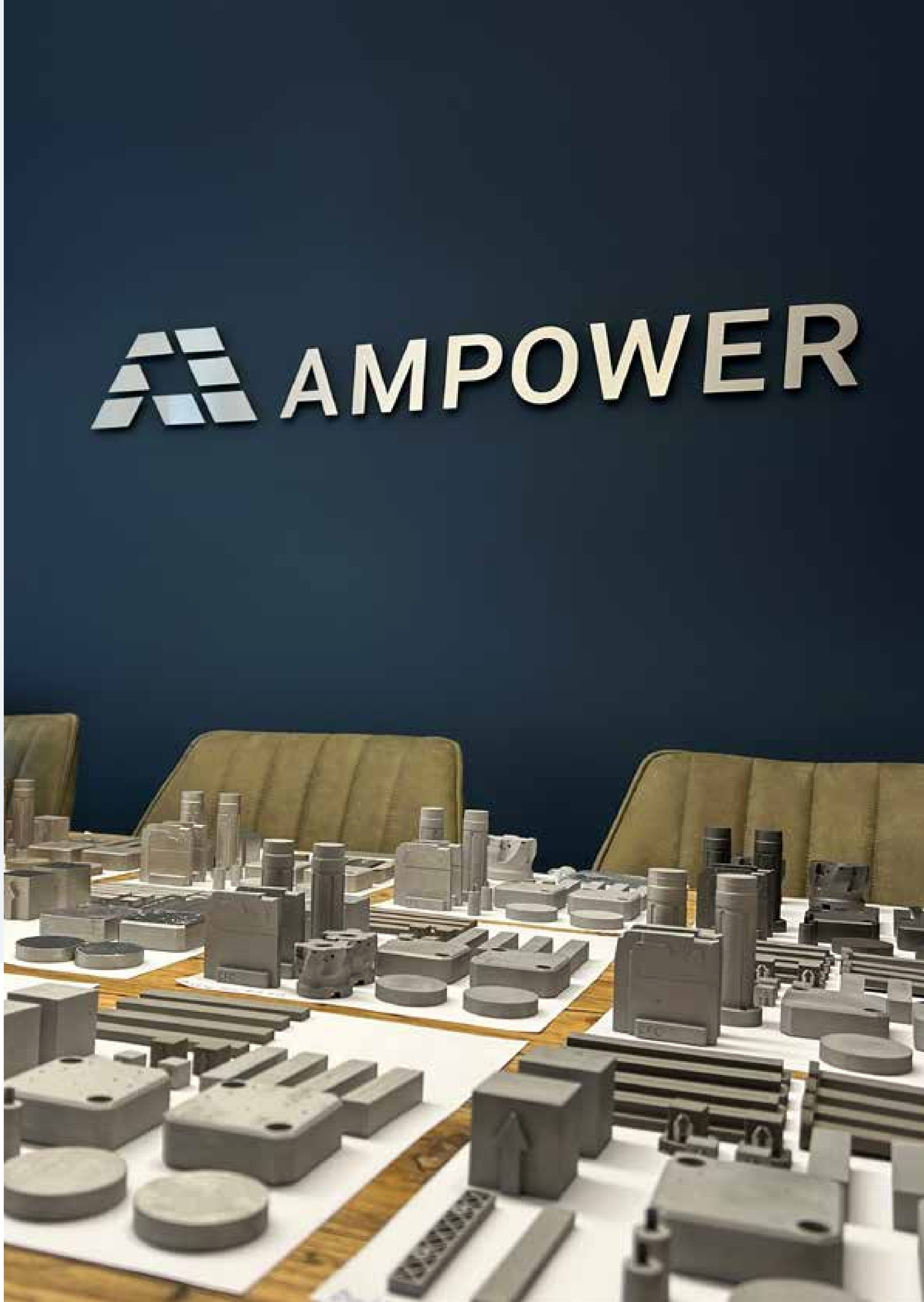

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