DOI: 10.2478/aucts-2025-0002

ACTA UNIVERSITATIS CIBINIENSIS – TECHNICAL SERIES
Vol. 77 2025

OPTIMIZATION OF ADDITIVE MANUFACTURING FOR MASS PRODUCTION THROUGH STANDARDIZED MODULARITY STRATEGY FOR HIGH-VOLUME FDM

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Abstract: *This paper addresses the emerging industrial need to optimize production chains and reduce lead times using Additive Manufacturing (AM). While AM is empirically associated with higher production times and costs compared to traditional Injection Molding (IM), this study proposes a flexible production strategy utilizing "Standardized Modularity." By discretizing a geometric part into functional modules—specifically a non-critical "Base" and a high-precision "Top" module—production parameters are optimized for each section. A comparative economic analysis between Fused Deposition Modeling (FDM) and Injection Molding was conducted for batch sizes ranging from 10,000 to 100,000 units. The study experimentally validates the modular approach using an UP! PLUS 2 printer and ABS material, testing various interlocking tongue-and-groove patterns. Results indicate that FDM remains cost-competitive with IM for series up to 15,000 units. Furthermore, the modular division strategy achieved a production cost reduction of approximately 13% compared to single-iteration printing, while mechanical testing confirmed that optimized modular interfaces retain up to 94% of the monolithic part's tensile strength.*

Key words: Additive Manufacturing, Mass Production, Standardized Modularity, FDM vs. Injection Molding, Cost Analysis.

1. INTRODUCTION

The current manufacturing scene is witnessing a definitive transition of Additive Manufacturing (AM) from a prototyping-centric technology to a cornerstone of industrial mass production. Driven by the convergence of high-speed hardware architecture and automated post-processing ecosystems, AM has successfully integrated into global supply chains, addressing critical needs for supply chain discretization and reduced lead times. While historically synonymous with "rapid prototyping," the technology has matured to support high-performance applications in defense, aerospace, and medical sectors, where the demand for complex, "born-qualified" components is rising.

Despite this trajectory, Fused Deposition Modeling (FDM) faces significant empirical barriers when compared to traditional methods like Injection Molding (IM). Specifically, FDM is often associated with higher unit costs for large series, slower production rates, and challenges in achieving repeatability for high-quality requirements. While IM remains economically superior for high-volume production (e.g., >100,000 units), the break-even point where AM remains competitive is expanding. Current literature suggests that for specific geometries and consolidated assemblies, AM can be cost-effective for quantities extending into the tens of thousands.

However, "time" remains the critical bottleneck. While AM eliminates the high initial cost and lead time of molds—potentially saving weeks in the development cycle—the effective manufacturing time per unit is significantly higher than the rapid cycle times of injection molding. To address this constraint, this paper proposes a flexible production strategy based on "Standardized Modularity." By discretizing a geometric part into functional modules (e.g., a "Base" and a "Top") at the design stage, manufacturing parameters can be optimized for each module's specific quality requirements. This approach aims to decouple the strict relationship between part volume and production time, offering a pathway to optimize the "Time-Cost-Quality" triangle for series production.

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2. RELATED WORK AND BACKGROUND

The trajectory of Additive Manufacturing (AM) has shifted definitively from a prototyping-centric utility to a pillar of industrial production [1]. While early adoption was driven primarily by design freedom, current industrial integration is propelled by the maturation of engineering-grade materials and the need for supply chain discretization. Ford et al. [2] highlights that the initial value proposition of AM was "Rapid Prototyping," where the elimination of tooling allowed for substantial time and cost savings during development.

A critical advancement in this transition is the emergence of "Born Qualified" parts. Historically, AM components required extensive post-production testing to ensure engineering standards were met. Recent developments in closed-loop control systems now allow for real-time process monitoring (melt flow, layer adhesion), facilitating the certification of end-use components in demanding sectors such as aerospace and automotive [3], [4].

The economic viability of AM versus Injection Molding (IM) is governed by the break-even point—the quantity at which the high per-part cost of AM exceeds the amortized tooling cost of IM. Traditional models categorize efficiency based on production volume. Atzeni and Salmi [5] demonstrated that specific AM technologies, such as Selective Laser Sintering (SLS), could be more efficient than injection molding for volumes up to 80,000 units, provided the design is optimized for part consolidation.

Recent comparative studies have further refined these thresholds for Fused Deposition Modeling (FDM). A study by Formlabs [6] analyzing a resin mixer latch geometry indicated that in-house 3D printing remained cost-effective for quantities up to 13,050 units before outsourced injection molding became more economical. This data supports the hypothesis that FDM is increasingly viable for mid-volume series production.

