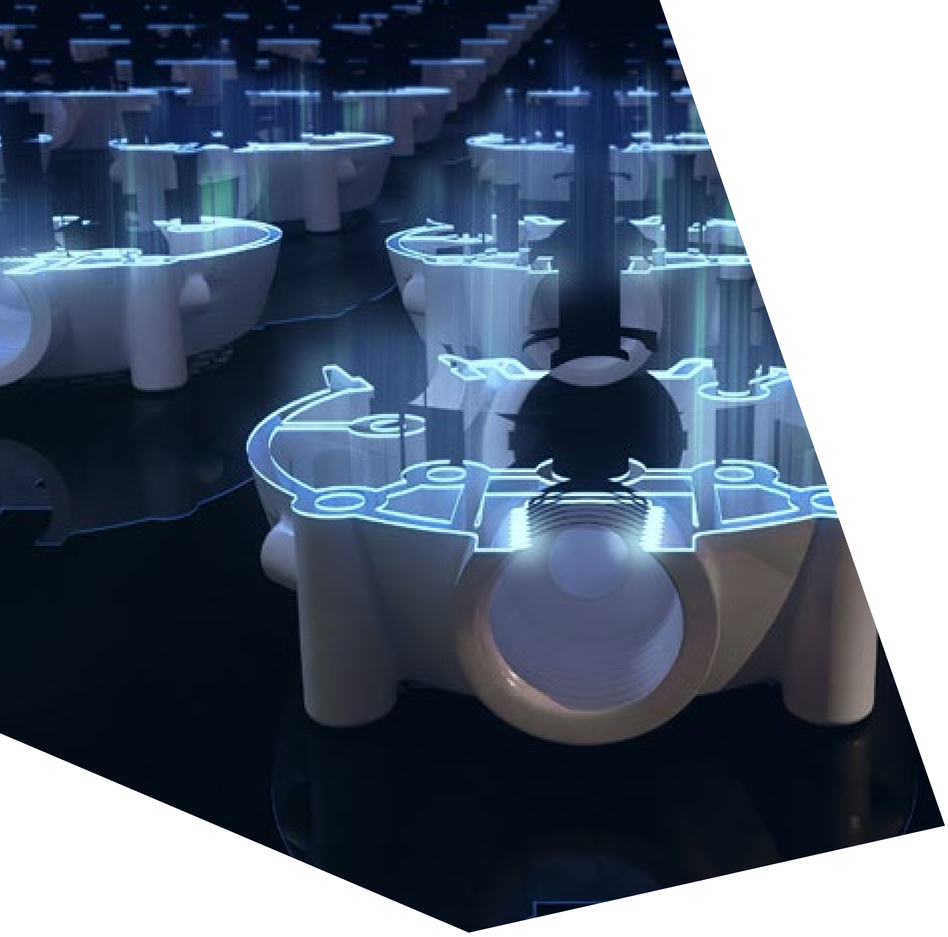

Whitepaper

Top three highlights:

- → The authors present a decision-making framework to unlock the potential of the best of Additive Manufacturing (AM) and Injection Molding (IM)
- → The paper illustrates how AM and IM can be combined in an advanced manufacturing approach based on an analysis of four scenarios throughout the product life cycle
- → The scenarios, each focusing on a different plastic part and industry, highlight the three main challenges and economic impacts of the decision to use either AM or IM as the manufacturing technology

The Best of Both Worlds: Combining AM and IM to Master the Whole Life Cycle of Your Parts

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Abstract

Additive Manufacturing (AM) and Injection Molding (IM) are often perceived as competing plastic processing technologies. However, organizations must be ready to utilize and switch between different production technologies to address changing product requirements, shift production schedules based on market demands, or respond to supply chain crises. This includes making both technologies complementary, not exclusive.

Consequently, organizations must not only continuously challenge their technical perspective on technologies, but also develop new capabilities and link them to a digital backbone in order to change between different manufacturing technologies easily. This paper introduces "advanced manufacturing" as the ability to switch between technologies. The term advanced manufacturing[1] was established before the growth of AM. For this paper, its definition is extended to "being able to combine the best of two state-of-the-art technologies – Injection Molding (IM) and Additive Manufacturing (AM)".

KraussMaffei and Additive Minds have introduced a decision-making framework to tackle the challenge of choosing a plastic manufacturing technology. The framework makes it possible to assess the quality of an application and highlights areas where both technologies can help organizations to overcome the challenges of today's polymer manufacturing world. Furthermore, the framework illustrates how high organizational readiness makes it possible to flexibly switch between both technologies, maximizing value creation within the manufacturing process. This paper highlights how AM and IM can be combined throughout the product life cycle for different plastic parts, focusing on the different product life cycle stages.

1 Advanced manufacturing has initially been defined as follows according to the European Commission: "Advanced manufacturing uses new technologies and innovative and cutting-edge technologies such as robotics, 3D printing, artificial intelligence, high-performance computing and modelling, to produce complex products […]"
Most sources highlight "a focus on innovation" as a core element in their definition. The authors of this paper extend the existing definition with the addition of the following: "Advanced polymer manufacturing refers to the ability to seamlessly switch between traditional and modern plastic processing technology to innovate throughout the product life cycle."

How Can Additive Manufacturing and Injection Molding Be Combined?

The media often portrays Additive Manufacturing (AM) and Injection Molding (IM) as two competing plastic processing technologies. Much of the AM-specific media focuses on AM as a disruptive production technology which takes market shares away from conventional offerings. On the other hand, Injection Molding is known for being a production technology that has been around for nearly a century and is thus considered mature. It offers high quality and repeatability in mass production for various applications.

Advanced manufacturing means that AM and IM are combined flexibly within a product's life cycle depending on the technical and economic requirements. KraussMaffei and Additive Minds, the consulting division of EOS, have conceptualized this approach in this paper.

To overcome current and future challenges associated with plastic manufacturing, decision-makers must be able to decide between AM and IM as a production technology based on a set of different criteria. For this purpose, the authors have introduced a decision-making framework. This decision-making framework allows users to choose a suitable plastic processing technology depending on technological and economic factors, as well as on the readiness of their organization for advanced manufacturing.

Four scenarios are analyzed to demonstrate how users can apply this framework and what an advanced manufacturing approach may look like. Each scenario represents a stage in the product life cycle of a polymer part, see Figure 1.

→ **Scenario 1:**
Applying AM for prototyping and switching to IM when the ramp-up phase starts.

→ **Scenario 2:**
AM and IM are both technically suitable for ramp-up and declining phases. Economic criteria decide at which batch size to switch from AM to IM.

→ **Scenario 3:**
Technological and economic criteria directly indicate the usage of AM.

→ **Scenario 4:**
Technological and economic criteria directly indicate the usage of IM

Furthermore, each scenario presents an exemplary application. The analysis illustrates the challenges associated with the production technology being used, along with the solutions and organizational capabilities that are required to overcome these challenges.
The results visualize the optimum applications for both IM and AM and highlight where both technologies complement each other or co-exist.

