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Review

A Technological Assessment: Aluminium Alloy Gigacasting vs. Conventional Sheet Metal Forming for Automotive Body-in-White Structures

Matteo Strano *, Filippo Caroli, Antonino Luongo, Davide Maglioli and Davide Monaci

Dipartimento di Meccanica, Politecnico di Milano, Via La Masa 1, 20156 Milan, Italy;
davide.monaci@mail.polimi.it (D.M.)
* Correspondence: matteo.strano@polimi.it

Abstract

Gigacasting is emerging as a disruptive manufacturing route for automotive body-in-white structures, especially for electric vehicles, by enabling large aluminium alloy components to replace assemblies traditionally produced from stamped and joined sheet-metal parts. This paper presents a technological assessment of aluminium gigacasting against conventional multi-material mix sheet-metal manufacturing. The comparison addresses product architecture, structural performance, manufacturability, factory organisation, cost, repairability, supply chain implications, and sustainability. Gigacasting offers benefits in part consolidation, reduced joining operations, shorter process chains, and potentially lower non-material manufacturing costs, making it attractive for high-volume, low-variant EV platforms and greenfield production. However, these advantages are counterbalanced by challenges, including high capital investment, limited die life, defect sensitivity, dimensional distortion, mechanical-property variation, and reduced repairability. Recent benchmark data also indicate that total part cost and production-phase CO_2 emissions may remain higher than conventional solutions when aluminium material cost, component mass, and aluminium carbon intensity are considered. Conventional sheet-metal architectures retain advantages in modularity, repairability, quality control, tooling flexibility, and lower-risk implementation in brownfield plants. The analysis concludes that gigacasting should not be regarded as a universal replacement for sheet-metal multi-material Body-in-White (BIW) manufacturing but as a platform-dependent technology whose success requires defect control, low-carbon aluminium supply, process-aware simulation and validation, and high and stable production volumes.

Keywords: aluminium die casting; high-pressure die casting; multi-material mix; structural integration; electric vehicle manufacturing; lightweight design; repairability; manufacturing sustainability; process efficiency; casting defects

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1. Introduction

The automotive sector is undergoing a major transformation driven by the need to improve production efficiency, reduce manufacturing costs, lower environmental impact, and enhance vehicle performance. In electric vehicle (EV) manufacturing, these drivers have accelerated the adoption of new structural concepts and advanced processing routes, including large-scale aluminium high-pressure die casting. In this context, gigacasting has emerged as a promising technology for Body-in-White (BIW) and underbody structures, supported by the development of cast aluminium alloys suitable for structural applications [1].

Gigacasting, also referred to as megacasting in some contexts, is a high-pressure die-casting process capable of producing large aluminium structural components in a single piece. Although the two terms are often used interchangeably, they generally differ in scale and application [2]. Megacasting usually refers to large-format die casting for structural components, whereas gigacasting describes the use of ultra-large high-pressure die-casting machines, typically in the range of 5000–12,000 tons, to manufacture highly integrated vehicle structures. Tesla pioneered the automotive application of gigacasting through its partnership with IDRA for the Model Y, followed by increasing interest from OEMs such as Volvo, Ford, Toyota, and Hyundai [3]. A timeline of the main industrial developments is shown in Figure 1.

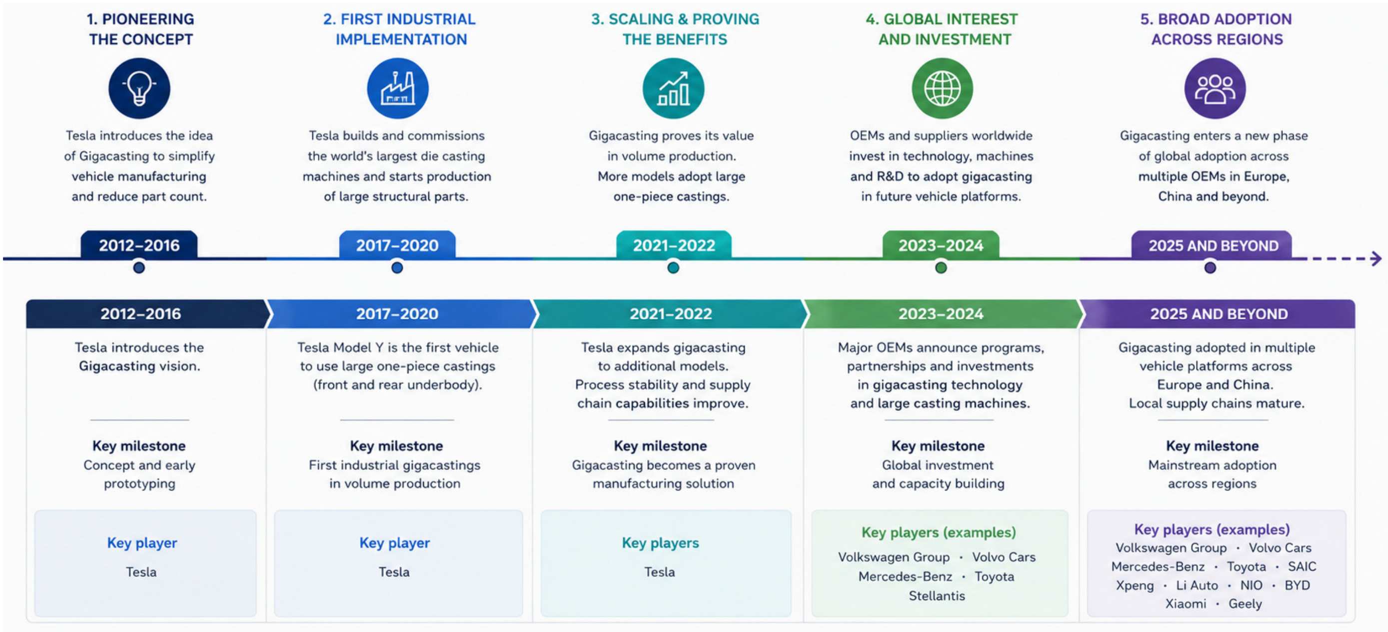


Figure 1. Chronological development of gigacasting in the automotive industry. This timeline highlights key milestones in the adoption of gigacasting by major original equipment manufacturers (OEMs), with Tesla pioneering the integration of giga-presses, followed by other companies like Volvo, Ford, Toyota, and Hyundai [4].

Conventional sheet-metal BIW manufacturing is based on a multi-material mix (MMM) architecture, in which numerous stamped steel or aluminium parts, together with selected extruded or forged components, are assembled through welding, riveting, and adhesive bonding [5]. This route is mature and flexible but requires extensive tooling, many joining operations, and complex assembly. By contrast, gigacasting integrates multiple components into a single large casting. A gigacast part can replace 70–80 elements traditionally produced via MMM, reducing the bill of materials and the number of welds [6]. However, these potential benefits are accompanied by challenges such as defect sensitivity, dimensional distortion, limited repairability, and significant capital investment requirements [1].

Conventional MMM sheet-metal BIW manufacturing should not be regarded as a static benchmark. Recent innovation has followed two main directions. The first includes flexible or localised forming processes, such as laser forming [7] and incremental sheet forming [8], which are useful for prototyping, low-volume production, repair, or local shape correction, but are generally unsuitable for high-volume BIW mass production because of their limited throughput. The second, more industrially relevant direction concerns advanced joining technologies for multi-material structures, including self-piercing riveting, clinching [9], flow-drill screwing, and adhesive hybrid joining [10]. These methods improve flexibility, material combination, and joint performance, whereas gigacasting acts at a different level by simplifying product and factory architecture through large-scale part consolidation.

Most available studies address individual manufacturing processes, specific material systems, or isolated performance indicators. A consolidated comparison of gigacasting and conventional MMM sheet-metal BIW manufacturing—covering product architecture, manufacturability, factory organisation, cost, repairability, supply chain, and sustainability—remains limited. This gap motivates the technological assessment presented in this work.

Organisation and Goals of the Paper

As with any radical manufacturing innovation, gigacasting requires major transformations across several domains [11], as summarised in Figure 2.

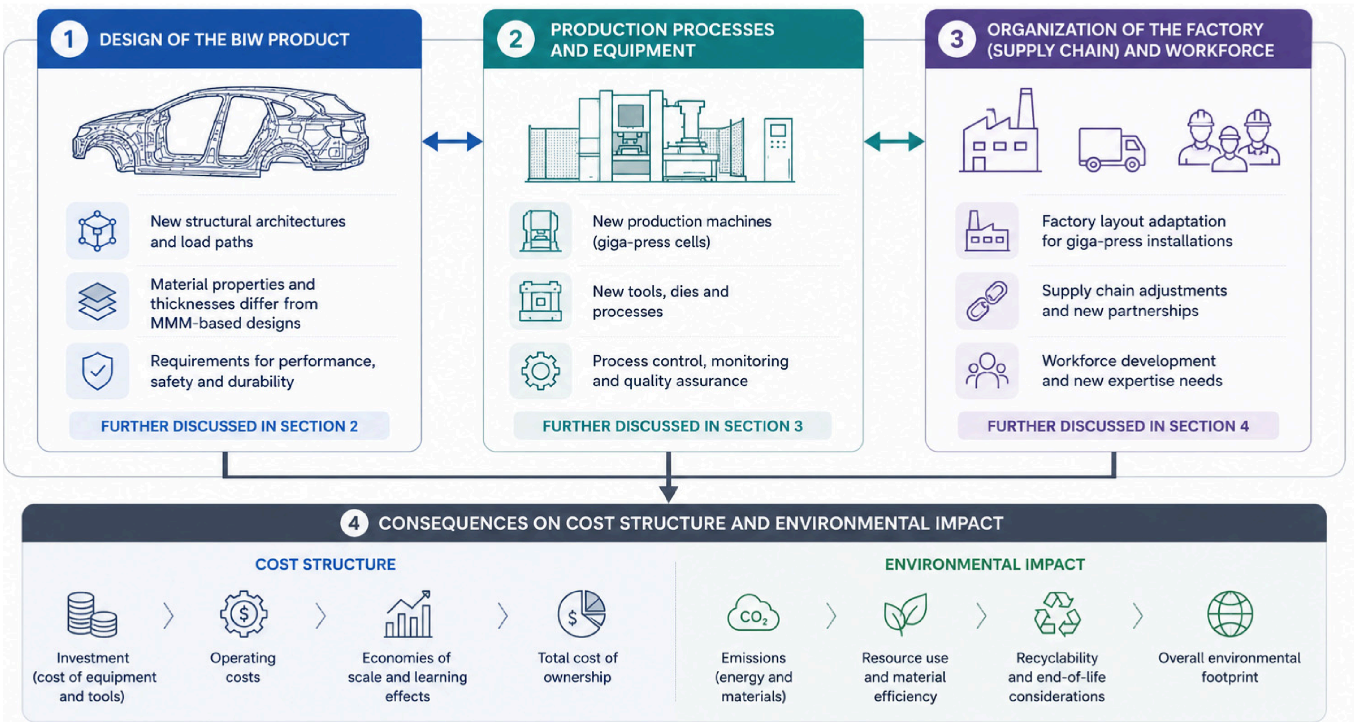


Figure 2. Primary domains of transformation induced by gigacasting implementation. The figure illustrates the key areas impacted by gigacasting technology—factory layout, product design, production equipment—each requiring significant organisational and technological adaptation [11].

These include:

- The design of the new BIW product: Structural characteristics and material properties differ significantly from MMM-based designs of BIW. This is further discussed in Section 2.
- The production processes and equipment: new production machines must be installed, and new tools and processes must be implemented. This is further discussed in Section 3.
- The organisation of the factory (including the supply chain) and the workforce. Factory layouts must be adapted for giga-press installations. New expertise is needed for gigacasting process management. This is further discussed in Section 4.

These transformations also affect cost structure and environmental performance, which are discussed in Section 5.

This study presents a technological assessment of gigacasting and conventional sheet-metal forming, focusing on five criteria: material efficiency, production speed, structural integrity, cost, and sustainability. The evaluation draws on academic literature, industry reports, and case studies from automotive manufacturers implementing gigacasting. The literature search was initiated in September 2024 and continuously updated until submission, using the keywords “gigacasting”, “megacasting”, and “high-pressure die casting” in Google, Google Scholar, Scopus, and ResearchGate. The search for “high-pressure die casting” was restricted to large-format or ultra-large structural castings relevant to automotive applications. Additional sources were identified by following references cited in relevant papers, especially review articles.