Despite favorable hardware economics, labor remains a significant variable in the Total Cost of Ownership (TCO). Manual post-processing (support removal, surface finishing) can act as a bottleneck. Research indicates that complex geometries requiring extensive manual intervention can drastically reduce the break-even point to as few as 130 units.

However, the integration of automated post-processing ecosystems—such as Volumetric Velocity Dispersion (VVD) for support removal—has been shown to reduce labor costs by up to 80% [7], [8]. This reduction in variable costs is critical for extending the viable production volume of FDM. The "Standardized Modularity" approach proposed in this paper aims to further address this constraint by discretizing geometry to optimize the printing process itself, reducing the reliance on complex supports and lengthy print times.

3. METHODOLOGY

To evaluate the feasibility of standardized modularity in mass production, this study employs a dual-phase methodology. The first phase consists of a comparative economic analysis between traditional Injection Molding (IM) and Fused Deposition Modeling (FDM) to establish cost and time baselines. The second phase involves the experimental validation of the proposed modular concept using a physical fabrication setup to assess process viability and mechanical integrity.

3.1. Reference Geometry

A neutral geometric component, designated as a "pivot," was designed using to serve as the reference for all simulations and experiments. The part features a functional geometry characterized by four horizontal through-holes for mounting and a transverse axis bore. As depicted in figure 1, the physical properties of the reference part are: Dimensions: 40x30x55mm, Material: ABS, Volume: 24.269mm3, Mass: 29,12g.

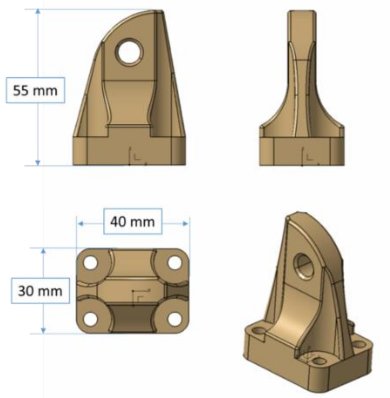

Figure 1 Isometric representation of the reference pivot part

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3.2. Economic Analysis Models

Injection Molding (IM) production cycle was modeled to define the standard efficiency for mass production and it considers both mold manufacturing and part manufacturing. The workflow design-for-manufacturability (DFM) analysis, mold execution, first off tool (FOT) validation, and optimization. The critical path is dominated by the mold manufacturing and optimization phase, estimated at 15 weeks lead time. Once in production, effective and total production time for specific production volumes is computed using a cycle time of 30 seconds per part.