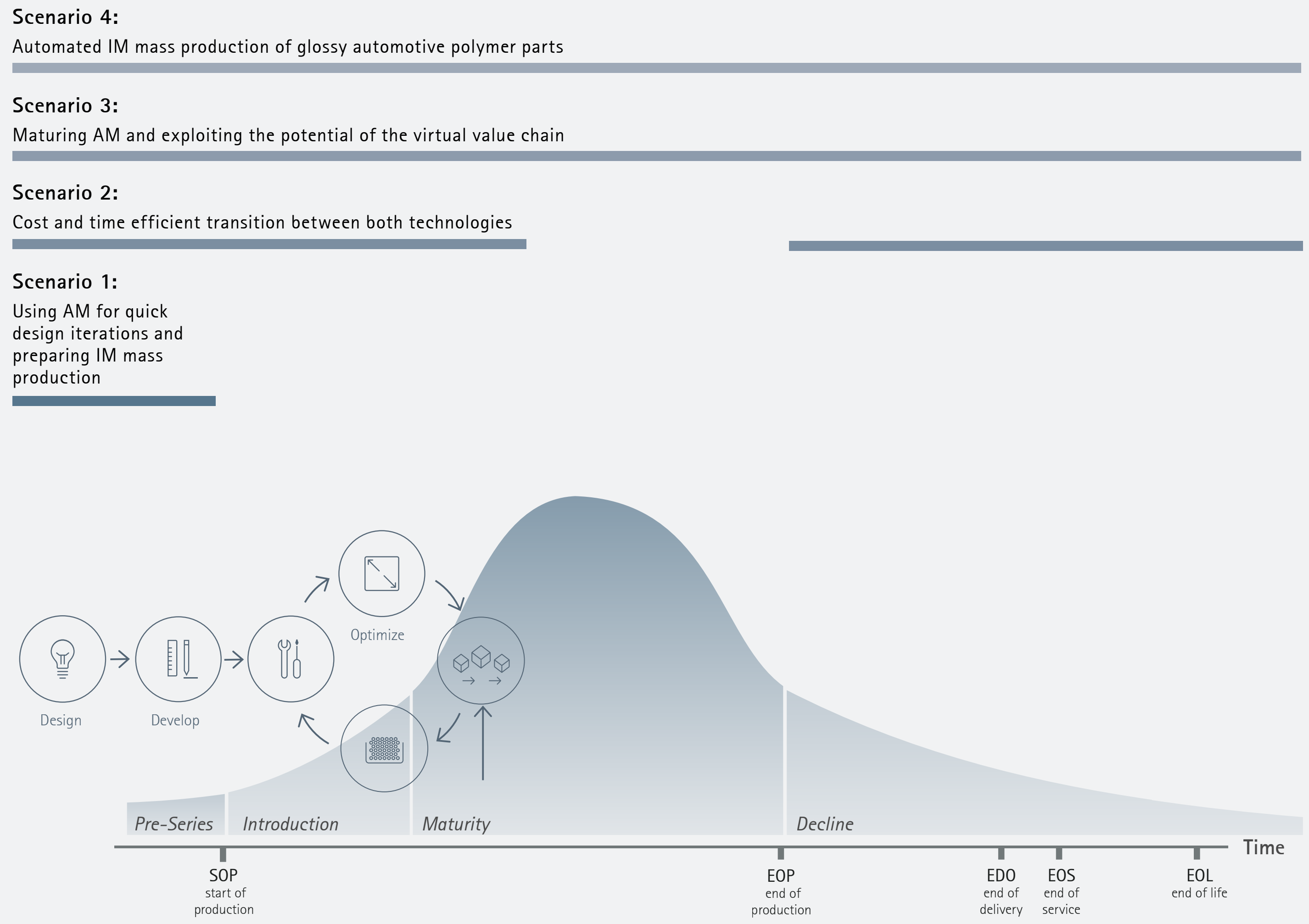


Figure 1: Four assessment scenarios based on the product life cycle

The KraussMaffei and Additive Minds Decision-Making Framework

Finding the most suitable manufacturing technology for an application can be challenging, particularly when trying to work out whether to focus on conventional manufacturing such as Injection Molding or, for example, industrial Additive Manufacturing.

To help readers select the most suitable manufacturing technology for each application, KraussMaffei and Additive Minds have developed a decision-making framework (see Figure 2).

This framework is based on three steps:

01

Assessment of economical and technical criteria in table (X) for an application

02

Rating of a company's organizational readiness

03

Plotting of results in the output graph based on the scores from (1) and (2)

Figure 2: The framework is based on three steps

01 Assessment of economic and technical criteria

The first step is to assess an application from an economic and technical perspective using the table below. The table and output graphs to plot the results are also attached as a template to fill out at the end of the paper. Each economic and technical dimension displays different characteristics with a specific scoring value. The applications can be evaluated according to the specified characteristics and dimensions. A higher or lower number merely serves the purpose of plotting the results at a later stage and does not represent a positive or negative impact.

Four of the characteristics in the table are highlighted in blue/orange. These characteristics are defined as "star characteristics". A star characteristic, as indicated above, pushes the scenario in either category three or four, i.e., complete AM (scenario 3 –blue star) or IM (scenario 4 – orange star). Star characteristics represent economic or technical reasons, indicating the pure IM or AM usage during the whole life cycle.

An example for such a scenario is an application with a series size greater than 500k/annum. In that case, the costs of tooling and productivity in IM will outweigh any AM solution in the market. On the other hand, if the application requires mass customization, then an AM scenario will outweigh the costs of producing multiple tools for customized applications; hence the application will completely shift to an AM complete production scenario, i.e., Scenario 3.

However, a manufacturing technology must not be chosen based on technical and economic decisionmaking criteria alone. A key aspect to consider is a company's organizational readiness.

02 Rating of a company's organizational readiness

This framework defines organizational readiness as a company's ability to evaluate and switch between technologies. Within this framework, the degree to which a company is prepared to injection mold or print a polymer part influences the decision-making process. Therefore, the decision-making space varies for different levels of organizational readiness.

In a similar way to the two dimensions above, organizational readiness is also assessed based on different characteristics in the third section of the table. Organizational readiness is rated according to the following points: Level of IM knowledge (in-house), risk of swapping technology, level of AM knowledge (in-house), cultural integration/openness to new technology/ risk aversity.

03 Analyzing the results

To assess the results, all values need to be added to all three dimensions. The first step is choosing the output graph based on the organizational readiness score. In the second step, the application is plotted based on the economic and technical score. This assigns the application to an area associated with a specific scenario, which guides you on how to proceed with your application.

How to use the framework?

The first step when using the framework is to mark the respective answers according to the application in each framework line. Subsequently, the market numbers of each of the answer options are added for each of the two meta dimensions. For explanatory and usability purposes, the following chapter shares an example of using the framework and the output graphs.

Figure 4 shows the completed framework for the medical inhaler described in scenario 1.

The marked answer options are based on the following circumstances:

Meta-Dim.	Dimension	Characteristics			
Economical	Series size p.a.	Small - < 10k (3)	Medium > 10k (2)	Large >100k (1)	> 500k
	Desired Time to part mfg.	< 1 -4 Weeks (3)	> 1 months (2)	> 3 months (1)	
	Product type (Supply Chain)	Standard Continuous (1)	Standard On Demand (2)	Non-Standard Customized (3)	
	Lifecycle Stage	Prototyping (3)	Ramp-Up Production (2)	Serial Production (1)	Aftermarket + Spare Parts (2)
	Mass Customization*	Yes	No (1)		
Technical	Material Availability in AM* *(fittting the part requirements)*	No *(Applies for 2k and multi mix materials)*	Moderate – substitute (2)	Yes (3)	Link to appendix *(for details)*
	Size*	< 100mm x 100mm x 100mm (3)	< 200mm x 200mm x 400mm (2)	> 300mm x 300mm x 400mm	
	Surface quality Needed	High (1)	Medium (2)	Low (3)	
	Tolerances	F (1)	M (2)	C (3)	*(According to table in Appendix ISO 2768-1)*
	Design Space / Complexity	None (1)	Adaptable (2)	Full Re-Design possible (3)	
	Regulatory Requirements * *(link to appendix)*	Low (3)	Medium (2)	High (1)	
Org. Readiness	Cultural integration / openness of new technology / risk aversity	Conservative (1)	Moderate (2)	Open Minded (3)	
	Risk to swap technology	Low (3)	Medium (2)	High (1)	
	Level of IM Knowledge *(Inhouse)*	Low (3)	Medium (2)	High-Expert (1)	
	Do you have AM Expert Inhouse?	Yes (3)	No (1)		
	Level of AM Knowledge *(Inhouse)*	Low (1)	Medium (2)	High-Expert (3)	

Figure 3: Table for analyzing a part in order to decide between AM and IM

*Star dimension – Can shift the scenario to extremes, i.e. complete IM or complete AM
If this characteristic applies to your application, it is complete IM, i.e. scenario 4
If this characteristic applies to your application, it is complete AM, i.e. scenario 3

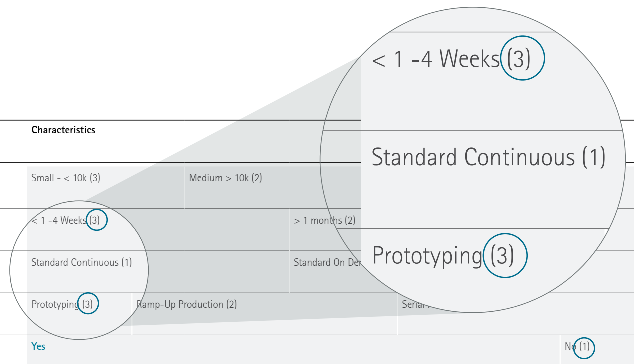
Economical meta dimension

The expected series size is less than 10 000 parts per year (Series size p.a.: Small < 10k (3)). The time to part manufacturing scheduled is less than four weeks (Desired time to part manufacturing: < 1-4 weeks (3)) since the part is non-standard and customized (Product type: Non-standard Customized (3)). The part is in the prototyping stage (Lifecycle stage: Prototyping (3)), and no demand for mass customization is expected (Mass customization: No (1)). Therefore, the sum of points of the economic meta dimension is 13.

Technical meta dimension

Regarding technical properties, the appropriate AM material is available (Material availability in AM: Yes (3)). The part size is less than 100 mm x 100 mm x 100 mm (Size: < 100 mm x 100 mm x 100 mm (3)). The surface quality expected for the medical inhaler is medium (Surface quality needed: Medium (2)), and the tolerance needed is medium (Tolerances: M (2)). The design can be adapted (Design space/ Complexity: Adaptable (2)), and the regulatory requirements expected for the part are minimal (Regulatory requirements: Low (3)). Looking at the corresponding figures, the combined score for the technical meta dimension is 15.