Since gigacasting is an emerging industrial technology, the scientific literature remains limited. A Google Scholar search using the keyword “gigacasting” identified only 287 references since 2022, about half published in the last 18 months, and many were not directly related to BIW applications or lacked original experimental or engineering content. Therefore, selected industry reports, OEM communications, patents, online magazines, and specialised websites were also included when they provided traceable technical information, quantitative data, or documented industrial implementation cases.

The central argument of this paper is that gigacasting represents a transformative shift in vehicle manufacturing, particularly for EV platforms, by enabling high levels of structural integration and production efficiency. However, it also introduces technical and operational challenges related to defect sensitivity, repairability, tooling costs, and supply-chain restructuring.

The novelty of this review lies in its integrated product–process–factory perspective, which compares gigacasting and conventional MMM sheet-metal BIW manufacturing not only as alternative manufacturing processes but also as competing vehicle-platform strategies with different implications for design, production, cost, repairability, supply chain, and sustainability.

2. The Product

The classification of Body-in-White (BIW) architectures can be described based on the extent of gigacast part integration into the vehicle structure. Currently, three primary categories are recognised:

The Multi-Material Mix (MMM) BIW represents the conventional manufacturing route, wherein the structure is assembled from numerous stamped components composed of steel, aluminium, or a combination thereof. Joining is performed using welding, riveting, and adhesive bonding. This approach offers flexibility in material selection and component replacement but entails greater manufacturing complexity and a higher number of joining operations.

In a 3 + 1 architecture, front, rear, and battery tray modules are gigacast, while the upper structure remains sheet metal. A 1 + 1 concept—integrating the entire underbody—has been explored by Hyundai and Tesla, though practical adoption remains uncertain.

The emerging 1 + 1 Hypercasting BIW concept further extends this integration by consolidating the entire underbody into a single gigacast component, combined with an MMM upper structure. Hyundai has publicly announced plans to adopt this approach in future models starting in 2026, aiming to maximise the benefits of part reduction, structural rigidity, and manufacturing efficiency. However, there are indications that the 1 + 1 Hypercasting might never be implemented by some OEMs [12]. As of May 2024, Tesla has reportedly paused its plans to manufacture entire vehicle underbodies as single pieces using gigacasting technology. Instead, the company is continuing with its existing approach of producing the underbody in three separate sections: two gigacast front and rear components, and a midsection composed of aluminium and steel to house the battery pack [13].

Currently, gigacasting applications are focused on the underbody due to its geometric simplicity and the critical demand for structural stiffness. The typical division involves three gigacast parts: a front module, a rear module, and a battery tray. These components serve not only as primary load paths but also as energy absorption structures during crash events (Figure 3). Extension of gigacasting to upper body structures remains constrained by challenges related to complex load distribution, occupant protection requirements, repairability concerns, and limitations in achievable casting geometries.

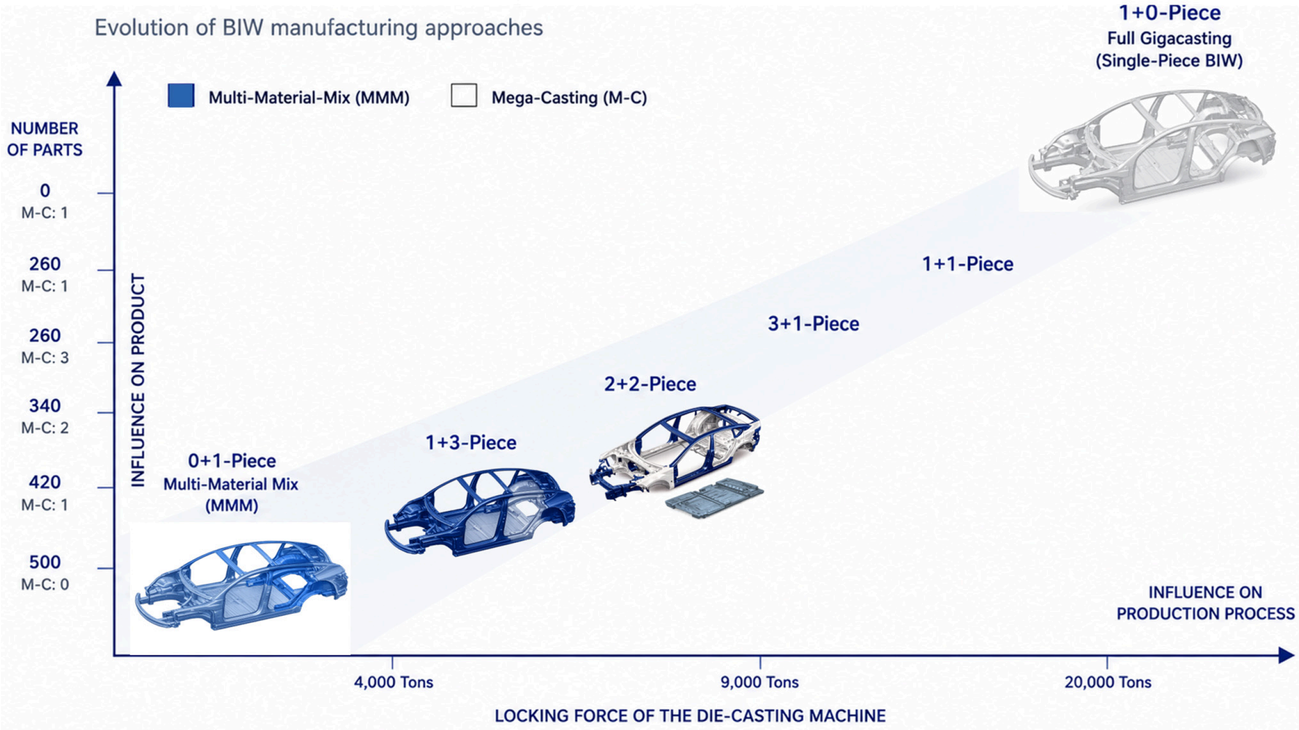


Figure 3. Architectural layout of alternative gigacasting BIW designs of EVs. The figure shows the evolution from the traditional MMM approach to the 1 + 3 design in which the rear underbody is gigacast, to the 2 + 2 variant in which both the front and rear underbodies are gigacast, and finally to the ideal 1 + 0 concept in which all BIW modules are cast [14].

2.1. Stiffness and Global Structural Rigidity

Gigacasting introduces a monolithic architecture that enhances torsional and bending stiffness by reducing the number of joints and welds, thereby improving global rigidity. Although aluminium exhibits a lower Young's modulus than high-strength steel, this limitation can be partially offset through increased section thickness and the resulting higher moment of inertia in cast components.

According to [15], several OEMs have reported performance gains in terms of stiffness. However, as with weight reduction claims, these reports lack transparent comparative data. Expert panels summarised in [14,16] agree that the structural superiority of gigacasting is highly design-dependent, and no universal advantage can be established across all cases. A very recent engineering benchmark comparing a steel front-end baseline with an aluminium giga-cast baseline provides useful quantitative support for the design-dependent nature of stiffness improvements. In the study, the aluminium giga-cast baseline reduced the front-end design-space mass from 94 to 76 kg and increased BIW torsional stiffness from 17.0 to 22.8 kN·m/deg and bending stiffness from 14.8 to 17.4 kN/mm (Table 1). Shock-tower stiffness in the vertical direction also increased from 5.8 to 9.1 kN/mm. However, lateral stiffness decreased from 6.3 to 5.0 kN/mm. The same study showed that optimised AHSS/UHSS alternatives could partially recover the torsional-stiffness advantage while offering competitive mass and lower production-phase CO_2 emissions. These results confirm that gigacasting can improve selected stiffness metrics, but that the benefit is load-case-dependent and must be evaluated against optimised steel or MMM alternatives rather than against conventional baseline designs only.

Table 1. Quantitative comparison of front-end stiffness and mass for an aluminium giga-cast baseline, a conventional steel-based baseline, and advanced steel alternatives. Data are adapted from [17], which compares a giga-cast aluminium front-end with a validated steel baseline and two optimised AHSS/UHSS concepts.

Metric	Aluminium Giga-Cast Baseline	Conventional Steel-Based Design	Advanced Steel Design (Average)
Front-end mass	76 kg	94 kg	83 kg
Part count	18		72
BIW torsional mode	40.2 Hz	38 Hz	39 Hz
BIW torsional stiffness	22.8 kN·m/deg	17 kN·m/deg	20 kN·m/deg
BIW bending stiffness	17.4 kN/mm	15 kN/mm	14 kN/mm
BIW lateral stiffness	5.0 kN/mm	6.3 kN/mm	5.3 kN/mm

Compared with conventional MMM sheet-metal BIW structures, gigacast architectures impose different requirements on dimensional control and assembly tolerances. Traditional BIWs consist of many smaller sheet-metal parts joined by welding, riveting, or adhesive bonding. Although geometrically complex, these assemblies retain some compliance because local misalignments can be partly absorbed by flexible stamped panels and distributed tolerance chains. Gigacast structures, by contrast, are monolithic and highly rigid, so dimensional inaccuracies are less easily accommodated and may propagate to the final assembly.

As emphasised by Wärmefjord et al. [18], gigacasting therefore requires a geometry-assurance approach based on early robust design, tolerancing, and simulation of part- and assembly-level deviations. Numerical simulation and digital process representations can support dimensional prediction, distortion compensation, inspection planning, and joining-interface assessment. However, geometry assurance still depends on robust datum schemes, fixtures, dimensional inspection, and correction strategies at the assembly level.

2.2. Crash Performance and Defect Sensitivity

Crash performance remains one of the most debated aspects of gigacasting. Conventional MMM BIW designs rely on engineered crumple zones composed of multiple interconnected stamped, extruded, or cast components, which dissipate crash energy through progressive deformation, controlled collapse, and distributed joining interfaces. By contrast, gigacasting integrates large portions of the crash structure into a single cast underbody or front-end component, using variable wall thickness, rib networks, flared profiles, waveform geometries, and cut-outs to guide load transfer, deformation, and fracture paths. However, microporosity and other casting defects may reduce crash integrity [15] and fatigue life [19] in cast aluminium components.

The apparent contrast between improved crash performance and defect sensitivity can be explained by distinguishing global structural behaviour from local material response. At the structural level, gigacasting may improve crash performance through fewer joints, higher geometric continuity, larger load-bearing sections, and optimised load paths. At the local scale, however, pores, shrinkage cavities, oxide films, cold flakes, and other defects may reduce ductility and promote crack initiation in highly strained or cyclically loaded regions. Therefore, any crashworthiness advantage depends on whether the local defect population is compatible with the strain demand of each region.

This requirement is reflected in process-aware crash modelling, where casting-process effects are incorporated by linking solidification time, flow length, and local elongation to position-dependent failure curves [20]. Gigacast structures should therefore not be modelled as homogeneous components with a single nominal stress–strain curve, especially in crash-relevant zones. The benchmark study in [17] further shows that advanced steel alternatives can meet crash-performance targets defined against an aluminium gigacast baseline, confirming that crashworthiness is a system-level outcome of architecture, material selection, load-path design, process quality, and validation assumptions.

Mechanical testing of large gigacast structural parts confirms that local properties are strongly affected by defect content and microstructural gradients. Ductility deteriorates significantly with increasing internal defect area [21], and regions with higher porosity fractions show earlier crack initiation and faster fracture propagation. In a GM-developed AA386 gigacasting, yield strength ranged from 131 to 166 MPa, ultimate tensile strength from 173 to 287 MPa, and elongation from 1.4% to 7.1%, depending on location [22]. These variations show that gigacast BIW structures require location-dependent material properties, conservative lower-bound design allowables, process capability data, NDT, process-aware crash simulation, and full-scale validation. By contrast, homogeneous material behaviour can generally be assumed more reliably in stamped sheet-metal components, whose properties and failure modes are supported by mature forming, joining, and crash-validation practices.