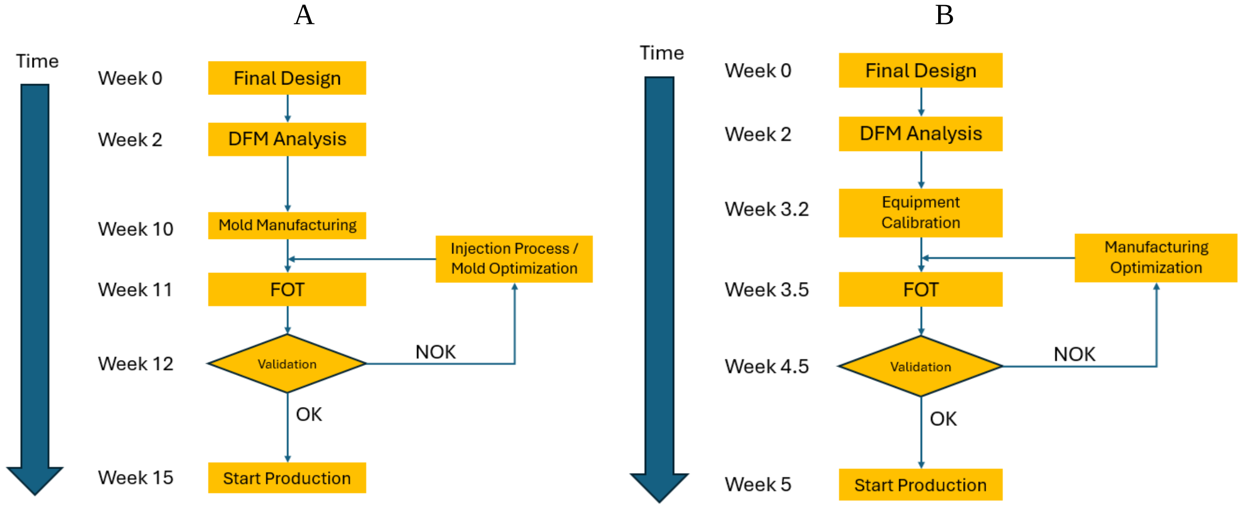

Figure 2 Manufacturing Process Workflow: A - Injection Molding B - FDM

For the cost model of injection molding, it is assumed that the process cost is closely linked to the required volume of parts, such that as the required quantity increases, the cost decreases. Costs were estimated using the CustomPartNet [9] platform based on a single-cavity mold configuration. Key input variables included: material cost 2,38 euro/kg; injection volume 24.269 mm3; runner volume 16.300 mm3; clamping force 200 t; setup 8 h; post-processing 8 h; post-processing cost 25 euro/h; mold cost 40.000 euro). The mold cost is estimated by analogy with similar products after consultation with economic entities specialized in injection molding.

Additive Manufacturing (FDM) simulations were conducted assuming an Ultimaker S5 printer managed via Ultimaker Cura slicing software. To replicate a production environment, a grid arrangement strategy was employed, positioning 45 parts per build plate with 5 mm spacing to maximize volumetric efficiency. In contrast to IM, the FDM workflow significantly reduces the initial lead time. As shown in Figure 2, the time from design to production is estimated at 5 weeks, primarily consisting of calibration and process validation.

Manufacturing Parameters: 0,2 mm layer height; infill 100%; extrusion speed 100 mm/s; travel speed 150 mm/s. Under these slicing and process conditions, the reported execution time for a production batch of 45 parts is 69 hours, and the preparation time per batch is 1 hour.

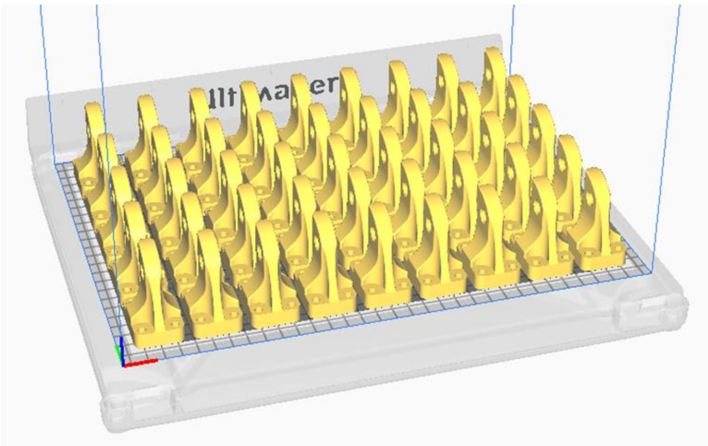

Figure 3 Components arranged in a grid

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Unlike IM, FDM unit costs by equipment cost, material cost, and the cost of calibration/handling operations, and it is treated as constant with increasing production volume under the stated assumptions. The cost parameters are an equipment purchase cost of 6,000 euro, an equipment lifetime of 10,000 h, an operating cost of 0.6 euro/h, a material cost of 45 euro/kg, and a handling cost of 20 euro/h.

3.3. Standardized Modularity Strategy

To reduce additive-manufacturing production time and the per-part manufacturing cycle time while maintaining the required surface and dimensional quality only where it is functionally needed, a standardized modularity prototype is implemented by dividing the case-study part into two manufacturing modules with different quality requirements. The underlying methodological premise is that manufacturing time is the dominant driver of additive-manufacturing cost, and that the hourly cost of fabrication depends on the relationship between equipment purchase cost and amortization time; therefore, applying high-quality (slower) process settings across the entire geometry can lead to unnecessarily long cycle times and higher costs when only a portion of the part requires such quality. The modular prototype addresses this by isolating the higher-quality region into a “top” module and assigning the remaining volume to a “base” module that can be produced using faster settings and, where applicable, lower hourly equipment cost, thereby decreasing the effective cycle time associated with the overall build. This approach is further linked to the capability to manufacture modules using different process parameters and even different equipment characteristics, so that dimensional tolerance and surface-quality constraints are met only where required rather than uniformly across the whole part.