Furthermore, the added values of the technical and economic dimensions can be used to create the result diagram in the final step. Nevertheless, first, the appropriate chart must be selected from the three result diagrams provided, depending on Organizational Readiness. The following paragraph describes this procedure.



Meta-Dim.	Dimension	Characteristics			
Economical	Series size p.a.	Small - < 10k (3)	Medium > 10k (2)	Large >100k (1)	> 500k
	Desired Time to part mfg.	**< 1 -4 Weeks (3)**	> 1 months (2)	> 3 months (1)	
	Product type (Supply Chain)	Standard Continuous (1)	Standard On Demand (2)	**Non-Standard Customized (3)**	
	Lifecycle Stage	**Prototyping (3)**	Ramp-Up Production (2)	Serial Production (1)	Aftermarket + Spare Parts (2)
	Mass Customization*	Yes	**No (1)**		
Technical	Material Availability in AM* *(fittting the part requirements)*	No *(Applies for 2k and multi mix materials)*	Moderate – substitute (2)	**Yes (3)**	Link to appendix *(for details)*
	Size*	**< 100mm x 100mm x 100mm (3)**	< 200mm x 200mm x 400mm (2)	> 300mm x 300mm x 400mm	
	Surface quality Needed	High (1)	**Medium (2)**	Low (3)	
	Tolerances	F (1)	**M (2)**	C (3)	*(According to table in Appendix ISO 2768-1)*
	Design Space / Complexity	None (1)	**Adaptable (2)**	Full Re-Design possible (3)	
	Regulatory Requirements * *(link to appendix)*	**Low (3)**	Medium (2)	High (1)	
Org. Readiness	Cultural integration / openness of new technology / risk aversity	Conservative (1)	Moderate (2)	Open Minded (3)	
	Risk to swap technology	Low (3)	Medium (2)	High (1)	
	Level of IM Knowledge *(Inhouse)*	Low (3)	Medium (2)	High-Expert (1)	
	Do you have AM Expert Inhouse?	Yes (3)	No (1)		
	Level of AM Knowledge *(Inhouse)*	Low (1)	Medium (2)	High-Expert (3)	

Figure 4: Exemplarily filled table for the analysis of scenario 1

Organizational readiness and advanced manufacturing: The AM- and IM-ready organization

Organizational readiness is the key facilitator of advanced manufacturing. It is assessed in the second step of the decision-making framework. This paragraph shows how it influences decision-making. Furthermore, the different stages of organizational readiness are introduced.

A company equally able to produce or procure a part by injection molding or by additive manufacturing has a high level of organizational readiness, see Figure 6. Mastering both technologies allows the company to extend its decision-making space, usually based on pure manufacturing costs, to a broader range. Within this range, the cost per part for additive manufacturing and injection molding are the same or in a similar field. Assuming the technical requirements are also met, other factors are considered and quantified for the decision.

The higher the Organizational Readiness for a particular technology, the greater the space for flexible decision-making (compare Figures 5 and 6).

These factors include

- → Lead time and time to market improvements
- → Flexibility in ramping up series production and consideration of decentralized manufacturing
- → Long-term digitization and thus reduction of inventory
- → Shift from capital expenditures to operational cost
- → Improved total cost of ownership due to application performance

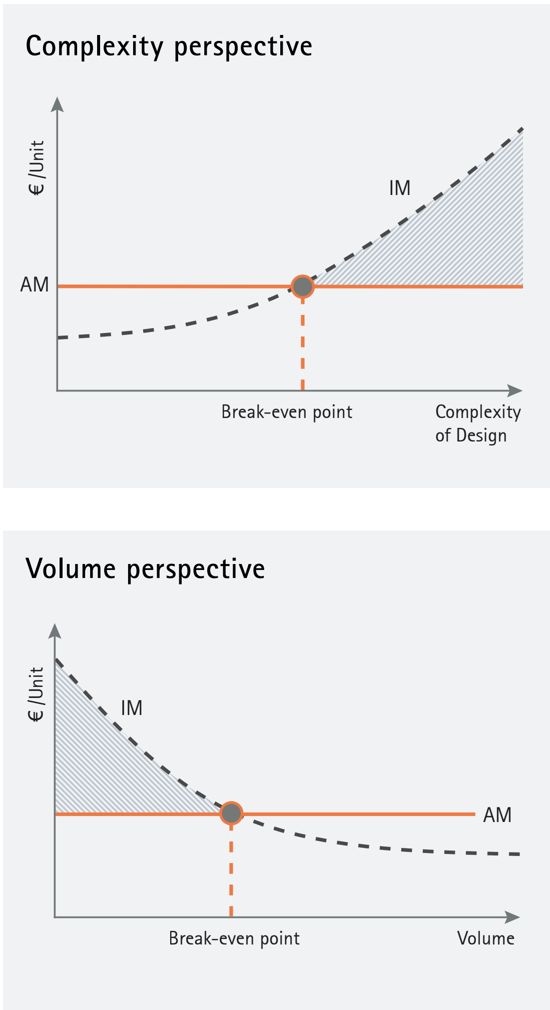


Figure 5: Cost break-even of AM and IM depending on complexity and volume

The higher the organizational readiness for a certain technology, the greater the space for flexible decision-making. Furthermore, the ability to understand the area where both technologies are economically viable:

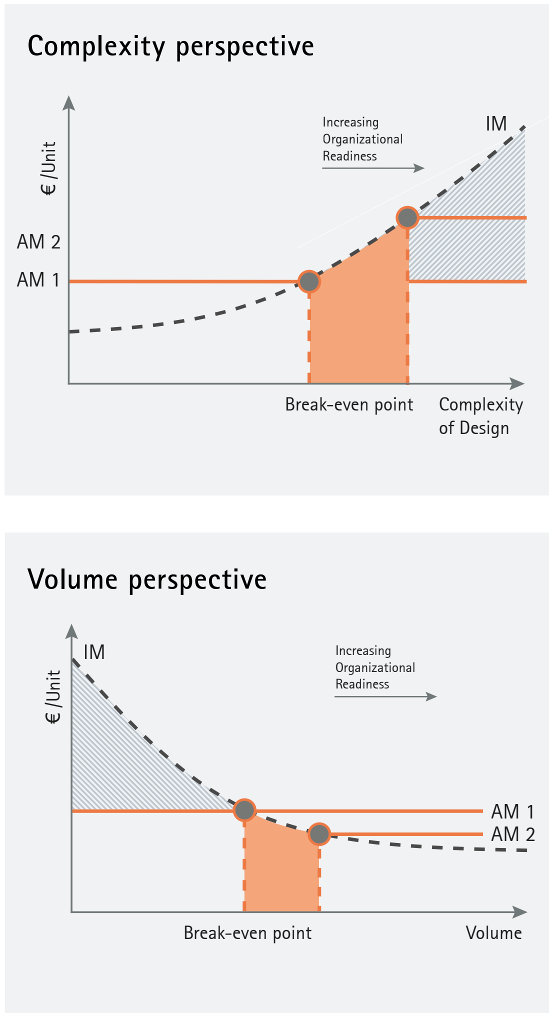


Figure 6: Extension of break-even point with organizational readiness

To get the "best of both worlds", organizations must have:

- → A strong design and process understanding of IM and AM
- → Established a culture where it is possible to experiment with new ideas and materials
- → A complete understanding of the possible risks of swapping technologies throughout the product life cycle
- → Defined internal standards and procedures to ensure that applications using either technology are qualified to go into the use phase
- → The trust and confidence to push the boundaries with AM
- → The ability to adopt a holistic perspective of the total cost of ownership combined with the ability to quantify TCO and challenge their sourcing strategies
- → The willingness to include more complex factors in their decisions which go beyond purely economic and technical analysis

The categories

There are three different categories of organizational readiness: Low organizational readiness, medium organizational readiness, and high organizational readiness. The organizational readiness can be analyzed using the decision-making framework evaluation table presented in Figure 3.

This is done precisely the same way as described in the previous chapter for the technical and economic meta dimension. The values of the individual response options for the Organizational Readiness meta dimension are added up. Once this task is done, the score indicates the Organizational Readiness of a company, see below.