Defect acceptance criteria for safety-critical gigacast structures should be component- and location-specific. The acceptability of a defect depends not only on its size, projected area, or volume fraction, but also on its morphology, distance from the surface, clustering, local wall thickness, residual stresses, and the stress–strain state expected under crash or fatigue loading. Stricter limits should therefore be applied in crash-critical load paths, highly strained regions, suspension attachment zones, and areas subjected to cyclic tensile stresses. For this reason, a single universal critical pore size is not appropriate. Defect acceptance should instead be based on a combined qualification approach, including NDT detectability limits, local mechanical-property mapping, conservative lower-bound material allowables, defect-sensitive fracture or fatigue assessment, process-aware crash simulation, and validation tests on representative castings.

Available crash and repairability studies suggest that gigacast structures can perform satisfactorily when properly designed and located. Thatcham crash simulations indicate that Tesla's rear gigacast withstands conventional RCAR crash standards without structural compromise [23], with significant casting damage only under more severe conditions, such as a 40° oblique impact at 25 km/h. Tesla has also patented energy-absorption concepts, including C-shaped and I-shaped configurations, designed to initiate fracture outboard and propagate it inboard in a controlled manner (Figure 4) [24]. Nevertheless, reliable assessment requires advanced finite element analysis, defect-sensitive crash simulation, and broader real-world validation across different impact scenarios.

2.3. Potential for Structural Optimisation and Lightweighting

The monolithic nature of gigacast sub-assemblies offers significant opportunities for structural optimisation. By reducing joints, welds, and interfaces, gigacasting increases design freedom and supports topology optimisation and simulation-driven development [25]. However, the sensitivity of topology-optimised gigacast structures to manufacturing defects has not yet been quantified in general terms. Defects and wall-thickness deviations affect optimised and non-optimised castings through similar mechanisms, including local stress concentration, reduced effective load-bearing area, and lower ductility. Topology-optimised designs may be more vulnerable when high stresses are concentrated in thin ribs or localised load paths. Therefore, gigacasting optimisation should include minimum wall-thickness constraints, manufacturability limits, process-aware casting simulation, and defect-sensitive structural validation.

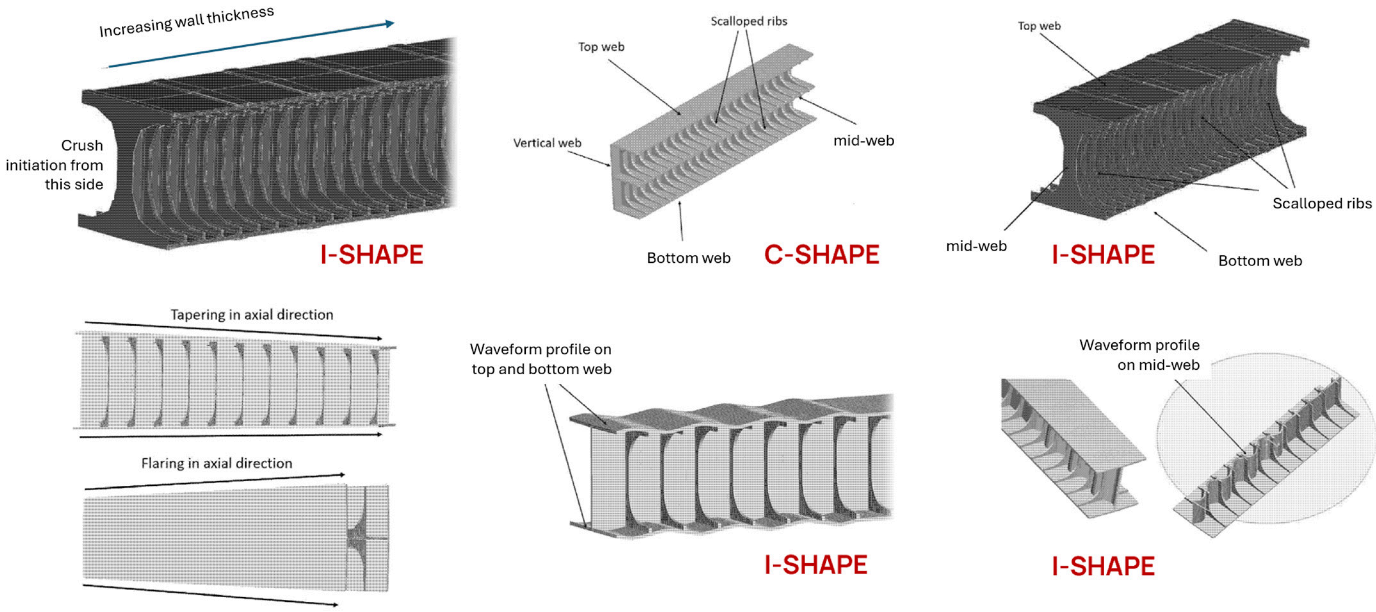


Figure 4. Energy absorption concepts in gigacast automotive structures. Illustrates patented deformation designs for aluminium castings that enhance crash performance by guiding fracture propagation in predictable ways, offering structural integrity with reduced material use [24].

Comparatively, traditional BIW architectures based on stamped and welded components offer a high degree of modularity, allowing for localised optimisation of structural elements, such as tailored thickness in crash zones, modular reinforcements, and gradual material transitions [26]. This modularity enables targeted lightweighting strategies at the component level without requiring large-scale redesigns. In contrast, gigacasting approaches consolidation at the assembly level, integrating multiple functions into a single part. While this can reduce the overall part count and eliminate joining flanges, it also results in larger minimum wall thicknesses (typically 3–5 mm compared to 0.7–1.2 mm for steel sheets), potentially increasing material usage if not carefully optimised [14].

Furthermore, the lightweighting potential of gigacasting remains highly design-dependent. OEM data suggest that when appropriately engineered, gigacasting can achieve weight reductions of approximately 7% to 20% for the underbody module compared to traditional designs [15]. A recent CAE benchmark [17] also shows that the mass advantage of gigacasting depends strongly on the functional boundary considered. In the analysed front-end design space, the aluminium giga-cast baseline had a mass of 76 kg, compared with 83 kg for the optimised AHSS/UHSS alternatives. However, when only the casting-equivalent portion was considered, the steel alternatives were lighter, at approximately 70.3 kg compared with 74.7 kg for the aluminium giga-cast design. This confirms that mass comparisons must be made on a functionally equivalent basis and cannot be inferred from material density alone.

Optimisation should not focus solely on maximising stiffness or crash performance. Lightweighting remains a central objective in vehicle engineering, as it affects energy efficiency, dynamic behaviour, and sustainability. Therefore, gigacast design must balance structural performance with sub-assembly and vehicle mass reduction. Without careful control of wall thickness, rib layout, and defect mitigation, cast parts may become heavier than their multi-piece stamped counterparts. For this reason, lightweight-oriented structural optimisation remains essential, as further discussed in the Sustainability section.

2.4. Repairability and Serviceability Challenges

Repairability is another critical aspect in the structural comparison between gigacasting and conventional BIW manufacturing. In conventional BIWs, localised damage can often be addressed by repairing or replacing individual stamped parts. By contrast, damage to gigacast structures may require larger repair interventions, especially when it affects load-bearing regions for which approved sectional repair procedures are not available. This has implications for repair cost, insurance risk, and sustainability. Repair procedures for cast structures are generally more invasive and expensive [27], and OEM repair guidelines or liability concerns may favour replacement of critical cast components after crash events. Although severe collisions often require extensive repairs regardless of BIW architecture, limited local repairability remains a potential barrier to the adoption of ultra-large aluminium castings in mass-market vehicles. Some manufacturers, such as GM, are therefore exploring modular design solutions with predefined "cut-and-replace" zones, but their widespread adoption remains limited. In this context, some experts consider repairability one of the most important obstacles to broader gigacasting deployment [14].

As a result, serviceability and insurance costs remain important considerations for the future adoption of gigacast vehicles. However, repairability should be regarded as an implementation-dependent issue rather than an intrinsic limitation of gigacasting. Its impact depends on component location, damage frequency, availability of approved repair procedures, spare-part strategy, and the ability of repair networks to perform sectional replacement.

Hybrid or compound casting approaches can be seen as extensions of monolithic gigacasting rather than as direct alternatives. By embedding optimised inserts, such as extrusions, steel reinforcements, or additive-manufactured features, into the casting mould, selected regions can be tailored for crash, thermal-management, joining, stiffness, or local repair requirements [27]. Although inserts, bolted elements, or predefined replacement zones may reduce the maximum part-consolidation benefit of integral gigacasting, they also expand the design space. Hybrid gigacasting can therefore provide an additional route to balance structural integration, repairability, manufacturability, and cost. Its value is application-specific: fully monolithic castings may be preferable in some cases, whereas hybrid architectures may offer a better system-level optimum in others.

Recent insurance and crash-repair studies also suggest that large cast aluminium structures do not necessarily increase repair costs when they are located away from common impact zones, supported by modular cut-and-replace procedures, and accompanied by appropriate workshop strategies. An Allianz-Thatcham study based on more than 2000 EV insurance claims found that less than 1.5% of claims involved repair costs influenced by gigacastings [23]. Even in these cases, partial replacement of damaged cast sections—similar to conventional side-member replacement—was technically feasible and cost-comparable with legacy steel body repairs (Figure 5). Therefore, gigacasting should not be considered categorically unserviceable. Nevertheless, repairability remains a relevant adoption barrier where repair procedures are not standardised, repair networks are not trained, or damage requires large component replacement.

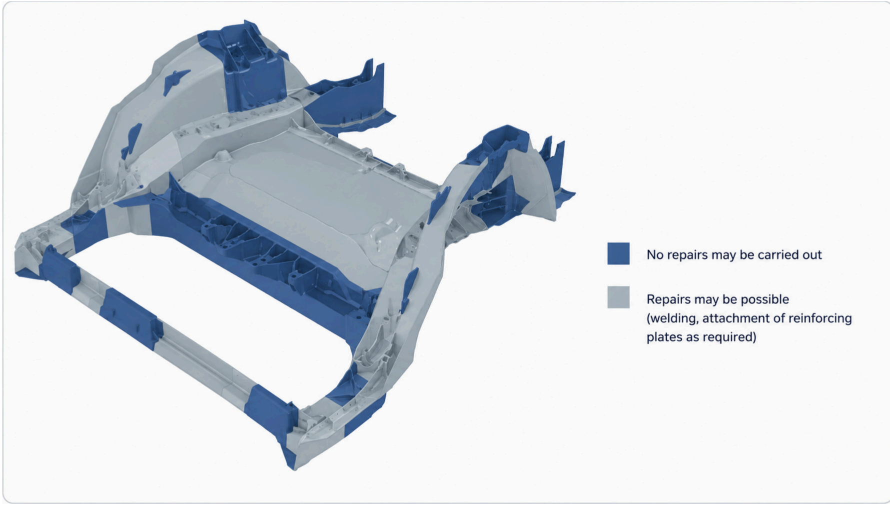


Figure 5. Repair options for cast rear underbody (one-piece), reproduced from Tesla 2020–2024 Model Y Collision Repair Procedures Manual [23]; grey parts can be repaired if damage is limited.

2.5. Comparative Summary

Gigacasting enables strong product integration by replacing many stamped and joined BIW parts with large monolithic aluminium castings. This can reduce part count, improve structural continuity, and support higher stiffness and NVH performance. However, its advantages are highly design-dependent: aluminium's lower Young's modulus, larger casting wall thicknesses, and local property variations can limit weight reduction and crash performance.

Compared with MMM sheet-metal BIW, gigacast structures are more sensitive to porosity, microstructural gradients, and local ductility loss, requiring advanced simulation and validation. Repairability also remains a concern, although recent crash and insurance studies suggest that this issue may be mitigated through protected casting locations, segmented repair strategies, and predefined replacement zones. Overall, gigacasting is most suitable for dedicated EV platforms, while MMM remains advantageous where modularity, local material tailoring, and serviceability are priorities.

3. Production Process and Equipment

The gigacasting process follows the fundamental principles of conventional high-pressure die casting (HPDC) but operates on a much larger scale, involving significantly higher forces, pressures, and material volumes. These extreme conditions require specialised giga-presses, which are discussed in more detail in the following sections. Gigacasting lines are highly automated, with robots managing the entire operation—from mould preparation to extraction and final inspection.