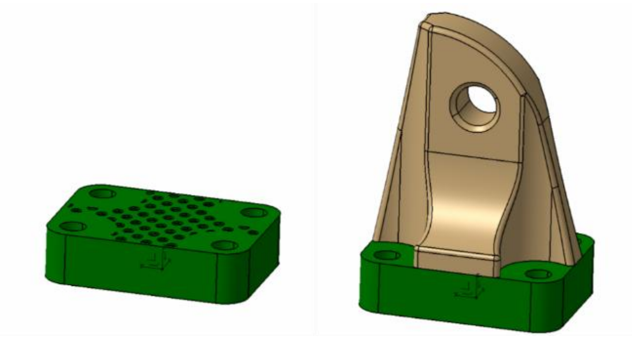

Figure 4 Modular prototype definition

In the modular prototype definition, as depicted in figure 4, the part is divided into a top module of 40x30x10 mm and a base module of 40x30x45 mm. The manufacturing order is constrained by vertical fabrication: the base is produced first, then—after full cooling—the top is produced above the base, with the separation interface defining the joining zone. Within the methodological framing, the base module is associated with lower surface-quality requirements and is therefore assigned accelerated fabrication settings, while the top module retains finer settings to preserve the quality of the functional/visible surfaces.

Experimental validation of the modular approach is conducted on a FDM 3D printer using ABS material and includes the complete pipeline from CAD export to fabrication and post-processing. The geometry is modeled in CATIA V5 and exported as an STL file using the “STL Rapid prototyping” plugin with tessellation settings that include a Sag value of 0.01 mm. The exported STL is subsequently processed in the slicing software and converted to machine instructions. Fabrication is carried out using an UP! PLUS 2 3D printer, and adhesion to the build surface is ensured using a perforated composite board support plate. The process includes post-processing limited to removal of the raft support where it is used. For the experimental prints, representative parameters are specified in table 1 and the specimens are fabricated using ABS material at an ambient temperature of 21°C, and an unheated build plate. The part is positioned centrally and oriented along the X axis. The raft is explicitly used for the base module and not used for the top module, reflecting the experimental control of interfacial conditions and adhesion behavior across the two-stage build.

Methodologically, this parameter split operationalizes the intended reduction of cycle time by applying rapid deposition only to the volume that does not require fine quality, while constraining slower settings to the limited region that does.

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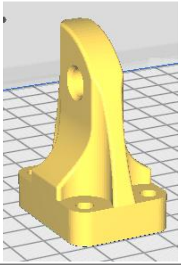
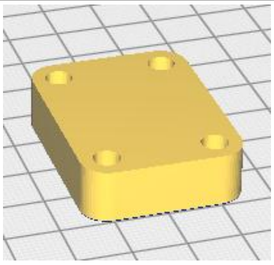
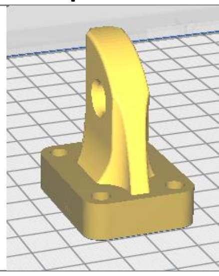
Table 1 Manufacturing Process Parameters

Parameter Name	One-piece manufacturing	Two-module manufacturing	
		Base Mode	Top Module
Isometric view			
Layer Height	0,2 mm	0,6 mm	0,2 mm
Infill	100%	100%	100%
Extrusion speed	100 mm/s	150 mm/s	100 mm/s
Travel speed	150 mm/s	150 mm/s	150 mm/s
Fabrication Time	1h 31min	15 min	52min

A key methodological component of the modular prototype is the joining geometry between base and top modules, implemented to increase contact area and thereby improve inter-module bonding and assembly stability. The joining concept is realized as an interlocking joint interface, and three distinct joining-pattern geometries are designed and fabricated (figure 5).

The first pattern is reported to generate manufacturing difficulties at the joining geometry due to the small perforation height, the second pattern is reported to improve manufacturability due to the perforation spacing and height, and the third pattern is reported to avoid manufacturing problems for the joining geometry.