The three categories of organizational readiness, depending on the number of points from the assessment framework

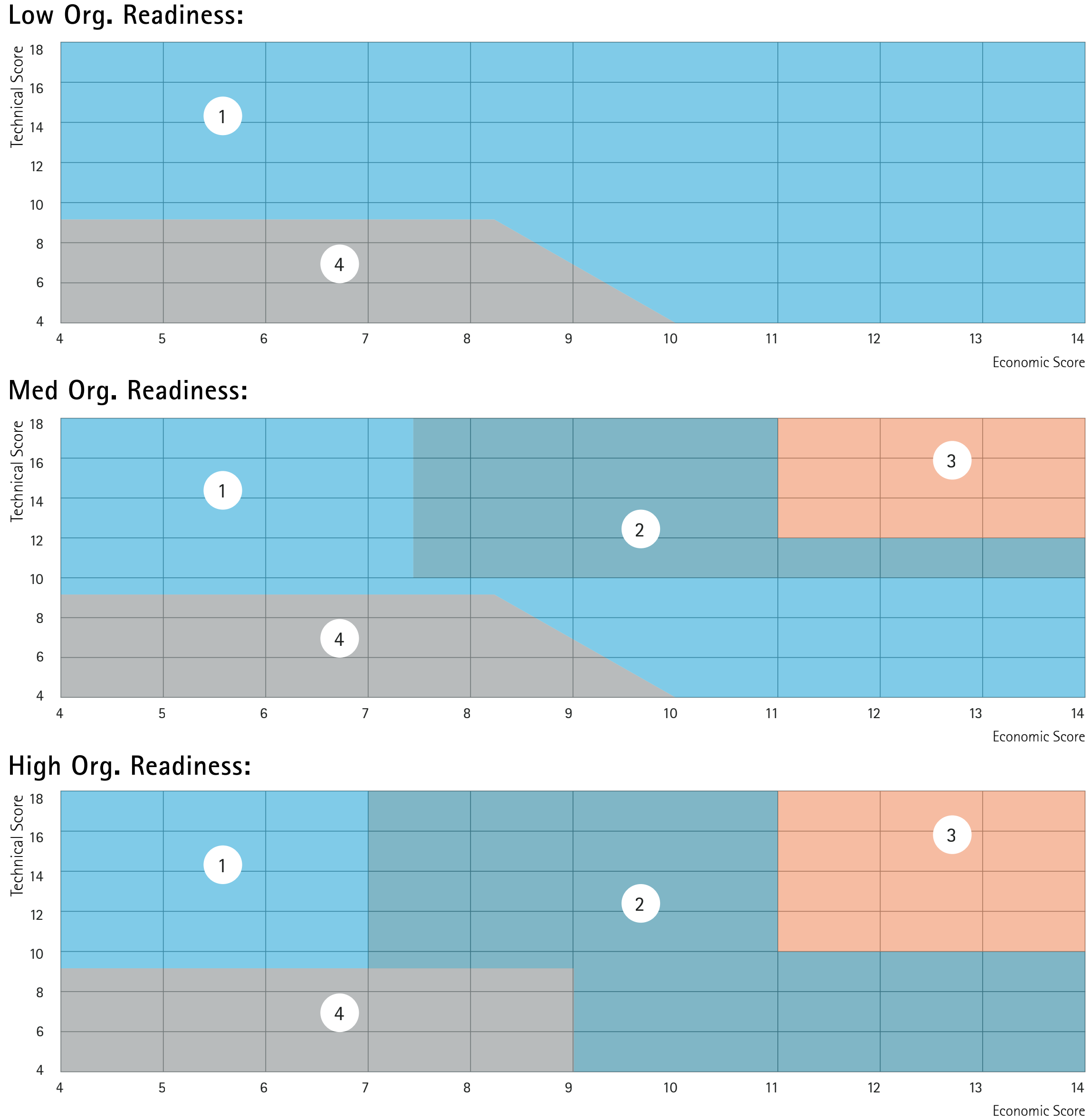
Low organizational readiness	4 - 6	The organization specializes in Injection Molding or Additive Manufacturing. It has established manufacturing capacities and experience in running the production line. It has an in-depth understanding of the relevant process, applications and associated machines and equipment.
Medium organizational readiness	7 - 9	The organization specializes in Injection Molding or Additive Manufacturing. Furthermore, it has the knowledge to apply the other technology on a beginner to moderate level. Decisions can be made in favor of one of the two technologies on the basis of a simple break-even analysis. The organization has manufacturing capacities for and experience in both technologies.
High organizational readiness – advanced manufacturing	10 - 12	The organization specializes in Injection Molding and Additive Manufacturing. The organization can switch between conventional and modern plastic processing technology seamlessly. It has the necessary knowledge of all materials, in-depth expertise in the processes of both manufacturing technologies and an understanding of available manufacturing output. The decision in favor of one technology or the other depends on the requirements of the final part and the product's life cycle stage.

Analyzing the results and output graphs

The basis for the recommendation of the manufacturing technology and the usage of the output graphs are the results of the decision-making framework, see Figure 3.

In the first step, the user selects one of the following diagrams depending on the Organizational Readiness level, see Figure 7.

After selecting, the economic and technical dimensions' results are plotted on the diagram. The economic score is plotted on the X-axis, and the technical analysis on the Y-axis. The point drawn on the chart is located in one of the four fields. Depending on which field the point is in, the application of the following manufacturing method is likely:



1. the use of AM for rapid design iterations and preparation for IM mass production is probable
2. cost- and time-efficient transition between both technologies is probable
3. the expansion of AM and the exploitation of the potential of the virtual value chain is probable
4. automated IM mass production is probable

Figure 7: Result diagrams depending on organizational readiness

The final result indicates whether AM, IM, or both technologies should be used within the manufacturing process. The next chapter includes insight into some of the use cases, which are, among others, the basis for developing the introduced decision tool.

Deciding between AM and IM throughout the Product Life Cycle

This chapter covers four examples of applications where the decision-making framework has been applied. Each scenario represents a certain life cycle stage. Furthermore, the analysis illustrates the challenges associated with the chosen production technology, along with the solutions and organizational capabilities that are required to overcome these challenges.

Scenario 1:

Using AM for quick design iterations and preparing for IM mass production

In this scenario, the preseries activities associated with developing an inhaler design are analyzed. The inhaler allows patients to treat asthma or chronic obstructive pulmonary disease (COPD) (see Figure 2). Essential product features are correct dosing and an easy-to-use design (self-administered). To ensure correct dosing, the inhaler has a complex mechanism: A long two-piece foil ribbon. The doses of medication are attached to the ribbon. Once the lever is activated, the dose is administered by peeling away the flat outermost layer, exposing the medicine that is ready to be inhaled.

Typically, an economic and technological evaluation is conducted within the pre-series stage of a product. The final part design and properties are evaluated, and series manufacturing technology is selected. With high-volume production, the inhaler will be manufactured using IM. A number of significant challenges must be overcome before the final design is established.

Three main challenges

→ Operations:
Developing an easy-to-use design for life-saving medication while providing an easy-to-manufacture product

→ Decision-maker:
Selecting the most suitable AM technology and material for developing the best possible prototype

→ Technology:
Optimizing the AM process with the aim of achieving an appearance and quality that best represent the final product properties of the injection molded part

Solution and implication for decision-making:

Since AM has its origins in prototyping, the reasons to use AM during this stage are manifold and wellknown: Short lead times, fast design iterations and low manufacturing costs for small batch sizes starting from a single part. AM offers a wide range of different technologies to choose from for prototyping. During prototyping, initial samples can be created quickly and inexpensively within a couple of hours using Fused Deposition Modeling (FDM), Stereolithography (SLA), or Polyjetting (PJ) prototyping equipment. You can then switch to a more productive 3D printing technology, such as Digital Light Processing (DLP), Multi-Jet (MJF), or Powder Bed Fusion (PBF), to manufacture small series of parts.

In the high-volume production phase, the medical inhaler will be mass-produced using Injection Molding. This is not only determined by the expected batch sizes but also the requirements for a cleanroom production environment and the required combination of mechanical properties and surface quality, for example. The investment in Injection Molding series production capabilities, especially in the required molds, is high. The final production line for the inhaler shown contains fourteen Injection Molding machines (see Figure 9).

Figure 8: Inhaler

Figure 9: Production line for an inhaler. The set-up is usually in operation for over ten years.