The gigacasting process consists of six main stages:

1. Mould Preparation: Proper preparation of the die ensures that molten aluminium flows correctly into the sealed cavity, minimising the risk of defects. A water-based die release agent—preferred for environmental reasons over oil-based alternatives—is sprayed onto the mould surface to facilitate smooth ejection and extend mould life by reducing sticking and thermal fatigue.
2. Molten Aluminium Injection: Aluminium alloy is melted in a high-temperature furnace and precisely metered before being injected into the die cavity by a high-pressure plunger. The injection occurs at high speeds to ensure that the entire cavity is completely filled before the onset of solidification. Maintaining proper injection dynamics is critical to avoid incomplete filling, air entrapment, and cold shuts. Controlling

oxides, porosity, and hydrogen content is more critical for gigacasting than normal HPDC. Techniques such as flux treatment, vacuum degassing, and optimised charge material selection are necessary to obtain high-quality large castings with defect populations compatible with structural requirements. Poor melt control can severely compromise mechanical properties and overall casting integrity [27].

3. Solidification: Following injection, the molten aluminium solidifies rapidly, typically within seconds. Careful control of cooling rates and temperature gradients during this phase is essential to minimise internal stresses, shrinkage porosity, and distortion. At the end of solidification, the part typically reaches a temperature of around 400 °C.
4. Extraction of the Cast Part: After complete solidification, the part is robotically extracted from the mould while still at elevated temperatures. Robotic extraction ensures consistent handling speed and precision, minimising the risk of damage, warping, or cracking during removal. Alternative demoulding systems may reduce or avoid the use of conventional ejector pins or rods, thereby limiting localised pressure marks, microcracks, and residual stresses in large thin-walled gigacast components [28]. Figure 6 primarily illustrates the injection and extraction phases of the process.

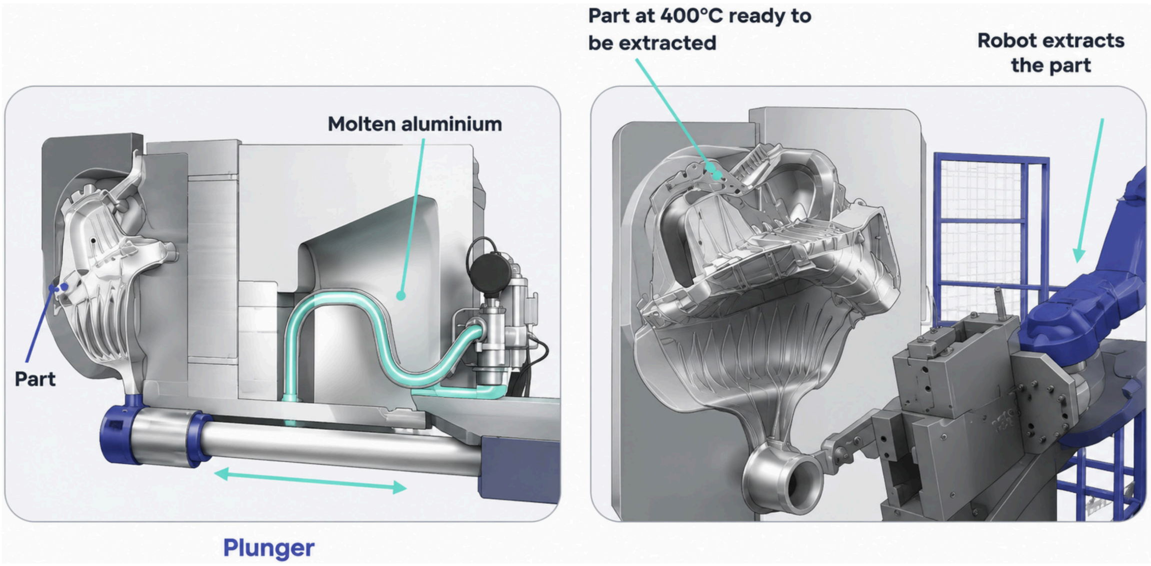


Figure 6. Visual representation of key stages in the gigacasting process. Focuses on the injection of molten aluminium and robotic extraction of the solidified part, emphasising automation, precision, and the scale of the equipment involved.

5. Final Inspection: Each gigacast component undergoes a thorough inspection to detect surface defects, dimensional inaccuracies, and internal flaws. Visual inspections are supplemented by non-destructive testing methods, such as X-ray or CT scanning, to identify porosity, shrinkage cavities, or inclusions that could compromise mechanical performance.
6. Post-Processing: After inspection, minor defects and excess material (such as flash or overflow) are removed using Computer Numerical Control (CNC) machining. Depending on the material and detected distortions, additional post-processing operations may include heat treatments to enhance mechanical properties, particularly for heat-treatable alloys, and mechanical straightening to restore dimensional accuracy. Surface finishing operations are performed where necessary to meet the stringent dimensional and structural standards required for vehicle integration.

Vacuum-assisted HPDC is increasingly used in gigacasting to improve filling quality and reduce internal defects [29]. In this process, a vacuum environment, typically reaching pressures as low as 50 mbar, is created in the die cavity before and during injection. This reduces gas entrapment, porosity, and oxide inclusions, while promoting more complete mould filling and improved mechanical properties. Vacuum assistance is particularly important for ultra-large automotive castings, where internal defects can compromise crash performance and durability.

After the production of the part, it must be assembled to the rest of the body-in-white (BIW). The solution of choice for this type of assembly operation tends to avoid welding and instead favours mechanical joining methods such as the combination of Flow Drilling and Thread Forming [30], the use of Self-Piercing Rivets (SPR) [31,32], and traditional riveting. These mechanical methods are preferred because they are cold connection processes that preserve the mechanical properties of the casting and avoid introducing thermal stresses [15].

3.1. Considerations on Materials

The success of gigacasting depends strongly on alloy selection. Ultra-large structural castings require high fluidity for complete mould filling, low shrinkage and hot-tearing susceptibility to limit dimensional inaccuracies and solidification cracking, and sufficient mechanical strength and ductility for structural use. These properties depend on alloy composition, pouring temperature, filling velocity, and mould design. Aluminium gigacasting alloys are mainly based on Al-Si and Al-Mg systems, although magnesium alloys are also being investigated for future lightweighting applications.

Al-Si alloys are widely used because silicon improves fluidity and reduces shrinkage. Common die-casting grades include ADC12, A380, and A356. Near-eutectic Al-Si alloys, with approximately 10–12% Si, offer excellent castability but limited ductility, whereas structural applications generally require a better compromise between castability and mechanical performance. For this reason, alloys with approximately 7% Si, such as C611, Aural 5, and AA386, are often preferred for structural castings.

Tesla's use of AA386 illustrates the challenges associated with copper additions. Even moderate copper contents can expand the freezing range, increase shrinkage porosity and hot-tearing susceptibility, reduce corrosion resistance, and degrade castability. Consequently, copper is generally limited or avoided in structural aluminium alloys for BIW applications. Other alloying elements are used to tailor performance: magnesium promotes strengthening through natural ageing, manganese mitigates the effect of iron impurities, and strontium modifies silicon morphology and may improve resistance to die soldering.

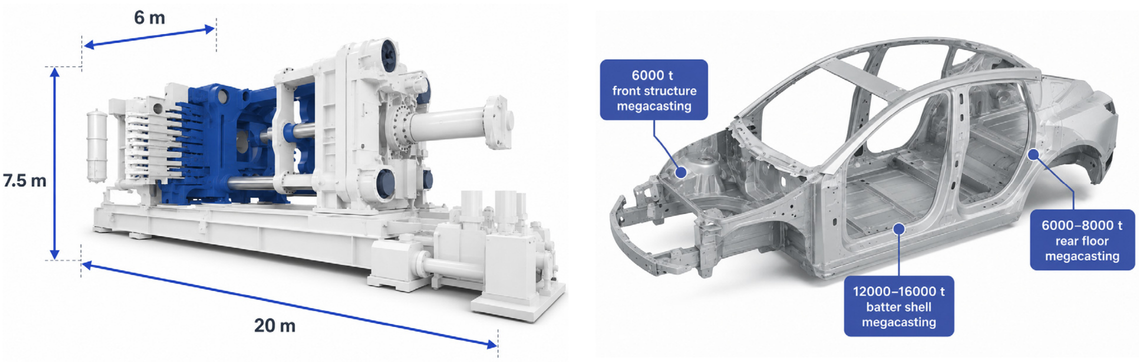
Al-Mg series alloys, while offering excellent corrosion resistance and good mechanical properties, are less favoured for gigacasting due to poorer castability and high sensitivity to wall thickness variations [27].

Traditionally, aluminium castings undergo T6 heat treatment to improve mechanical properties. However, the large size and complex geometries of gigacast parts make them prone to severe distortion during thermal cycles. Therefore, significant efforts have focused on developing non-heat-treatable alloys that achieve the necessary mechanical performance in the as-cast condition. Avoiding heat treatment enhances dimensional stability, reduces energy consumption and CO_2 emissions, and improves production efficiency [15]. Design strategies for these alloys include solid solution strengthening (via magnesium additions), optimised silicon content for balanced properties, microstructure refinement through minor alloying additions (Mn, Cr, Zr, Ti), and defect minimisation through process control. Prominent examples include Tesla's proprietary Al-Si-Mg alloys, Rheinfelden's Castasil®-37 (AlSi9MgMn), Magna's Aural™ 5S and 6S series, and Alcoa's C611 alloy. Despite advances, challenges persist in balancing strength and ductility, sensitivity to process variations, and managing internal defects such as microporosity and oxide inclusions, necessitating extensive non-destructive testing.

Magnesium alloys are emerging as a potential future solution for gigacasting. Magnesium offers a density two-thirds that of aluminium and one-fourth that of steel, promising up to 32% weight reduction. Magnesium alloys also exhibit superior fluidity, allowing thinner wall sections and lower injection forces, potentially reducing energy consumption. However, magnesium casting faces challenges, including oxidation sensitivity, bifilm defect formation, and hot tearing. Advanced processing methods, such as vacuum-assisted casting and electromagnetic purification, are needed to overcome these barriers. Although not yet mainstream, magnesium gigacasting represents a promising direction for future automotive lightweighting and sustainability [33].

3.2. Considerations on Equipment

Gigacasting is made possible by giga-presses, enormous die casting machines (max force of the press ranging from 5500 tons to 12,000 tons), i.e., horizontal hydraulic presses, capable of producing massive structural components in a single casting cycle (Figure 7a). Reported mega/gigacastings involve shot weights of approximately 80–100 kg [34]. The first giga-presses designed specifically for automotive applications were developed by Idra Group, an Italian manufacturer that collaborated with Tesla to produce large castings for the Model Y. Beyond early adopters like Tesla and Volvo, the global automotive industry is witnessing rapid expansion of gigacasting infrastructure. Chinese OEMs—including Nio, Xiaopeng, and HiPhi—have made significant investments in large-scale HPDC systems, often benefiting from greenfield factory setups that are suited for this new paradigm [35].



(**a**) (**b**)

Figure 7. (**a**) Scale and dimensions of a typical gigacasting press used in automotive applications. Demonstrates the size and structural layout of a giga-press, showcasing its industrial footprint and the infrastructure required for operation. (**b**) Typical press tonnage required for front (~6000 t), rear (6000–8000 t), and battery tray (12,000–16,000 t) megacastings in a 3 + 1 BIW architecture [36].

These state-of-the-art machines operate with exceptionally high clamping forces (Figure 7b), ranging typically from 55,000 kN to 130,000 kN, a value that for some machines reaches a maximum of 160,000 kN. The growing demand for 1 + 1 hypercasting (single-piece underbody structures) is driving the need for larger and more powerful giga-presses.

The shift toward gigacasting has required parallel advances in die design and tool-material selection. Conventional die materials, such as H13 tool steel, may be insufficient for ultra-large castings because of the severe thermal loads, long flow paths, and high production stresses involved. Recent developments include high-thermal-conductivity tool steels, which can improve heat extraction, shorten cycle times, and reduce scrap rates [2]. Additive manufacturing is also increasingly used to produce die components with conformal cooling channels, improving thermal control and potentially extending die life. Combined with embedded sensors and real-time monitoring, these solutions can improve process stability, reduce energy use, and limit waste generation.