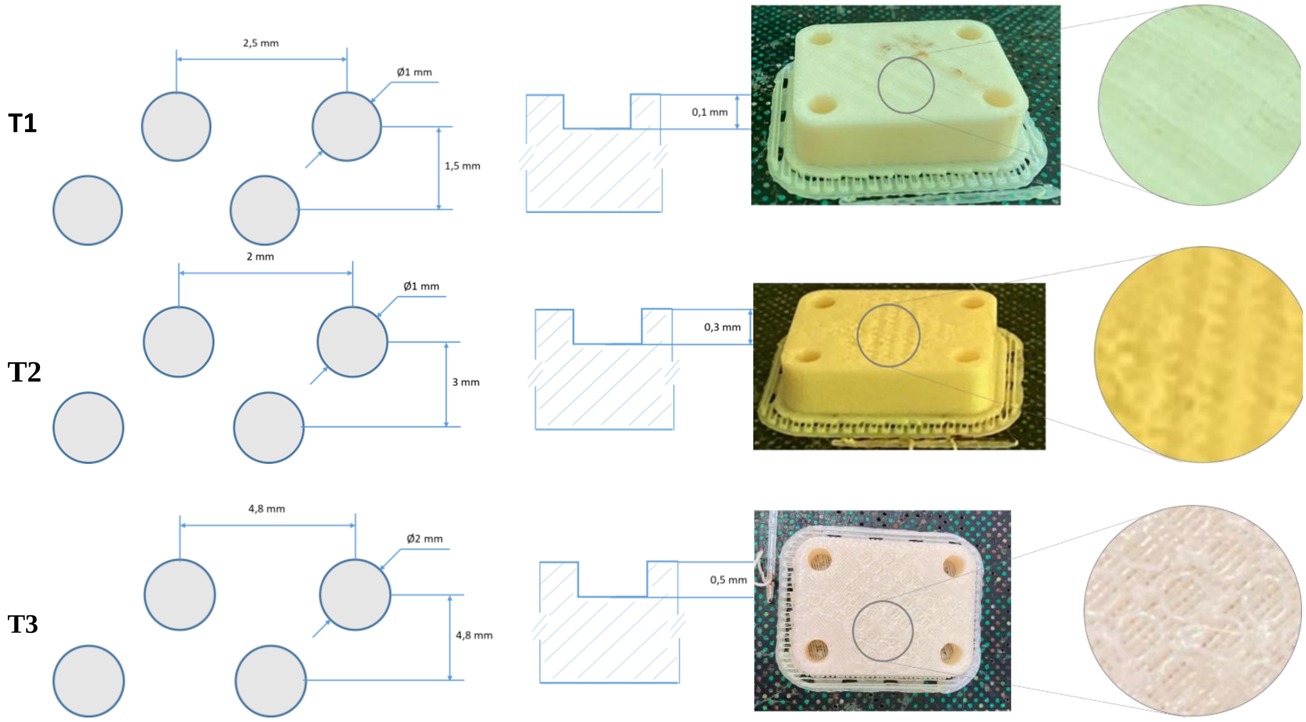


Figure 5 The three distinct joining-pattern types

These joining patterns are integrated into the modular specimen designs and are assessed through a structured sample matrix that varies infill density and joining pattern while including a single-iteration reference.

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The design of experiment includes single-iteration specimens and modular specimens manufactured in two iterations using joining pattern 1,2 and 3. Each specimen type is built using 3 different infill settings (20, 60 and 100%), in order to determine the joining pattern strength. For the tensile evaluation a total of 60 specimens were built (5 specimens of each type) so that we could exclude outliers generation due to the anisotropic material structure.

The two-iteration fabrication procedure is executed as a controlled sequential build. After printing the base module, a waiting interval of 20 min is introduced to emulate storage at room temperature prior to printing the top module. The base height is then measured using an electronic caliper and the machine setup is adjusted by modifying the extruder height relative to the base in preparation for printing the top module.

As depicted in figure 6, the separation zone between the base and top modules is part of the fabrication control, in order to focus on the interfacial region where mechanical failure may occur.

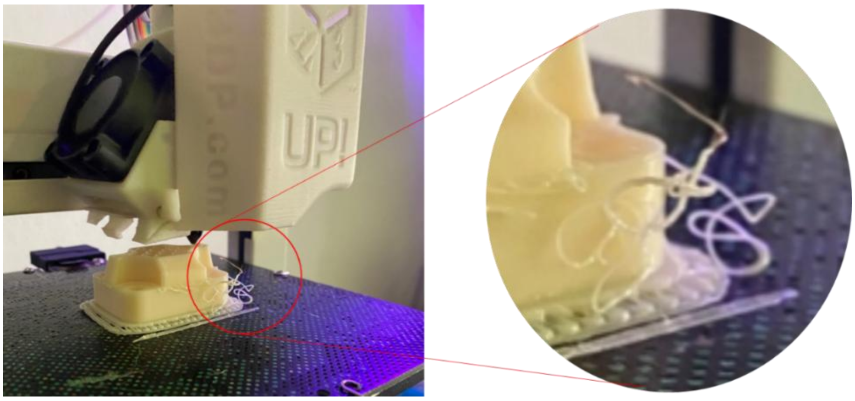

Figure 6 Separation zone between the base and top module

Mechanical testing is conducted to evaluate the structural performance of the modular joining concepts under tensile loading along the Z direction. Testing is performed on a Quasar 25 tensile testing machine using a dedicated fixture strategy designed to ensure repeatable gripping. The lower grip fixture is manufactured by CNC milling to secure the specimen consistently, while the upper grip is implemented using an electrical cable with protective sheath and a cross section of 2.5 mm². The procedure applies an initial pretension of 20 N, after which the force measurement is tared to 0 N and the tensile test is executed until fracture. The maximum force at the moment of rupture is recorded as the principal response, together with the fracture zone classification (reported as either the joining surface or the minimum section, depending on configuration).