The average cost of each tool is more than 400 000; therefore, extensive prototyping and fast iteration is crucial for the project's economic success. The organization can explore the functionalities and design of the product first and test them with potential customers or in the market with AM quickly and inexpensively before committing to investing in a production line for series production. Once the design is defined with AM, the application reaches the necessary maturity level and the transition to Injection Molding can be initiated and the molds ordered

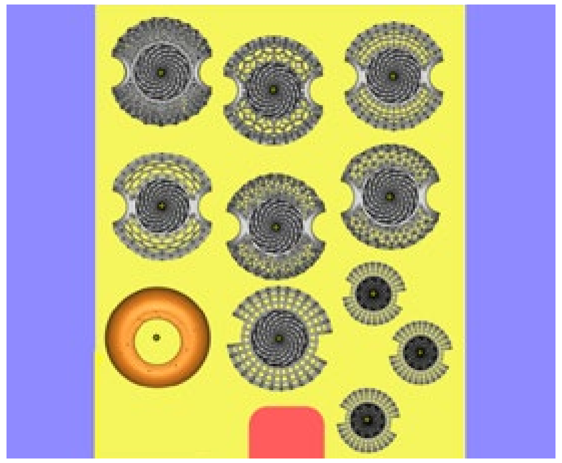


Figure 10: Different prototypes in a single production run; illustrative part design

Impact on value creation

- → Flexible product development at the lowest possible cost
- → Reduced risk of late design changes, which cause mold adaptions and project delays
- → Testing of small batches (< x00) without a mold

Organizational capabilities

- → Understanding of different AM technologies
- → Extensive prototyping capabilities incl. printing
- → Knowledge of how to design a part for production using IM and access to mold-making capabilities

Scenario 2:

Cost- and time-efficient transition between both technologies

In scenario 2, the production of face shields is analyzed and the focus shifts from proto-typing to production. During the spread of the COVID-19 pandemic, the demand for personal protective equipment (PPE) increased significantly. In particular, the demand for face shields nearly doubled from 2019 to 2020. However, as supply chains were interrupted, the lead times for the necessary tools were unpredictable, and products could not reach the users in time. Consequently, the globally available IM production capacities for producing the holders for the transparent shield were unable to meet the urgent demand. Whereas AM parts had formerly only been considered in prototyping, they were now being introduced to bridge the shortage. Face shields were produced using SLS (Selective Laser Sintering) until the tool was ready and its investment paid off. This, however, was only possible for com-panies with medium to high organizational readiness to produce face shields, utilizing both economic and technical advantages.

Three main challenges

- → Operations:
  Reacting quickly to an urgent demand when established supply chains are interrupted
- → Decision-maker:
  Managing the switch from AM to IM to produce at the lowest possible cost while satisfying customers' functional requirements
- → Technology:
  Developing and managing two different cost-optimized designs for each of the technologies

Solution and implication for decision-making:

The two main factors influencing the cost- and time-efficient transition from AM to IM in this case are lead time and cost per part (CPP). In most cases, the lead time for an Injection Molding tool is longer than the processing time for AM. Therefore, until the tool arrives, AM is the technology of choice, satisfying an urgent demand regardless of the CPP of both technologies. Once a tool is available, the CPP becomes the decisive factor.

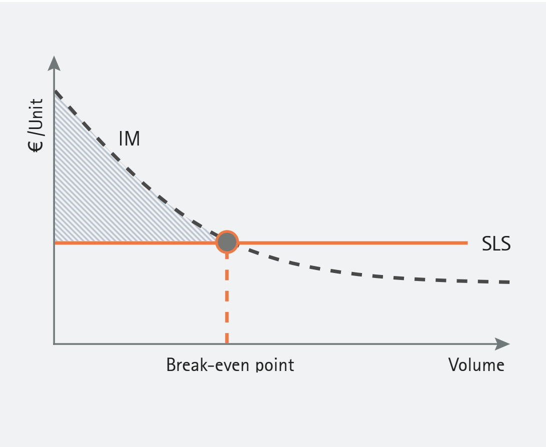


Figure 11: Cost break-even curve for face shields manufactured using Injection Molding or SLS Additive Manufacturing

The lead time for the Injection Molding tool for producing face shields was about two weeks, and during those two weeks, the first face shields were already produced using AM. To meet the high demand, the initial trials for this application were completed using FDM, but in the production phase, the design was adapted for SLS by the Additive Minds application engineering team. Not only does the face shield's new design perform better from an economic perspective, it also has additional functions integrated and can be customized.

The costs for analyzing the break-even point include system, material (powder) and post-processing using AM for a finished part.

Injection Molding costs include tooling costs, process/production costs, material and post-processing costs.

For this new design to go into production and transition from IM to AM, the material was adapted from PP for IM to PA12 for AM[3], both fulfilling the end customers' requirements. Consequently, the break-even point was extended as a new design pushed its boundaries. The break-even point was expanded to production of 10 000 face shields per year, after which point the initial tooling costs justified the IM production from an economic perspective, see Figure 11.

Similar examples and case studies that were analyzed in scenario 2 include medical devices such as nasal swabs and sunglasses. Scenario 2 describes a case where organizations push the boundaries with AM from prototyping to small-series production.

Figure 12: Transition from the FDM design (far left) to the updated SLS design (far right)

The face shield offered an additional revenue source by adapting the design for SLS and integrating additional functionalities, for example adjustable sizes in the same face shield design. For limited series production of customized face shields, AM, specifically SLS, can then take on a greater role and offers the possibility of a new business model for decision-makers.

Impact on value creation

- → Reduced investment in molds by printing smaller batch sizes (< x00 000 parts)
- → Fulfillment of urgent demand along with functional integration using AM
- → Cost-efficient production of larger batch sizes (> x00 000 parts) using IM

Organizational capabilities

- → Design and process expertise in optimizing AM and IM design
- → Understanding of the cost drivers of each technology
- → Knowledge of materials for choosing the right material for each technology

3 Refer to material table in appendix

Spare parts on demand with AM

In addition to pushing the boundaries beyond prototyping with AM, a "second cost-efficient way to transition between both technologies" can be achieved by manufacturing spare and aftermarket parts using AM.

The increasing complexity in spare part management entails challenges throughout each phase of an aftermarket process chain, e.g. planning, production, warehousing and logistics. Demand forecasts for spare parts are often inaccurate, resulting in over-flowing inventories or shortages.

Once the need for a spare part becomes apparent, and no part is in stock, reproducing the part itself poses additional challenges. This can lead to the reordering of spare parts in the case of shortages or the scrapping of parts or tools in stock if demand is not fore-casted correctly, incurring additional costs. For obsolete or legacy spare parts, the availability of a CAD file, technical drawing, or reliable supplier is often not guaranteed. If these documents are unavailable, a resource-intensive reverse engineering process must be initiated, and the tool or manufacturing drawing will usually need to be recreated. Depending on the supplier, intellectual property, manufacturing expertise and storage of the necessary tools can swiftly become a pitfall for a reliable after-market set-up.

This was the case for the automotive part analyzed in scenario 2.2, a spare part in the truck and bus industry. The tool for manu-facturing this polymer cover had become worn. There was an immediate demand for the part to be manufactured in a single-digit series size and the forecast for the rest of the end-of-life phase was unknown. There was some flexibility regarding the material class; however, the testing and qualification requirements had to be met.

From a mechanical perspective, this included specific heat deflection, UV resistance and elongation at break. Furthermore, specific design criteria were laid down, such as a particular surface texturing and coloring

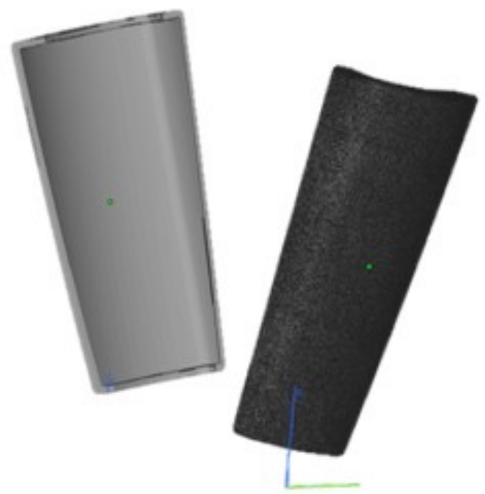


Figure 13: Printed spare part for injection molded cover

The challenges in conventional spare part manufacturing are manifold. When reordering a part due to a shortage or to a missing tool, minimum order quantities (MOQs) can lead to overpriced small-series production. This spare parts category is often associated with long lead times, potentially impacting the end customer's product in use or, even worse, negatively impacting scheduled uptime and utilization at the end customer. Consequently, AM is often relied upon as a digital manufac-turing technology to provide a quick solution. It must be noted that high economic and technical suitability alone is not enough to make the shift towards aftermarket and spares viable. Companies also need medium to high organizational readiness to make decisions and react to supply shortages or urgent requirements for single parts swiftly.

Three main challenges

→ **Operations**:
Recovery of 3D and production data - or AM production to make or source a spare part

→ **Decision-maker:**
Analysis of total cost of ownership to identify the most cost-efficient manufacturing technology for producing the spare part, including direct and indirect costs

→ **Technology:**
Introduction and cost-efficient qualification of a new technology for one-off parts and small series

Solution and implication for decision-making:

In addition to small series production, as stated in scenario 2.1, in spare part production AM can provide similar benefits to a single part or small-series production. After the delivery or end of service obligations, obsolete or one-off parts occasionally need replacing. AM helps overcome the issues experienced in the aftermarket and is used to manufacture parts on demand to avoid high MOQs, small-batch production, worn tools, and storage.