Given the large size of typical moulds, dual injection systems have been proposed to reduce the effective flow length and filling time in integrated underbody castings [36]. This can reduce cold-shut susceptibility by allowing distant regions of the cavity to be filled before excessive cooling. However, the benefit depends strongly on the synchronisation of the two flow fronts, gating design, vacuum/venting efficiency, and melt temperature control. Poorly balanced dual injection may instead increase turbulence, oxide-film entrainment, air entrapment, and weld-line formation where the flow fronts meet.

3.3. Manufacturability: Process Risks and Technical Limitations

Beyond cost considerations, the manufacturability of BIW structures using gigacasting versus conventional stamped sheet metal methods reveals critical distinctions in risk profiles, defect susceptibility, and flexibility.

3.3.1. Gigacasting-Specific Manufacturing Challenges

Gigacasting may produce several defect types, including gas porosity from trapped air during mould filling, shrinkage porosity from insufficient feeding during solidification, oxide inclusions from molten aluminium exposure to air, and cold flakes from partially solidified metal fragments. These defects, especially when located near gating ends, thermal hotspots, or highly stressed regions, can significantly impair mechanical properties [19]. Recent experiments on large aluminium HPDC parts show that increasing dynamic casting pressure can reduce porosity and improve mechanical performance. In a 7000 T gigacasting setup, increasing pressure from 266 to 390 bar reduced porosity by 88.5%, increased yield strength by 12.3%, improved elongation consistency, and reduced mean grain diameter by up to 33% [37]. However, recent work also emphasises that the dominant quality barriers in automotive HPDC are not limited to hydrogen-related porosity, but include air entrainment, oxide bifilm formation, melt handling, and fill-front instability [38]. Quality assurance for gigacast BIW parts should therefore combine post-process NDT with real-time monitoring of melt cleanliness, filling stability, and process conditions.

Dimensional instability and residual stresses, resulting from uneven cooling across thick-walled sections, can cause warping or distortion, especially during downstream thermal events like paint baking [18]. Recent cost modelling of gigacast rear floors shows that dimensional inaccuracy—particularly warpage and surface waviness—can cause a non-linear rise in unit costs, with a 4% increase in defect rate leading to up to 15% cost escalation due to rework and scrap. These findings underscore the importance of up-front design features, such as ribs and compensation strategies, to ensure geometric stability and cost control in large-scale casting [39].

To address dimensional distortions, mechanical straightening operations are often employed, utilising multi-pin systems and algorithmic optimisation [40]. While effective, these processes add energy consumption, processing time, and complexity, contrasting with the simpler corrections typically needed in conventional stamped assemblies. Recent physical testing showed that increasing die temperature by 30 °C, using warmer quenching media, and extending quenching duration led to significant improvements in dimensional stability, particularly in thin-walled areas. Moreover, predictive tool compensation and in-quench fixturing have been proposed as key strategies to control distortion in high-volume automotive megacasting [41].

Both shrinkage porosity and thermal stresses and distortion arise, especially in regions where a sharp transition occurs between small and large wall thicknesses, such as in the proximity of ribs and bosses (Figure 8). During solidification, thicker “hot spot” regions tend to cool and solidify much slower than thinner surrounding areas. This thermal mismatch prevents effective feeding of the shrinking material, leading to internal shrinkage porosity that critically undermines mechanical properties [27]. Thermal-management strategies used in conventional die casting, such as localised die cooling, can also be applied to mitigate thermal problems are common to the traditional regular-sized die casting (e.g., localised die cooling), but the large dimensions involved amplify all problems. For this reason, advanced virtual casting simulations are increasingly necessary to engineer these complex parameters before production.

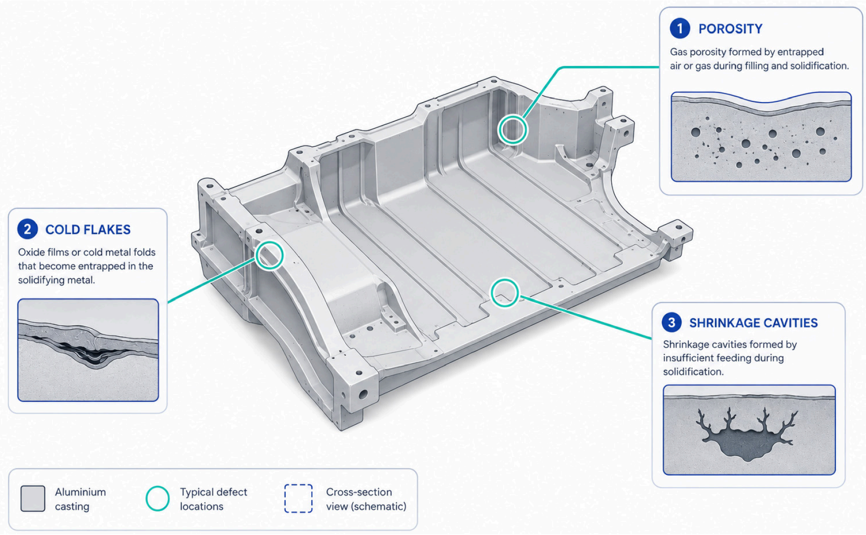


Figure 8. Common defect types in large-scale aluminium gigacasting. Visualises typical manufacturing defects such as porosity, cold flakes, and shrinkage cavities that can compromise mechanical properties and structural reliability in gigacast components [27].

Due to the stochastic nature of ultra-large castings, gigacasting depends heavily on advanced digital simulation tools, including Artificial Intelligence-based systems [42]. Digital twins or numerical models of both the die and the casting process will become essential for accurate prediction of solidification patterns, thermal gradients, and defect formation. These tools guide real-time control strategies, mould cooling optimisation, and quality improvement in high-variability regions, such as rib-to-wall transitions and hot spots [28]. Thermal simulation is particularly crucial in designing conformal cooling systems embedded in the die, helping to reduce cycle times while preventing localised shrinkage porosity. Advanced casting simulation software, integrated with sensor-driven feedback from the shop floor, supports first-time-right manufacturing, reducing development loops and scrap rates during ramp-up phases.

Semi-solid processing, particularly rheocasting or rheo-HPDC, may represent a relevant evolution of gigacasting [34]. Because semi-solid slurries are processed at lower temperatures and with non-dendritic microstructures, they can reduce porosity and hot tearing while potentially extending die life. However, current limitations include equipment cost, melt-volume limitations, and the need for further optimisation before application to very large structural castings.

Gigacast parts also suffer from material property non-uniformity. Hot zones near the gating system exhibit slower solidification, resulting in more uniform grain structures and higher ductility, while cold zones farther from the gates are prone to defect accumulation and reduced mechanical performance [21]. Gating design, local cooling rate, and spatial mechanical-property variation are closely linked in gigacasting, as in conventional HPDC. The gating system controls melt-flow path, filling time, turbulence, and the thermal history of different regions of the component. These factors influence local cooling rate, porosity formation, microstructure, and therefore yield strength, ultimate tensile strength, and elongation. Although the underlying mechanisms are common to conventional casting, they are amplified in gigacasting by longer flow paths, larger thermal gradients, and more demanding solidification conditions.

In recent implementations, vacuum-assisted HPDC combined with local loading strategies has proven effective at mitigating typical gigacasting defects. By creating a vacuum environment (~50 mbar) and applying localised pressure during solidification, manufacturers can significantly reduce porosity, suppress the growth of coarse Fe-rich intermetallic phases, and achieve more homogeneous mechanical properties across large castings. Nevertheless, areas farther from the gating system, with slower cooling rates and longer filling times, remain prone to defect accumulation, requiring careful process optimisation [29].

Because most critical gigacasting defects are internal, advanced non-destructive testing (NDT), such as X-ray or computed tomography (CT), is required. Visual inspection alone is insufficient, and scrap rates can increase without precise control of die temperature, filling time, melt cleanliness, and solidification conditions [43].

A further challenge is the limited tool life of gigacasting dies. Unlike conventional stamping tools, which can typically withstand several million strokes, gigacasting moulds are exposed to repeated injection of large aluminium volumes at high temperature and pressure. This promotes thermo-mechanical fatigue, erosion, soldering, and heat checking, leading to a much shorter useful life, often reported in the range of approximately 30,000–100,000 shots depending on alloy, die material, cooling strategy, insert design, and maintenance practice.

Die wear also affects manufacturability over the die lifecycle. Progressive heat checking, erosion, soldering, fatigue, and local loss of cooling efficiency can alter die surface condition, cavity geometry, heat transfer, and melt-flow behaviour. In gigacasting, these effects are amplified by large die size, high thermal loads, and large molten metal volumes. Die ageing can therefore contribute to dimensional drift, warpage, surface defects, porosity, and local mechanical-property variation, while repair or replacement introduces downtime and significant cost. This reinforces the need for robust die maintenance, process monitoring, and predictive maintenance.

Although the reduced number of tools required by gigacasting partially compensates for this drawback, recent industry benchmarking confirms that tool-related costs, maintenance, repair, and capital depreciation remain important elements in the economic assessment of gigacast front-end structures [1,2,44].

3.3.2. Manufacturing Limitations of Conventional BIW Assembly

The traditional MMM approach relies on forming numerous sheet metal parts through stamping and then assembling them via welding, riveting, and adhesive bonding. This multi-step process is mature and broadly industrialised, but it comes with its own set of risks.

The most prominent issue is the risk of weld fatigue and failure, especially in joints between dissimilar materials. Spot welds, commonly used in steel-intensive structures, can become corrosion sites and are prone to variable quality, especially in automated mass production [18].

Furthermore, formability limits, including wrinkling, springback and tearing in high-strength steel components, require compensatory design and tooling iterations [26].

Process complexity is inherently higher: managing dozens of forming and joining stations increases variability, alignment issues, and integration risks, particularly for high-mix low-volume production scenarios [11]. Another challenge is tolerance stack-up across multiple joined parts, which can lead to body dimensional inaccuracies if not managed through referencing and adjustment strategies.

In conventional sheet-metal BIW manufacturing, post-processing mainly concerns corrosion protection and property adjustment. Steel sheets may be galvanised before forming or protected after assembly, while annealing or bake-hardening treatments can be applied when required to restore or enhance properties affected by forming. Surface and dimensional defects are also generally easier to detect than in gigacast structures, since they can often be identified through visual or automated inline inspection, and non-conforming parts can usually be reworked or scrapped with lower complexity.

Although gigacasting has introduced a disruptive manufacturing model, recent advances in sheet-metal forming continue to support the competitiveness of conventional BIW manufacturing. Hot Forming and Quenching (HFQ®), for example, enables high-strength aluminium alloys such as AA6082 and AA7075 to be formed at elevated temperature, improving formability while preserving high post-form mechanical properties [26]. The HFQ® process uses temperature-controlled dies to combine forming and rapid quenching, allowing high-strength aluminium components to be shaped while controlling microstructural evolution during solution treatment and ageing. Hydroforming also remains relevant for producing complex, high-strength tubular structures with optimised geometries and reduced joining requirements [45]. In parallel, advanced FEM tools support accurate prediction of forming limits, springback, and anisotropic behaviour, improving the reliability of sheet-metal process design. Third-generation advanced high-strength steels (AHSS), tailored welded blanks (TWBs), and hot stamping with press hardening further allow sheet-metal BIW assemblies to meet lightweighting and crash-performance targets while retaining repairability and design flexibility [46].

3.4. Comparative Summary

Gigacasting simplifies the manufacturing chain by reducing the number of parts, tools, joining operations, and assembly steps. However, this simplification shifts complexity upstream into the casting process. Large HPDC components require tight control of melt quality, filling, vacuum, cooling, die temperature, solidification, and dimensional stability.

Typical risks include porosity, oxide bifilms, shrinkage, cold flakes, warpage, internal defects, and local mechanical-property variation. These defects are often difficult to detect visually and require advanced simulation, process monitoring, and NDT. A further limitation is the shorter life of gigacasting dies compared with stamping tools, due to thermal fatigue, erosion, soldering, and heat checking. Conventional MMM manufacturing is more complex at system level, but remains more mature, modular, inspectable, and easier to rework.

Table 2 summarises the main findings of Section 3.

Table 2. Manufacturing risks and technical characteristics of gigacasting vs. conventional sheet metal BIW assembly. Compares defect types, complexity, repairability, inspection needs, and other critical manufacturing attributes between the two technologies.