4. RESULTS

The results are presented in two distinct categories: the comparative economic analysis based on the theoretical models defined in Section 3, and the experimental validation of the proposed modular manufacturing strategy.

4.1. Production Time Analysis

For the time comparison, the total production time is defined as the sum of the lead time (new-product introduction activities, including setup/mold realization and process optimization) and the effective manufacturing time required to deliver the specified production lot.

Injection molding is characterized by a front-loaded timeline dominated by mold realization and process validation/optimization. The average time required to deliver the first optimized parts from the moment of design completion is 15 weeks, reflecting the mold realization and optimization process. Once production begins, the process throughput is high; the injection cycle time used for the computations is 30s, and effective manufacturing times are reported for multiple production lots.

In contrast, the additive manufacturing route is characterized by a shorter new-product introduction cycle. The time required to deliver the first optimized parts is reported as 5 weeks. However, the effective manufacturing time is large when production is executed on a single machine, and therefore large-volume feasibility depends on parallelization using multiple machines. The reported time conversions from hours to days/weeks in the FDM tables (e.g., 15.777 h (657 days or 93 weeks) for 10.000 parts) are consistent with continuous production (24 h/day, 7 days/week), and the comparative time analysis is presented under this continuous-production interpretation. A consolidated comparison of total production times (including lead time and effective manufacturing time) for injection molding and FDM is given table 2.

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Table 2 Comparative total production time for injection molding and FDM across production volumes and machine counts.

Number of produced units	Manufacturing time				Total production time			
	IM	FDM (1 machine)	FDM (10 machine)	FDM (20 machine)	IM	FDM (1 machine)	FDM (10 machine)	FDM (20 machine)
10.000	83h	15.777h	1.577h	789h	15,5 weeks	98 weeks	14,3 weeks	9,6 weeks
20.000	166h	31.555h	3.155h	1.577h	16 weeks	19 weeks	23,7 weeks	14,3 weeks
50.000	417h	78.888h	7.889h	3.155h	17,5 weeks	474 weeks	51,9 weeks	23,7 weeks
75.000	625h	130.000h	13.000h	6500h	18,7 weeks	779 weeks	82,4 weeks	43,7 weeks
100.000	833h	173.333h	17.333h	8666h	20 weeks	1036 weeks	108 weeks	56,5 weeks

Within the discrete production volumes, the 20-machine FDM scenario achieves a shorter total production time than injection molding at 10.000 and 20.000 parts, while injection molding is shorter at 50.000, 75.000, and 100.000 parts. In addition, the differentiated time analysis identifies that, for the simulated case with 20 additive manufacturing machines, the total production time for injection molding and the total production time for additive manufacturing reach the same level around 30.000 parts.

4.2. Cost Analysis

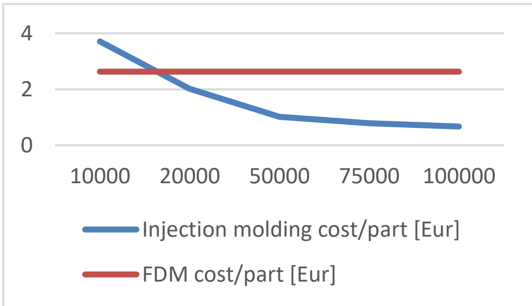
The injection molding cost model uses the reported production parameters (including a mold cost of 40.000 eur) and the cost computation workflow implemented via the custompartnet.com [9] tool, with resulting cost-per-part values decreasing as production volume increases.

For FDM, the unit cost is reported to remain constant with increasing production volume under the defined assumptions. The computed value is 2,63 euro/part, and the cost is decomposed into three components: fabrication cost 0,90 euro, material cost 1,29 euro, and handling cost 0,44 euro

The direct cost comparison between injection molding and FDM is reported in table 3.

Table 3. Comparative cost per part for injection molding and FDM across production volumes.

Production volume [parts]	IM cost/part [Euro]	FDM cost/part [Euro]
10.000	3,71	2,63
20.000	2,02	2,63
50.000	1,01	2,63
75.000	0,79	2,63
100.000	0,67	2,63



Based on this comparative analysis, FDM (Fused Deposition Modeling) is identified as the more competitive technology up to 15.000 parts.

4.3. Impact of Modularity on Cost

To evaluate the impact of a standardized modularity strategy on production economics for additive manufacturing, manufacturing simulations are performed for a part produced in a single build and a part produced in two geometric modules ("Base" and "Top"). The approach assumes that the Base module has lower quality requirements while the Top module has high quality requirements, and therefore the Base can be produced using an equipment option with lower performance and lower cost.