AM can help meet the need to manufacture one-off spare parts, such as the described automotive truck and bus cover. Typically, within this phase, the issue being exper-ienced, i.e. obsolete part, is serious enough to outweigh any reticence to introduce new technology, as it often provides the only efficient solution. The application require-ments are more comprehensive than in the prototyping phase and often require requali-fication/certification. For this part, temper-ature and crash resistance as well as texture and finish, among other characteristics, were thoroughly tested to comply with all require-ments for automotive interiors.

Having fulfilled the required quality aspects and satisfied the need for a one-off spare part, the credibility of AM grows within the organization and in the opinion of its end customers. With this newly established trust, AM is now considered for small-scale spare part production runs.

In a similar way to scenarios 1 and 2.1, there will be a break-even point at which the investment in a tool (if worn for example) or the justification to scrap some of the overstocked parts (last order and MOQ challenge) will pay off. From there on, Injection Molding becomes the more suitable alternative once more, due to technical or economic reasons.

Let us assume that AM remains the production technology of choice for the aftermarket after establishing both trust and the relevant processes, e.g. part family qualification for small series. In that case, the next question is to investigate the impact of AM on the inventory strategically. If stocking and ensuring the physical availability of parts outweighs the cost of virtually storing them, many spare parts will find their way into the digital inventory. Furthermore, Additive Manufacturing will be an essential pillar of this aftermarket strategy, paving the way for an entirely virtual value chain from the end of the product life cycle.

Impact on value creation

→ Cost-efficient manufacturing of small batch sizes and overpriced sourcing for minimum order quantities

→ Printed one-off spare parts provide the basis for exploring the technical requirements of AM high end-customer satisfaction

Organizational capabilities

→ Reverse engineering capabilities for recovering 3D data if needed

→ Expertise in AM part production or sourcing

→ Persistence for pushing AM through the internal qualification process without a mold

Scenario 3:

Exploiting the full potential of AM with a fully digital, integrated value chain ploiting the full potential of AM with a fully digital, integrated value chain

For scenario 3, AM is considered in all stages of the product life cycle, allowing its full potential to be addressed. The application being analyzed is a tablet holder for a businessclass seat in an aircraft. The scope was to develop a product that fulfils the design requirements and offers additional functionalities. The total series size was in the three-digit range with an unknown demand in the "decline" phase of the life cycle. Furthermore, certain technical requirements and air safety criteria had to be met.

During the design and prototyping phase, different geometries had to be developed. After a short field-testing period, the product was launched. The functionalities needed to offer flexibility for different tablet sizes and an adaptable mechanism for viewing the screen from different angles. Lastly, all moving parts had to be securely connected to prevent them from coming loose.

Three main challenges

→ Operations:
Identification of application types that fully exploit the potential of AM while adding value from a product or supply chain innovation perspective

→ Decision-maker:
Truly understanding the benefits of AM and being able to quantify them

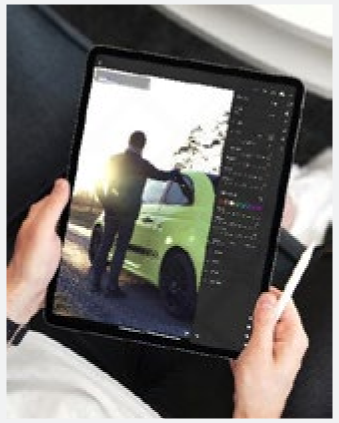
→ Technology:
Fully robustly designed application that is also qualifiable with AM to enter the end-use phase while ensuring consistent industrial grade AM production

Solution and implication for decision-making:

Scenario 3 unlocks the full potential of AM and the digital value chain. The product is fully designed for and can only be produced using AM. The benefits of the technology are clear and include the software-driven design, flexibility to adapt the product on the go and to manufacture on demand.

AM – positioned as complementary production technology alongside the existing mix of manufacturing technologies – can be a game changer, if new applications are created from scratch and product designs are not simply copied from conventional files.

It then offers the potential to enhance value creation at each step of the product life cycle: Starting from "digital product development", to the digital inventory enabled by a digital twin of the part itself.



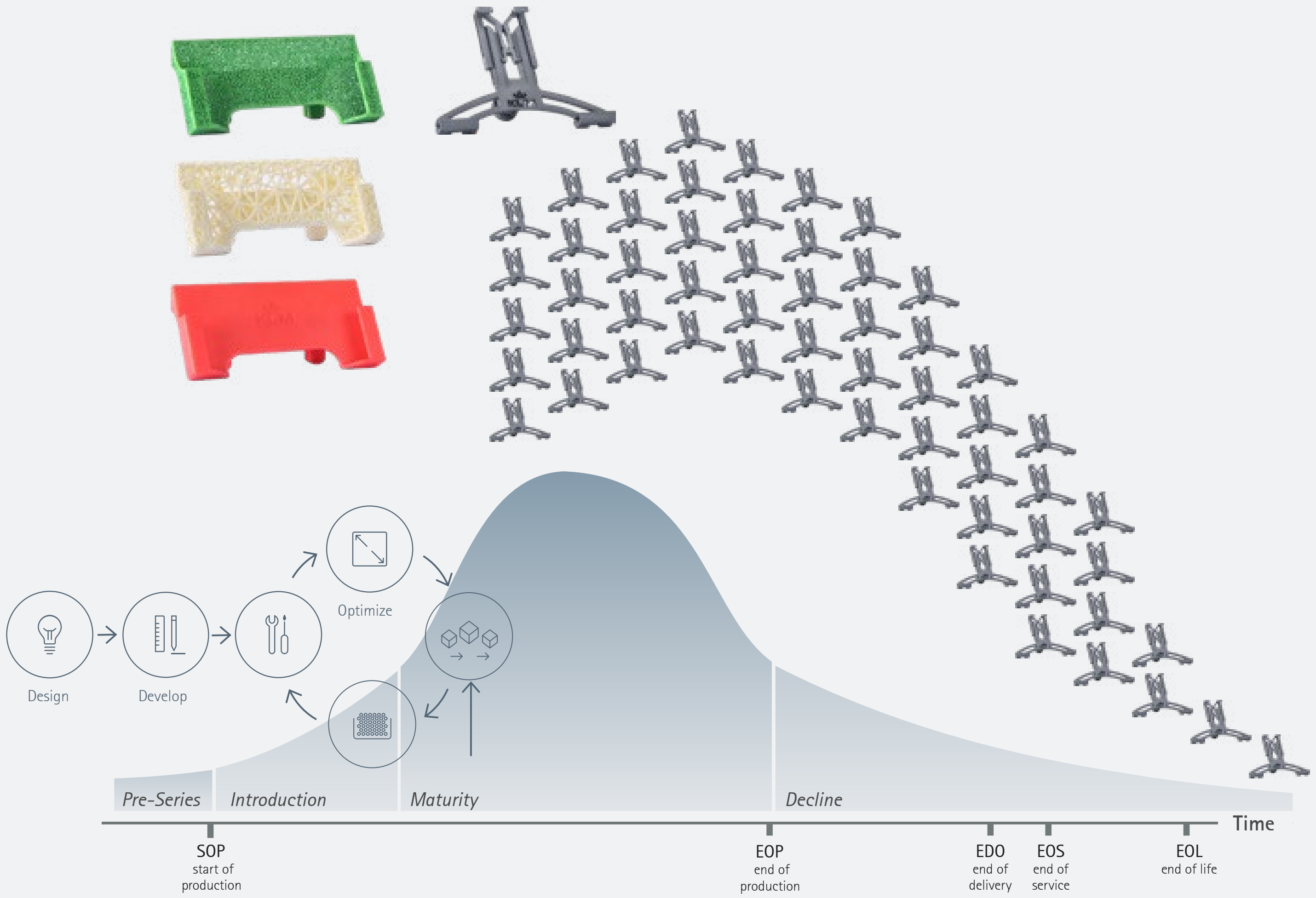


Figure 14: Full potential of AM throughout the product life cycle. Application development cycle.

The full benefits of digitization and Additive Manufacturing can be unlocked by optimizing economic factors throughout the entire product life cycle. The flexible series size allows producers to address shifting demands flexibly and regardless of location during the ramp-up and decline phase. AM does not require tooling or fixturing and therefore minimizes the costs for switching between different designs (pre-qualification).

This digital value chain will allow for constant data modifiability and control upfront, with a complete digital part, production twin and the corresponding documentation.

Thanks to decentralized manufacturing close to the final demand location, virtual product transfers will help to reduce lead times. Shifting to on-demand production also enables complete production flexibility in terms of batch size and product mixing. These "made-to-order" scenarios have already been successfully implemented in different industries, such as in the eyewear industry, for example. In addition to the economic benefits, creating eyewear using AM is even more sustainable as the overproduction of demo glasses, etc. for every optometrist is eliminated, and production is solely based on demand (source: YOU MAWO study).