Aspect	Gigacasting	Conventional Sheet Metal BIW
Defect Sensitivity	Porosity, cold flakes, dimensional warping	Weld fatigue, cracks at joints
Geometrical Accuracy	Sensitive to solidification shrinkage, residual stresses, thermal distortion, and warpage; requires dimensional inspection, compensation/straightening, and robust process control	Controlled through mature tolerance-management strategies, datum schemes, fixtures, and distributed correction points

Table 2. *Cont.*

Aspect	Gigacasting	Conventional Sheet Metal BIW
Process Complexity	Fewer parts but more casting parameters to control	High part count, more joining steps
Repairability	Very limited, often full part replacement	Localised panel repair possible
Tooling Flexibility	Low (large, costly, slow to adapt)	High (modular dies, easier to replace)
Assembly Tolerance	Low tolerance stack-up; challenge at interfaces	High stack-up risk, but distributed correction
Scrap Rate	High without precise control	Moderate, mostly from stamping failures
Post-Processing	Straightening, NDT, limited heat treatment	Galvanising, annealing, simpler inspection
Quality Control	Requires X-ray/CT for internal defects	Visual/automated detection, reworkable parts

4. Transformation of the Factory Organisation

Tesla has been one of the earliest adopters of gigacasting, demonstrating its benefits in terms of part integration. The Model Y (Figure 9), for example, replaced 171 sheet metal components with a single casting in the rear floor module, eliminating 1600 welds and 300 robots, which resulted in a 40% reduction in manufacturing costs and substantially lower factory space requirements [14]. Toyota has similarly achieved space optimisation by replacing 86 individual parts with a single aluminium casting, reducing a 33-step process into a single casting operation [47]. The company plans to scale gigacasting for front and rear underbody structures by 2026, aiming for 1.5 million EVs annually.

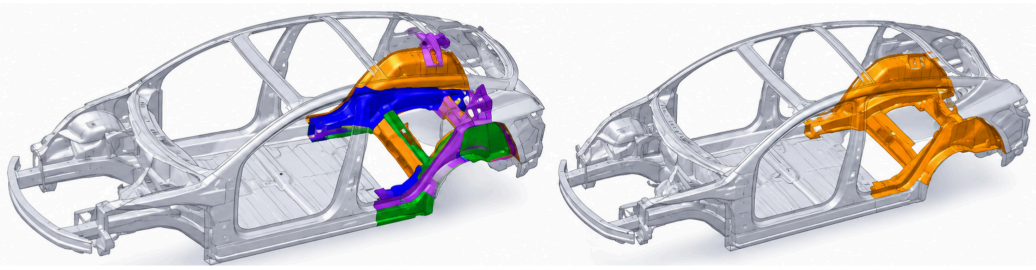


Figure 9. Schematic comparison of Tesla Model 3 (**left**) and Model Y BIW (**right**) designs. It shows the transition from traditional MMM design in Model 3 to a 1 + 3 design with a gigacast aluminium rear bottom structure, highlighting reductions in part count, welds, and factory complexity [6].

The following subsections discuss the main differences between gigacasting and conventional MMM sheet-metal BIW manufacturing in terms of productivity, factory logistics, production costs, and operational flexibility.

4.1. Productivity and Lead Times

Gigacasting changes BIW manufacturing by replacing multiple forming, trimming, joining, and assembly operations with a single large HPDC cycle followed by extraction, trimming, inspection, and limited post-processing. Conventional MMM sheet-metal manufacturing, by contrast, relies on stamping, cutting, joining, and robotic assembly operations, each requiring dedicated tooling, equipment, and fixtures. The main advantage of gigacasting is therefore the reduction in part count and assembly complexity, which can shorten production cycles and simplify factory layout.

However, conventional sheet-metal manufacturing is also evolving in response to these challenges. Recent developments in hot-stamped ultra-high-strength steel (UHSS) provide alternative routes to lightweighting, part consolidation, and lower environmental impact.

For example, Gestamp's Ges-Gigastamping process consolidates up to 18 components into one, reduces weight, and can lower CO_2 emissions through the use of recycled steel and renewable electricity [48]. Similarly, increased use of hot-stamped steel in recent Volvo platforms and VW's application of MBW 1900 steel in BEV floor structures show that advanced steel solutions can still deliver weight, cost, and crash-performance benefits within conventional or semi-conventional BIW architectures [49].

The key differences between gigacasting and conventional MMM sheet-metal manufacturing are discussed below.

- Reduced number of operations. Fewer parts result in fewer forming and welding processes, as these are fully integrated into the casting, as shown in Figure 10.

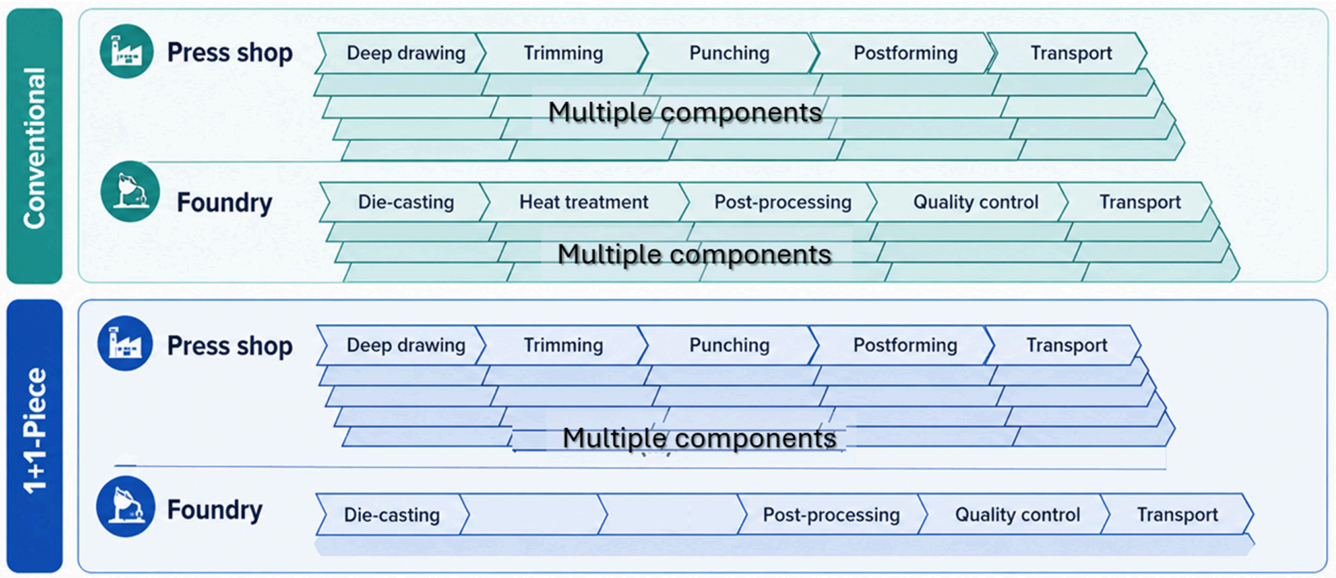


Figure 10. Comparison of process chain complexity between conventional multi-part BIW manufacturing and 1 + 1-piece gigacasting integration. The diagram contrasts the sequential operations involved in component manufacturing under conventional (multi-material mix) and 1 + 1-piece (hypercasting) strategies. It illustrates how the integration of large gigacast components into the foundry stage reduces the number of operations in the press shop and simplifies downstream joining and transport. The gigacasting route consolidates tasks like deep drawing, trimming, and punching into fewer die-casting and post-processing steps, streamlining the overall production workflow [14].

- Reduced complexity. A lower number of parts reduces the number of elements that need to be produced and included in the bill of materials (BOM) of the car. Additionally, it provides greater flexibility in optimising structural shapes.
- Assembly simplification. The reduction in part count enabled by gigacasting can simplify BIW assembly by eliminating many welding, joining, handling, and fixturing operations. Large cast components can also integrate mounting points for suspension, battery, powertrain, and auxiliary systems, reducing the need for separate brackets, reinforcements, and secondary assembly steps. This may improve dimensional consistency by limiting tolerance stack-up across multiple stamped parts and joined subassemblies. However, simplification is not automatic: gigacast parts still require trimming, machining, inspection, handling, and mechanical joining to the remaining BIW structure, while their size and weight introduce new logistics and positioning challenges within the assembly line.
- Unboxed concept. A radical evolution of the simplified assembly is represented by Tesla's so-called "Unboxed" manufacturing concept [44], in which vehicle modules would be built in parallel and joined only at a later stage of final assembly [50]. This

approach could, in principle, improve accessibility for operators and robots, allow pre-integration of components before body closure, and reduce the inefficiencies associated with installing interior and functional systems inside an already assembled vehicle body. Nevertheless, this method should currently be regarded as a future manufacturing concept rather than an established industrial standard. Public information indicates that Tesla has pursued and patented elements of this strategy, particularly for future products such as the Cybercab, but its large-scale industrial implementation and actual performance benefits still require validation in volume production.

- Reduced production lead times. Each gigacast underbody section can be produced in less than 100 s, whereas the equivalent conventional process chain may involve up to 33 forming, trimming, joining, and handling operations, with a cumulative duration approaching 30 min, although many operations can be parallelised [51]. Therefore, the advantage of gigacasting is strongest at the local process-chain level, while system-level throughput also depends on uptime, yield, tooling changes, and press availability.
- Annual throughput. While the lead time for a single part is dramatically shorter with gigacasting, traditional sheet metal forming benefits from parallelised operations that distribute tasks across multiple machines, potentially achieving higher overall throughput. According to [52], a 6000 ton press dedicated to rear floor module fabrication can produce 100,000 to 150,000 pieces annually, with a cycle time of 120 to 150 s per piece while operating 16–20 h per day for up to 300 working days per year, assuming a 90% yield rate. Furthermore, frequent tooling changes for different parts on the same gigacasting machine could further reduce its effective output. Unlike MMM-based stamping, which allows multiple machines to work in parallel, gigacasting operations are more centralised, making them potentially more susceptible to downtime if tooling adjustments or maintenance are required.
- Handling issues. On the downside, gigacasting results in larger and heavier components, making them more difficult to handle. This is an inherent and unavoidable consequence of the process. The cast parts, which weigh over 100 kg, are bulky and require specialised equipment for transportation and positioning within the assembly line.

4.2. Factory Lay-Out and Floor Space

Giga-presses require significantly more floor space than traditional MMM-based production lines. A single giga-press installation typically occupies over 6000 square metres, including areas for molten metal handling, cooling infrastructure, and automated extraction. This footprint is considerably larger than that of a conventional stamping or welding station, which can be distributed more flexibly across a factory layout in a modular and scalable manner. However, traditional MMM production requires multiple stamping and welding stations, often spread across different workshops or even different tiers of the supply chain.

Overall, gigacasting can lead to a reduction in total factory size. With fewer press shop operations, the number of robots is significantly reduced, as many of them are replaced by giga-presses. This results in a more compact, albeit complex, facility. Tesla reported a 40% reduction in factory size and the replacement of over 600 robots following the adoption of gigacasting. By eliminating multiple welding robots and stamping presses, gigacasting decreases the total plant footprint, optimising floor space utilisation and factory layouts.

Dies for giga-presses frequently exceed 100–150 tons, limiting transportation options and requiring reinforced foundations, overhead crane systems, and dedicated logistics—often ruling out brownfield retrofits in favour of purpose-built factories [28].

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For greenfield factories, gigacasting allows the production layout to be designed around large casting cells, dedicated material handling, trimming, inspection, and post-processing areas from the outset. By contrast, integrating a giga-press into an existing brownfield facility is more challenging, since conventional MMM stamping and body shops were not designed for ultra-large single-piece castings. Retrofitting may require floor reinforcement, removal or relocation of existing equipment, and major reconfiguration of material flow, leading to substantial conversion costs [15].