The process parameters used for the one-piece simulation and the two-module simulation are provided in Table 1 and reflect this quality-driven parameter split (e.g., different layer heights and different hourly manufacturing costs). Using the calculation methods referenced for the economic evaluation, dividing the geometry into modules yields an approximately 13% cost reduction compared to manufacturing in a single iteration, all due to a total manufacturing time reduction.

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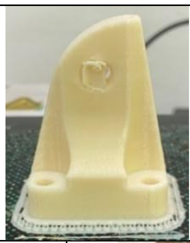
Table 4. Manufacturing observations based on the different fabrication strategy

Manufacturing type	**Images during manufacturing process**	**Observations**
One-piece manufacturing		-
Two module using pattern type 1	 	Difficulties in making the link geometry
Two module using pattern type 2	 	The link geometry is improved
Two module using pattern type 3	 	There are no problems in making the link geometry

The experimental program includes manufacturing observations relevant to part adhesion, dimensional stability, and interface formation for the two-iteration process. Initial manufacturing trials conducted without a support layer (“raft”) failed due to insufficient contact area with the build plate and internal stresses generated during cooling of the lower layers, leading to detachment from the build surface and process failure. Additional contributing causes are due to the lack of build-plate temperature control and the absence of a separation shield between the printed part and the ambient environment; combined with ABS shrinkage during cooling, these factors are associated with additional stresses, warping, and first-layer detachment.

For the two-iteration build, the interface between modules is formed by printing the top module above the base module after complete cooling, such that the upper surface of the base becomes the support surface for the first layer of the top. The feasibility of implementing patterned joining geometries at the separation surface is shown to be strongly linked to equipment capability and the manufacturability of small features. For Pattern 1, the joining geometry dimensions were sufficiently small relative to the production equipment capability that the printed patterning geometry did not conform to the CAD model. For Pattern 2, the joining geometry was optimized such that the distance between two perforations was greater than or equal to 1 mm, and the resulting joining geometry was improved, enabling adhesion of the two modules also through a mechanical connection. For Pattern 2, a tendency of agglomeration of the first layers at the separation surface is still observed (similar to Pattern 1), while the use of a larger patterning geometry facilitates more uniform material distribution. Pattern 3 is designed to maximize the mechanical connection and to create favorable conditions for equipment with inferior specifications and performance.

4.4. Mechanical testing

Tensile testing outcomes are reported as the maximum force at rupture and the corresponding rupture location (joining surface or minimum section). The configuration set includes single-iteration reference specimens (one-piece fabrication) and two-iteration modular specimens produced using interlocking Patterns 1–3, each manufactured at infill levels of 20%, 60%, and 100%. Specimen codes follow a consistent convention: “1b” denotes the one-piece reference strategy, while “p1”, “p2”, and “p3” denote modular

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specimens connected using Pattern types 1–3, respectively. The symbol “i” indicates the infill percentage; for example, p2-i60 corresponds to a modular specimen manufactured at 60% infill using the Pattern 2 interface.

As detailed in figure 7, the solid one-piece reference manufactured at 100% infill (1b-i100) established the highest measured load capacity in the dataset, reaching 1329 N and failing in the minimum section, rather than at the joining surface. This behavior indicates that, under this condition, fracture was governed by the specimen geometry rather than by interfacial separation. The best-performing modular configuration was p2-i100, which reached 1249 N and failed at the joining surface. Although interfacial rupture occurred, the maximum force achieved by this modular specimen remains close to the one-piece 100% infill reference (this corresponds to approximately 94% of the 1b-i100 maximum force, computed from the reported values), supporting the mechanical effectiveness of the Pattern 2 modular interface under high-density fabrication