Impact on value creation

- → Innovations beyond what is imaginable with conventional manufacturing technologies
- → Unveiling the potential of a digital value chain
- → Generation of additional revenue streams through untapped markets/ applications

Organizational capabilities

- → Comprehensive understanding of the AM design, process and materials
- → Methods and tools for assessing and quantifying the value added by AM
- → Curious and cross-functional team to develop, implement and scale AM applications

Scenario 4:

Automated IM mass production of glossy automotive polymer parts

A large number of parts are produced and sold during an application's maturity life cycle stage to meet significant demand. This figure might reach up to > 10 million parts for some applications. This paper takes the pillar blade of a premium automotive brand as an example, see Figure 15. This technical part is included in almost all commercial vehicles. A batch size of 1 000 000 parts is considered in this paper. The part must be manufactured at the lowest possible cost and the highest possible quality while using a stable and reliable process. Furthermore, the stringent requirements include high scratch resistance, high UV resistance, high abrasion resistance, high accuracy and high-gloss surfaces.

Figure 15: Pillar blade from a premium automotive brand

Three main challenges

→ **Operations**:
Manufacturing a three-component part at the lowest possible cost and the highest possible quality

→ **Decision-maker:**
Finding a process that can combine the manufacturing of the three components in one step without upstream and downstream steps

→ **Technology:**
Setting up a reliable multi-component automated IM production line in an automotive environment

Solution and implication for decision-making:

Nowadays, automobiles reflect the owner's lifestyle and attitude towards life. The interior and exterior must be coherent down to the most extraordinary detail, matched to each another in terms of significance and function. Therefore, in the automotive sector, haptics, surface aesthetics and process must all meet the highest standards while remaining below challenging cost targets in manufacturing to the greatest possible extent. IM is the technology of choice for producing a part from three different materials, where there is a batch size of fewer than 100 000 parts, a stable design and strict requirements for cost-efficiency. To get the most out of IM technology, reducing production steps is critical in the case of the blade. For this reason, a multi-component Injection Molding technology is used. This is notable because the primary carrier is flow-coated with polyurethane (PUA) as a surface material in the second cycle after Injection Molding the thermoplastic base body and the sealing lip made from the thermoplastic elastomer, see Figure 16. This provides an exceptionally high-quality, scratch-resistant surface. This unique process replaces the typical painting steps and all upstream and downstream working steps. The completed parts with the most refined high-gloss surface finish are taken straight from the production system, see Figure 17.

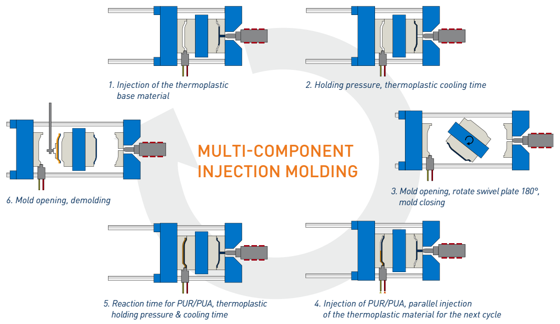


Figure 16: The multi-component injection molding process

Figure 17: Production line for pillar blades

Impact on value creation

→ Quick processing thanks to the reduced number of process steps

→ Reduced logistic costs and scrap rates

→ Extremely robust part thanks to excellent bonding of PU/PUA paint and thermoplastic part

Organizational capabilities

→ In-depth knowledge of multi-component Injection Molding processes

→ Experience in running and maintaining complex industrial production lines

→ Knowledge of mold flow simulation and tool design

Additive Manufacturing and Injection Molding Are Complementary Manufacturing Technologies

This paper shows that Additive Manufacturing and Injection Molding are two complementary plastic processing technologies. Injection Molding is an established technology allowing users to economically produce plastic parts in batch sizes of up to 10 million parts with a wide range of materials. On the other hand, Additive Manufacturing enables users today to manufacture mass-customized parts, complex geometries and small batch sizes of up to 200 000 parts economically with a fully digital value chain.

Part designers, product managers and technology owners often choose or are already set on one plastic production technology for a part. The reasons for this are manifold: Habits, lack of knowledge, lack of resources, or fear of change. This means that only the advantages of this one production technology can be converted into added value for the stakeholders of a product. This paper shows how the ability to decide between Injection Molding and Additive Manufacturing based on the specific requirements of an application and its life cycle opens up new approaches, offering added value. This added value includes, for example, lower manufacturing costs, improved availability, or greater flexibility.

The authors have summarized the flexibility in making decisions and combining the production technologies in the vision of advanced manufacturing: A seamless change between conventional and digital manufacturing technologies depending on the part properties, economic aspects, life cycle stage and overarching organizational readiness.

The authors have conceptualized a step-by-step technical decision-making approach into a framework to make it easier to initiate the transition to advanced manufacturing. The framework provides the reader with a tool to ask the right questions and decide whether to use Injection Molding or Additive Manufacturing. It highlights that a technical and economic evaluation, combined with an assessment of the product life cycle stage, is important for that decision. However, it is the organizational readiness on the other hand, and the openness to change and innovation, which is truly critical. Therefore, companies with high organizational readiness can significantly expand their strategic manufacturing toolbox with a wider range of potential solutions, benefitting more from the best of both worlds.

To demonstrate how to use the framework, this paper gives examples of applications in the different life cycle stages and illustrates how the decision about the manufacturing technology is taken. Each of the scenarios covered reflects a particular life cycle stage.

Scenario 1 focuses on the prototyping phase. It highlights how AM is used to speed up and reduce the cost of the development of an inhaler. Furthermore, it describes the transition from AM prototyping to IM series production.

Scenario 2 introduces an example for the ramp-up phase. It focuses on using a combination of AM and IM in the ramp-up phase when producing face shields. The urgent demand is quickly met with a cost-optimized AM product until a mold is produced and production scaled with AM.

Scenario 2.2 illustrates another aspect of the challenges associated with changing demand. Scenario 2.2 proves how printing spare parts can reduce costs when producing extremely small batch sizes for spare parts while fulfilling the requirements of the qualification processes of the automotive industry.

Scenarios 3 and 4 focus on the maturity phase, but while scenario 3 is dedicated to AM series production, scenario 4 concentrates on IM series production. The AM scenario presents the potential of the entire digital value chain by printing an iPad holder for the aviation industry. On the other hand, the IM scenario shows how the advantages of IM can be scaled by producing a high-end automotive part.

When AM and IM are considered for manufacturing a part and are flexibly combined throughout the product life cycle, additional value is created. This added value is generated because the two plastic processing technologies are complementary and can counteract the disadvantages of each other in the different life cycle stages of a product.

To become an expert in advanced manufacturing, you must possess knowledge of how to combine both technologies or enable the transition between the two. This knowledge includes process and material expertise, but also experience in the cost structure of both technologies. Furthermore, as the paper shows, organizational readiness is an essential driving force for advanced manufacturing.

Are you interested in finding out more about advanced manufacturing?

Do you want to learn how to combine AM and IM in the life cycle of your part?

Or would you like to discuss this whitepaper with us?

Don't hesitate to contact us – or visit us at our booths at the K Show and formnext.

Appendix A:

Material overview for the whitepaper by Additive Minds and KraussMaffei

The framework contains several star dimensions, indicating a pure AM or IM scenario. For example, a technical star dimension is material availability. The following paragraph provides more information on the challenge of selecting a material for AM and, or IM.

Selecting the right material for the right application is a challenging issue for all product developers. It requires an in-depth understanding of material science and the manufacturing technology being used. This becomes even more challenging when AM and IM are combined within a product life cycle and the same product is manufactured using two different technologies and materials, but in the end have the same function and fulfill the same customer requirements.

In general, AM processes amorphous and semicrystalline thermoplastics and thermosetting polymers. Compared to conventional plastic processing, the range of available materials is small. There are about 1 800 options for AM, including different colors and suppliers[4]. For IM, there are more than 10 000 different plastic types available, not including different suppliers and colors[5].

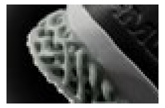
In general, IM processes most known elastomers and thermosets, and almost all thermoplastics. Apart from some exceptions, the plastics are modified with lubricants and stabilizers to enable them to be manufactured and used. To further adapt the material, reinforcing and filling materials are often added, and fire protection modifications are carried out.

When choosing a material for an application, material properties should be examined closely. Among others, these could be mechanical properties, biocompatibility, transparency, color, moisture resistance, fire retardancy, hazardous emissions, sterilization and costs.

The materials in AM and IM processes may come from a similar class, however the processes are very different from a technical perspective, making the approach for choosing a material complex. It is therefore better to ask which material can fulfill the requirements of an application, rather than to look for an exact replica.

The following table is a decision-making tool for finding the right SLS material depending on the IM material and vice versa.