In this context, hybrid casting has been proposed as an intermediate solution for OEMs constrained by legacy infrastructure. Mielke et al. [53] investigated aluminium–steel hybrid castings produced by HPDC, showing that steel inserts can provide localised reinforcement without requiring the full component to be overdesigned. Compared with full gigacasting, this approach may reduce equipment requirements, improve design flexibility, and support partial structural integration in brownfield scenarios. However, hybrid casting is not equivalent to monolithic gigacasting: it reintroduces material interfaces, insert-integration challenges, and potential joining issues, while reducing some part-consolidation and process-simplification benefits. Its relevance is therefore mainly in intermediate scenarios where OEMs seek a compromise between structural integration, investment risk, and production flexibility.

According to industry estimates and automotive benchmarking data, the unboxed assembly concept described above can reduce general assembly lead times by up to 25% and total production costs by nearly 50% in specific vehicle programmes leveraging gigacasting [54]. These gains stem from parallelised subassembly, reduced plant footprint, and integrated process flows enabled by the gigacasting-compatible modular architecture.

4.3. Supply Chain Implications of Gigacasting

Gigacasting also introduces supply-chain challenges, particularly in the sourcing and handling of aluminium alloys. Unlike conventional BIW production, which relies on mature and diversified supply networks for standardised steel sheets, gigacasting requires a stable supply of high-quality aluminium with strict metallurgical specifications. This may increase exposure to aluminium price volatility, supply delays, and the need for dedicated agreements with aluminium producers and die-casting specialists. The transition may also reduce the role of traditional sheet-metal suppliers, requiring OEMs to restructure established sourcing relationships and ensure consistent material flow and casting quality [15].

At the same time, a short, vertically integrated, and regionally reliable aluminium supply chain may become a strategic advantage by reducing dependence on globally traded materials and improving resilience against geopolitical disruptions, trade disputes, or tariffs. However, the regional impact may be significant in areas built around dense sheet-metal supplier ecosystems, such as parts of Italy, Germany, or the U.S. Midwest. In these regions, SMEs specialised in stamping, welding, tooling, and subassembly may be affected by reduced part counts and lower demand for stamped subcomponents. Without diversification strategies, the diffusion of gigacasting could weaken established supplier networks and regional manufacturing employment.

4.4. Operational Flexibility and Design Adaptability

From the standpoint of production organisation, traditional Multi-Material Mix (MMM) sheet metal forming offers notable flexibility. It relies on modular and distributed equipment for stamping, welding, and assembly, enabling production to be scaled incrementally. In contrast, gigacasting necessitates a concentrated production area due to the extensive floor space required by a single giga-press, along with its operational constraints.

A facility dedicated to gigacasting must accommodate not only the press but also auxiliary processes such as molten aluminium handling, die cooling stations, extraction systems, and post-casting finishing.

While gigacasting boosts efficiency and part integration, it imposes limitations on design flexibility and adaptability. Unlike MMM sheet metal forming, which supports incremental design changes and modular assembly, gigacasting depends on custom moulds tailored to each vehicle platform, making any design modification significantly more costly. For example, the rear floor casting of Tesla's Model Y is specific to that model and cannot be repurposed for other Tesla models, necessitating separate tooling investments for each design iteration [15]. This lack of interchangeability is in stark contrast to MMM-based vehicle structures, where modifications to components can be made during the stamping, welding, or assembly stages without necessitating a complete overhaul of the tooling. It is also important to note that while gigacasting limits flexibility in some respects, it can serve as a foundational underbody for a family of products, as demonstrated by Volvo cars. This approach allows for the development of multiple vehicle models from a single cast platform, potentially offsetting some of the initial investment costs associated with the gigacasting technology.

5. Manufacturing Cost and Environmental Impact

5.1. Cost Analysis

5.1.1. Cost Analysis: Capital Expenditure (CAPEX)

The adoption of gigacasting technology incurs substantial capital expenditures, driven by the need for specialised giga-presses, large-scale dies, and increased maintenance requirements. Gigacasting equipment, featuring giga-presses that operate at a clamping force ranging from 6000 to 9000 tons, demands a reinforced factory foundation and specialised infrastructure for installation. The typical cost of a gigacasting press is about 1000 € per ton of die closing force, hence a 10,000 tons press costs about 10 M€. This is in stark contrast to traditional Multi-Material Mix (MMM) sheet metal forming, which uses stamping presses with considerably lower tonnage distributed across multiple production stations, allowing for greater flexibility in plant layout. The benchmark in [17] reinforces the conclusion that part-count reduction (i.e., a reduced number of tools) does not automatically imply lower total cost. Their cost study, based on the WorldAutoSteel cost model, indicates that optimised steel alternatives can be cost-competitive depending on production volume, tooling strategy, equipment amortisation, and material cost. The authors also report that aluminium casting tooling costs may exceed steel tooling costs at annual volumes slightly above 200,000 units, highlighting the sensitivity of the economic comparison to capacity utilisation and tooling assumptions.

Moreover, the cost of dies in gigacasting far exceeds those in traditional MMM sheet metal forming. While conventional stamping dies can endure up to six million production cycles, gigacasting dies typically require replacement after just 100,000 cycles, significantly adding to the overall cost burden and diminishing their economic efficiency over time, as noted by [1,44]. To improve the longevity of gigacasting dies, metal inserts are used in high-wear areas, extending their usability to between 30,000 and 80,000 cycles (see Table 3). Simulation of high-pressure die casting for giga-scale aluminium components shows that effective die cooling and spray cycles are essential to control thermal gradients and extend tool life. A study using MAGMASOFT® reported die temperatures exceeding 555 °C without cooling, whereas the addition of seven cooling circuits and spraying reduced peak temperatures to 239 °C and stabilised thermal equilibrium after four cycles, with a measured thermal gradient (ΔT) of ~462 °C [55].

Table 3. Typical lifespan of manufacturing tools in gigacasting vs. conventional stamping. Contrasts tool durability, showing significantly longer tool life in conventional sheet metal stamping compared to gigacasting, which requires more frequent die replacements.

Manufacturing Route	Main Tool	Gigacasting
Gigacasting	Main mould	~100,000 shots/cycles
Gigacasting	High-wear inserts	~30,000–80,000 shots/cycles
Traditional Stamping	Stamping dies	up to several million strokes

However, even with these enhancements, die replacement remains more frequent than in MMM stamping, where dies last significantly longer due to lower operational stresses. In aluminium HPDC, die inserts are exposed to repeated thermal stresses, impact loads, liquid-metal pressure, high-velocity flow, soldering, erosion, and thermal-fatigue cracking, which makes die life strongly dependent on cooling strategy, heat treatment, coatings, nitriding, and maintenance practice [56]. This frequent replacement not only adds to ongoing maintenance costs but also impacts the overall cost-effectiveness of gigacasting technology, presenting a substantial challenge in justifying the initial investment despite its long-term operational advantages.

Another challenge associated with the large size and high cost of gigacasting moulds is the potential restriction they impose on the release of model variants and the implementation of design updates [11]. The geometric rigidity of these moulds can limit flexibility in adapting to evolving design requirements. While the finite service life of gigacasting moulds theoretically offers an opportunity to introduce changes during scheduled replacements, in practice, their substantial size and expense often lead manufacturers to prioritise repair over full replacement.

5.1.2. Cost Analysis: Operational Expenditure (OPEX)

Gigacasting may offer long-term operational cost savings by reducing labour requirements, factory footprint, energy use, welding stations, and robotic assembly operations. According to [15], workforce requirements may decrease by about 20% compared with traditional MMM-based vehicle production. However, the shift to giga-press-based manufacturing also requires specialised training for operators and maintenance staff due to the scale of the equipment, high-tonnage presses, and complex die assemblies. These requirements can increase initial labour and training costs during factory conversion or ramp-up.

A recent white paper estimates that gigacasting may contribute approximately $2800 in direct cost savings per vehicle in the context of producing a next-generation Tesla Model 3, as part of a broader multi-pronged strategy to deliver an electric vehicle at a $25,000 price point [54]. These savings result from reduced part count, simplified assembly, and elimination of many welding operations.

The operational cost reduction offered by gigacasting remains debated because the technology relies primarily on aluminium alloys, which are lighter but generally more expensive than the steel sheets used in MMM-based production. Therefore, the economic benefit cannot be inferred from mass reduction alone. Although recent gigacasting studies report potential weight reductions of approximately 15–20% for selected structural applications [15], benchmark studies show that higher aluminium material cost can offset part of the savings from part consolidation, reduced joining, and simplified assembly [57].

Wegner et al. [57] estimated the cost of a functionally equivalent front-end structure produced domestically in the EU, US, and China at annual volumes of 50,000, 150,000, and 300,000 units/year. When material, manufacturing/conversion, and tooling-related costs are included, gigacasting remains more expensive than the corresponding MMM front-end across all investigated regions and volumes (Table 4). These values should therefore be interpreted as benchmark estimates for a specific front-end application, not as a complete bottom-up cost model for an entire BIW or vehicle platform.

Table 4. Front-end production cost comparison between conventional multi-material mix (MMM) and gigacasting architectures. Estimated 2025 domestic production costs are reported for a functionally equivalent automotive front-end structure manufactured in three regions—EU, US, and China—and at three annual production volumes: 50,000, 150,000, and 300,000 units/year. Costs are expressed in €/front-end and include material, manufacturing, and tooling-related contributions. The "Difference" column is calculated as the gigacasting cost minus the MMM cost.

Region	Volume (k/Year)	MMM Cost (€/Front-End)	Gigacasting Cost (€/Front-End)	Difference (€)
EU	50	326	453	+127
EU	150	300	391	+91
EU	300	295	390	+95
US	50	356	471	+115
US	150	330	405	+75
US	300	325	404	+79
China	50	268	415	+147
China	150	242	355	+113
China	300	237	353	+116

Several assumptions are embedded in the benchmark model, including regional aluminium and steel prices, labour and energy costs, equipment depreciation, tooling amortisation, die life, maintenance, repair costs, and capacity utilisation. Since these assumptions are not fully disaggregated in the public source, they are not recalculated here. Table 4 is therefore used to identify cost trends and sensitivities rather than to establish a universally valid cost advantage for either technology. This is especially important because gigacasting dies have shorter useful lives, typically 30,000–100,000 shots, whereas conventional stamping tools last substantially longer.

For a front-end structure produced in Europe, gigacasting has lower non-material costs than the MMM route: 165 versus 177 €/front-end at 50,000 units/year, 103 versus 151 €/front-end at 150,000 units/year, and 102 versus 147 €/front-end at 300,000 units/year. However, when material costs are included, the total cost remains higher for gigacasting. For EU domestic production, the estimated gigacast cost decreases from 453 €/front-end at 50,000 units/year to approximately 390 €/front-end at 150,000–300,000 units/year but remains above the corresponding MMM values of 326, 300, and 295 €/front-end. Similar trends are reported for the US and China. These results indicate that economies of scale are largely achieved at around 150,000 units/year, but that scale alone does not offset the higher aluminium material cost.

Therefore, part-count reduction should be interpreted as an indicator of process simplification and potential non-material cost reduction, not as sufficient evidence of lower total manufacturing cost. Total cost must be assessed at the component or platform level, including material cost, tooling amortisation, die life, capacity utilisation, casting yield, and scrap-related losses. A further comparison for a rear floor module is provided in Table 5.

The transition to giga-press-based manufacturing, in conclusion, presents a complex balance between cost and efficiency that must be carefully managed to optimise long-term benefits.

Table 5. Cost and productivity comparison of rear underbody manufacturing across steel stamping, aluminium stamping, and aluminium megacasting. The comparison refers to the production of 100,000 rear underbody units per year, assuming 16 operating hours per day, 22 working days per month, and 12 months of production. Investment costs are reported in million USD, while variable costs are reported in USD per rear underbody. Data adapted from [52].

Category	Sub-Category	Steel Stamping and Joining	Aluminium Stamping and Joining	Aluminium Megacasting
Production efficiency	Yield	97%	92%	85%
	Jobs per hour	24.4	25.7	27.8
Investment costs	Stamping machine	1.0–1.5 MUSD	1.4–1.8 MUSD	—
	Stamping tooling	0.7–1.1 MUSD	1.0–1.3 MUSD	—
	Joining line	0.6–0.8 MUSD	1.2–1.6 MUSD	—
	HPDC machine	—	—	6.0 MUSD
	HPDC tooling	—	—	1.2–1.5 MUSD
Variable costs	Labour costs	28.3 USD	31–37 USD	11–23 USD
	Indirect costs	47.2 USD	42–52 USD	9–14 USD
	Raw material	75.6 USD	264–377 USD	151–226 USD

5.2. Sustainability and Environmental Impact

The adoption of gigacasting in Body-in-White (BIW) manufacturing introduces both opportunities and challenges from a sustainability perspective. This section discusses the environmental implications of gigacasting compared with conventional stamped and joined structures, focusing on carbon footprint and life-cycle assessment (LCA) indicators.