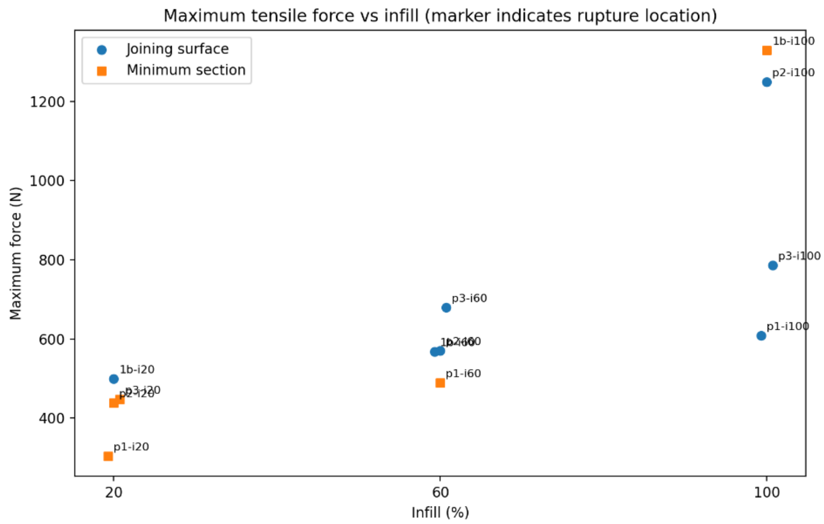
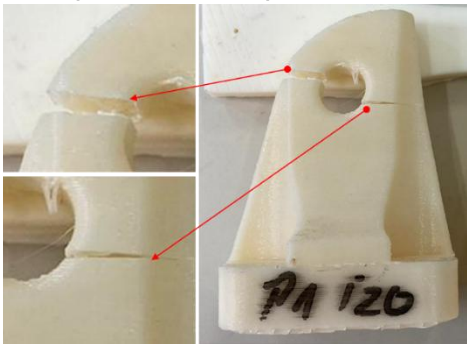
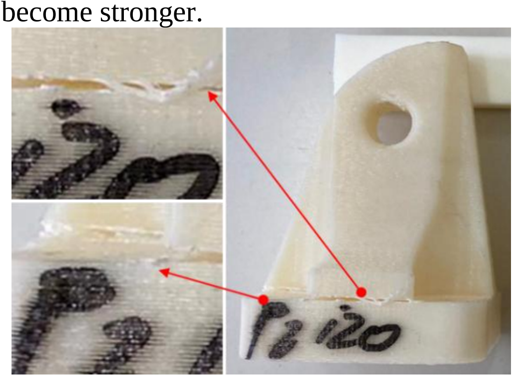


Figure 7 Tensile test results

Rupture-location trends (figure 7 and 8) show that at 20% infill all modular patterns fail in the minimum section (p1-i20: 304 N; p2-i20: 438 N; p3-i20: 447 N), whereas at higher infill the governing failure mode shifts toward the joining surface (notably at 100% infill for all modular patterns: p1-i100: 609 N; p2-i100: 1249 N; p3-i100: 786 N). Overall, the existence of modular configurations that fail outside the joint confirms that the interface is not inherently the weakest region, while the joining-surface failures at higher infill identify interface design as the limiting factor as the module bodies become stronger.



Minimum section rupture (p1-i20)



Join surface rupture (p2-i20)

Figure 8 Rupture location

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5. CONCLUSIONS

This study investigated the feasibility of integrating Fused Deposition Modeling (FDM) into industrial mass production through a strategy of Standardized Modularity. The analysis confirms that FDM is no longer solely a prototyping utility but a viable alternative to Injection Molding (IM) for medium-volume production series. The comparative economic analysis identified a specific window of viability where FDM competes effectively on both cost and time. Specifically, the break-even analysis established that FDM remains cost-effective for volumes up to approximately 15,000 units, below which the high fixed costs of mold tooling render traditional manufacturing economically inefficient. Furthermore, while the layer-by-layer deposition process of FDM is inherently slower than the rapid cycle times of injection molding, this study demonstrated that parallelization can effectively mitigate this bottleneck. Simulations indicate that a farm of 20 printers can match the total lead time of injection molding for volumes up to 30,000 units, thereby offering a rapid "time-to-market" solution for agile supply chains.

The core hypothesis of this research—that discretizing geometry into functional modules can optimize the manufacturing process—was validated both economically and mechanically. By separating the component into "Base" and "Top" modules and optimizing printing parameters for non-critical sections, a production cost reduction of 13% per unit was achieved compared to single-iteration printing. Mechanically, the experimental tensile testing proved that modular parts can achieve near-monolithic performance. The optimized interlocking design (Pattern 2 with 100% infill) withstood a maximum force of 1249 N, retaining 94% of the strength of the solid reference part.

However, the study also highlighted a critical sensitivity in failure modes relative to part density. At lower infill percentages (20%), the inter-modular bond exceeded the structural strength of the material, leading to failure at the geometric neck. Conversely, at higher densities (100%), the interface became the limiting factor, underscoring the necessity for precise Z-axis calibration and optimized interlocking geometry in high-stress applications. Future research should therefore focus on automating the slicing workflow to eliminate manual calibration errors and investigating thermal post-processing techniques to further enhance the interfacial bond strength of modular components.

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