Focus on SLS portfolio EOS

IM material class	Main properties	Applications	AM material class
Polyamide 12	– Multipurpose material – Balanced property profile	– Functional parts – Industrial devices – Food processing – Medical equipment	Polyamide 12
	 Gripper for packages: FORMRISE	 Customized gripper: trinckle, Kuhn-Stoff	
PA 12 GF	– High stiffness – Wear resistance – Improved temperature performance	– Rigid housings – Parts with wear and abrasion requirements – Parts used under more challenging thermal conditions	Polyamide 12, glass bead filled
PA 12 FR	– Flame-retardant material – Certificates available	– Aerospace interior parts – Electrical devices – Consumer electronics	Polyamide 12, flame-retardant
	 Plug housing: ATI	 Aircraft interior air duct PA2241FR: Zodiac	
PA 11	– High ductility and impact resistance – Balanced property profile (similar to PA 2200) – Made from renewable sources	– Functional parts requiring impact resistance – Parts with functional elements such as film hinges – Eyewear – Automotive interior parts	Polyamide 11
	 Indicator inlay: MINI	 Ankle and foot orthoses: plus medica	
PAEK	– High-performance material	– Substitute for metals Aerospace	Polyetherketoneketone, carbon-fiber-reinforced
PEEK	– High temperature performance, strength, stiffness and chemical resistance – Excellent wear resistance – Inherently flame-retardant	– Automotive and motorsports – Electrics and electronics – Medical and industrial	
	 Air duct in HT23	 Front wing cascades: Williams Martini Racing	
TPU/TPE	– High-performance material – High temperature performance, strength, stiffness and chemical resistance – Excellent wear resistance – Inherently flame-retardant	– Substitute for metals – Aerospace – Automotive and motorsports – Electrics and electronics – Medical and industrial	Thermoplastics TPU/TPE
	 Shoe sole element	TPU midsole	
PP	– High-performance material – High temperature performance, strength, stiffness and chemical resistance – Excellent wear resistance – Inherently flame-retardant	– Substitute for metals – Aerospace – Automotive and motorsports – Electrics and electronics – Medical and industrial	Polypropylene
PA 6		Various demanding applications in – Automotive – Electronics – Aviation – And many other sectors	Polyamide 6

Detailed information can be found at: http://senvol.com/material-search/ www.eos.info/material-p

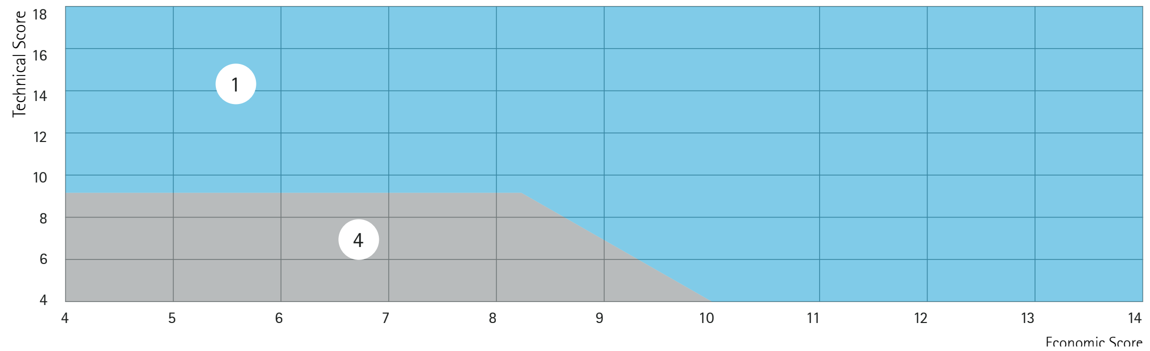
4 Senvol LLC, 2021.
5 Friedrich Johannaber and Walter Michaeli, 2014: 57.

Appendix B:

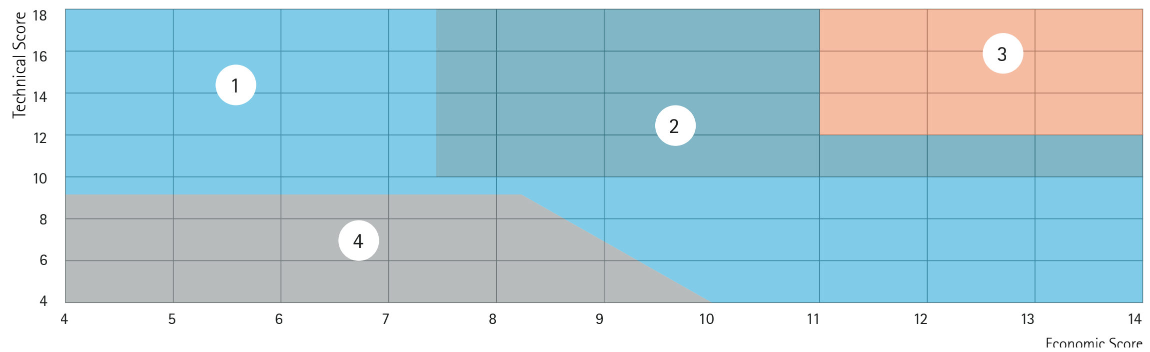
Meta-Dim.	Dimension	Characteristics			
Economical	Series size p.a.	Small - < 10k (3)	Medium > 10k (2)	Large >100k (1)	> 500k
	Desired Time to part mfg.	< 1 -4 Weeks (3)	> 1 months (2)	> 3 months (1)	
	Product type (Supply Chain)	Standard Continuous (1)	Standard On Demand (2)	Non-Standard Customized (3)	
	Lifecycle Stage	Prototyping (3)	Ramp-Up Production (2)	Serial Production (1)	Aftermarket + Spare Parts (2)
	Mass Customization*	Yes	No (1)		
Technical	Material Availability in AM* *(fittting the part requirements)*	No *(Applies for 2k and multi mix materials)*	Moderate – substitute (2)	Yes (3)	Link to appendix *(for details)*
	Size*	< 100mm x 100mm x 100mm (3)	< 200mm x 200mm x 400mm (2)	> 300mm x 300mm x 400mm	
	Surface quality Needed	High (1)	Medium (2)	Low (3)	
	Tolerances	F (1)	M (2)	C (3)	*(According to table in Appendix ISO 2768-1)*
	Design Space / Complexity	None (1)	Adaptable (2)	Full Re-Design possible (3)	
	Regulatory Requirements * *(link to appendix)*	Low (3)	Medium (2)	High (1)	
Org. Readiness	Cultural integration / openness of new technology / risk aversity	Conservative (1)	Moderate (2)	Open Minded (3)	
	Risk to swap technology	Low (3)	Medium (2)	High (1)	
	Level of IM Knowledge *(Inhouse)*	Low (3)	Medium (2)	High-Expert (1)	
	Do you have AM Expert Inhouse?	Yes (3)	No (1)		
	Level of AM Knowledge *(Inhouse)*	Low (1)	Medium (2)	High-Expert (3)	

*Dimension "special features": can move the scenario directly into a "maximum range", i.e. complete IM or complete AM.
If this characteristic applies to your use case, then complete IM is recommended here, i.e. scenario 4
If this characteristic applies to your use case, then complete AM is recommended here, i.e. scenario 3

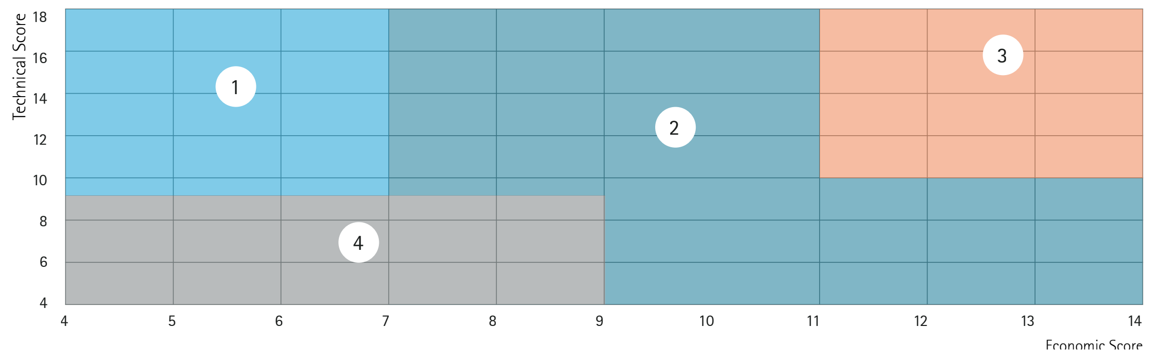
Low Org. Readiness:



Med Org. Readiness:



High Org. Readiness:



1. the use of AM for rapid design iterations and preparation for IM mass production is probable
2. cost- and time-efficient transition between both technologies is probable
3. the expansion of AM and the exploitation of the potential of the virtual value chain is probable
4. automated IM mass production is probable

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If you have any queries or comments, please get in touch with us.