A rigorous comparison between MMM and gigacasting architectures would require a dedicated cradle-to-grave LCA of functionally equivalent vehicles, covering raw material extraction, component manufacturing, vehicle use, repair, and end-of-life treatment (Figure 11). Such an assessment is beyond the scope of the present review and would require primary data on component mass, alloy sourcing, recycled content, regional energy mix, casting yield, scrap recycling, repair scenarios, use phase, and end-of-life routes. Therefore, the sustainability comparison presented here should be interpreted as a literature-based assessment of the main production-phase and material-related drivers, rather than as a full LCA of equivalent vehicles.

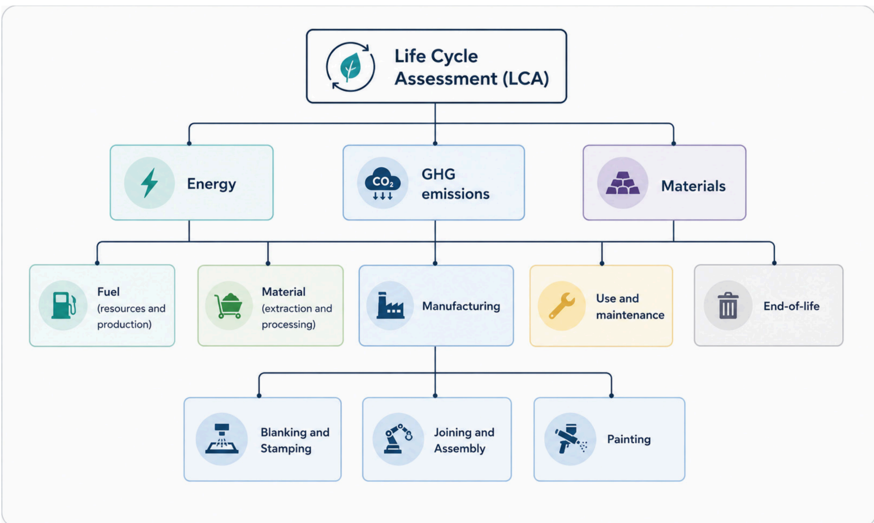

Figure 11. Lifecycle assessment phases of automotive Body-in-White (BIW) components. Outlines the stages of environmental impact analysis from raw material sourcing to end-of-life, serving as a framework for comparing the sustainability of gigacast versus traditional BIW structures [58].

To the authors' knowledge, no published LCA currently compares a complete EV based on gigacast architecture with a functionally equivalent EV based on a traditional MMM structure. However, recent LCA work on lightweighting and battery technologies shows that aluminium-based mass reduction can lower use-phase energy consumption, but these gains may be partly offset by higher production-phase greenhouse gas emissions. For example, replacing 300 kg of steel with aluminium in a Tesla Model 3 reduced use-phase emissions by 1580 $kgCO_2e$, but increased production-phase emissions by 810 $kgCO_2e$, yielding a net reduction of only 770 $kgCO_2e$, approximately 3% of total life-cycle emissions. If vehicle lifetime was reduced to 160,000 km, the environmental benefit was nearly halved [59].

In what follows, we attempt to break down the main drivers of life cycle impact, distinguishing between the production phase and the use phase.

5.2.1. Production Phase

LCA literature consistently identifies raw material production as the dominant contributor to environmental impact in the production phase. The carbon footprint of aluminium alloys varies from 3 to 9 kg CO_2 per kg, depending on energy source and production route [60]. By comparison, automotive-grade steel sheet has a lower carbon intensity, typically between 1 and 2 kg CO_2 per kg.

According to [58], the total CO_2 equivalent for a BIW structure ranges from 135 kg (for an aluminium-intensive design) to 270 kg (for a low-strength steel design). A mixed-material MMM design typically weighs around 250 kg. When comparing material production and manufacturing phases, all-steel structures produce about 5.5 kg CO_2 per kg, while all-aluminium designs can reach 17 kg CO_2 per kg—a 3:1 ratio. Scaled by weight, the total production-phase carbon footprint of a steel-based design is approximately two-thirds that of an aluminium-based design.

Gigacasting requires additional processing steps, such as high-pressure die casting and subsequent machining, which increase energy consumption by approximately 23% [61]. These processes add about 3 kg CO_2 per kg of aluminium. While stamping itself is relatively energy-efficient, the traditional MMM approach involves the assembly of many individual parts—often sourced and transported between multiple suppliers—and numerous joining operations. These add a similar level of emissions, estimated at 3 kg CO_2 per kg [62]. Thus, when isolating the production phase, gigacasting does not present clear environmental advantages over conventional approaches. Indeed, a study [17] reports a large production-phase CO_2 difference between the aluminium giga-cast baseline and steel alternatives. For the analysed front-end structure, material production emissions were estimated at 1255 kg CO_2 for the aluminium giga-cast design and 143 kg CO_2 for the steel alternative, while total manufacturing emissions were 1339 kg CO_2 and 192 kg CO_2, respectively. Although this is not a complete cradle-to-grave LCA, it supports the conclusion that gigacasting's environmental performance is highly sensitive to aluminium carbon intensity and cannot be assumed to be superior a priori.

Material utilisation is another relevant factor in the assessment of production-phase environmental impact. In conventional sheet-metal BIW manufacturing, material losses are mainly associated with blanking and nesting. Horton and Allwood reported that, on average, only about 56% of the purchased sheet metal is used in the vehicle, corresponding to yield losses of approximately 44% [63].

In gigacasting, material losses arise from different mechanisms, including runners, overflows, trimming, defective castings, and rejected parts. The rear-underbody benchmark discussed above reports a lower production yield for aluminium megacasting than for steel or aluminium stamping [51]. Therefore, gigacasting can reduce blanking scrap associated with sheet-metal processing, but its material-utilisation advantage depends strongly on casting yield, internal recycling of return material, and defect-related scrap.

A recent FEV front-end benchmark study [57] questions the assumption that gigacasting is intrinsically more sustainable than conventional MMM architectures. For 2025 domestic production, the estimated production-phase footprint of a gigacast front-end is 290 $kgCO_2eq$ in the EU and 282 $kgCO_2eq$ in the US, compared with 217 and 202 $kgCO_2eq$ for the corresponding MMM front-end. The difference becomes much larger in China, where the estimated footprint is 1337 $kgCO_2eq$ for gigacasting and 518 $kgCO_2eq$ for MMM. These values should be interpreted as component-level production-phase estimates for a front-end structure, not as complete vehicle-level cradle-to-grave LCA results.

The strong regional dependence of these results reflects the high sensitivity of gigacasting to aluminium sourcing and electricity mix. While Rajulwar et al. report typical carbon-footprint values of approximately 3–9 kg CO_2/kg for aluminium alloys and 1–2 kg CO_2/kg for automotive steel sheets [60], International Aluminium Institute data show that cradle-to-gate footprints for primary aluminium can vary widely, from approximately 4.5 to 22 tCO_2e/t Al, with optimised low-carbon supply chains reaching about 4 tCO_2e/t Al or less [64]. Recycled aluminium has a much lower reported footprint, with the IAI indicating a gate-to-gate value of approximately 0.52 tCO_2e/t Al, although this should not be interpreted as a full cradle-to-gate value because scrap-allocation methods can differ [65]. Therefore, the environmental performance of gigacasting depends strongly on aluminium carbon intensity, recycled content, regional electricity mix, component mass, casting yield, and internal recycling of return material. It should not be considered an intrinsic property of the casting route alone.

Although the environmental advantage of gigacasting remains controversial in terms of emissions and energy requirements, recent studies [66,67] suggest that gigacast structures may positively affect the aluminium material cycle. Compared with traditional multi-material sheet designs, gigacasting can reduce the number of different materials in selected vehicle modules and may allow broader alloy-composition tolerances, facilitating the use of post-consumer recycled aluminium without extensive alloy matching. This could reduce part of the energy penalty associated with recycling wrought aluminium components and partially mitigate production-phase carbon emissions.

However, the feasibility of using higher fractions of secondary aluminium in structural BIW castings remains under investigation, particularly regarding microstructure, defect formation, and mechanical reliability [65]. The issue is still controversial. According to [34], a key limitation is impurity tolerance: primary Al-Si casting alloys typically restrict Fe to below approximately 0.15–0.2 wt.%, whereas secondary alloys may contain 0.8–1.2 wt.% Fe. Such higher Fe levels promote brittle platelet-like AlFeSi intermetallics, reducing ductility and increasing shrinkage-porosity and crack-initiation risks. Therefore, the sustainability potential of gigacasting depends not only on increasing recycled content, but also on developing alloys and melt-treatment routes capable of tolerating or removing impurities.

Recent alloy and recycling developments are promising in this respect. For example, recycled aluminium alloys have been reported to reach strength and ductility levels comparable to primary Al-Si structural die-cast alloys, with one Al-8.6Si-0.32Mg-0.44Fe alloy achieving a yield strength of 194 MPa in T5 condition and elongation up to 8% in T6 condition [68]. In addition, "Liquid Metallurgy" techniques may enable the removal of brittle Fe-rich phases, such as β-Al_5FeSi, from molten scrap, supporting the upcycling of low-grade post-consumer aluminium with limited energy input and reduced need for conventional sorting [68].

5.2.2. Use Phase

The use phase plays a dominant role in the LCA of any vehicle. Weight is a critical factor influencing energy consumption and CO_2 emissions during vehicle operation. For internal combustion vehicles, aluminium-based designs become environmentally preferable only after driving distances exceed 100,000 miles [58]. Due to the higher initial production emissions associated with aluminium, substantial operational mileage is required to realise a net environmental benefit through reduced energy consumption during vehicle use. In the case of EVs, the added mass of battery systems increases the demand on structural components, amplifying the importance of weight reduction. A more recent study by [62] compared various EVs and concluded that an aluminium-intensive sheet metal BIW provides only a marginal advantage over steel in terms of total life cycle emissions. For EVs, lightweighting benefits are more case-dependent, because use-phase savings must be balanced against production-phase emissions from lightweight materials and batteries. Mayyas et al. [69] showed that aluminium-intensive vehicle structures may provide only marginal life-cycle emission benefits over steel-intensive alternatives under some LCA assumptions.

When evaluating aluminium gigacasting specifically, the literature is divided. Ref. [14] suggest that the total BIW weight remains comparable between gigacasting and stamped-metal designs—around 250 to 260 kg. The reason is that while the density of aluminium is approximately three times smaller than steel, the typical thickness that can be produced through die casting is more than three times larger than the one used for sheet metals. Considering a typical steel sheet thickness of approximately 1 mm, the same panel made of aluminium must be thinner than 2.9 mm in order to be lighter, and Table 6 clarifies that this is not always the case.

Table 6. Wall thickness (mm) capabilities of gigacasting and MMM sheet metal structures. Presents the range of achievable wall thicknesses for both technologies, highlighting casting's limitations in producing thin-walled sections relative to sheet metal.

Technology	Minimum Allowed Thickness	Average Thickness	Maximum Thickness
Gigacasting	2.5 mm	5 mm	8 mm
MMM Sheet Metal	0.4 mm	0.9 mm	1.5 mm

Some OEMs report weight reductions in gigacast structures [6]. Reference [15] cite reductions of 7% to 20%, depending on the model. However, these figures are not always supported by publicly available technical comparisons. The most direct case study—Tesla's transition from a conventional rear underbody to a gigacast one in the Model Y—has not been accompanied by official data on weight savings. The absence of disclosed figures suggests that any weight reduction may be limited or offset by other structural requirements. Independent teardown analyses support this view, indicating that gigacasting's true advantage lies in manufacturing simplification rather than dramatic reductions in BIW mass.

The expert opinions reported in [14] show some scepticism on weight reduction, as crash performance requirements necessitate different structural designs. The consensus among experts is that the primary motivation for adopting gigacasting is cost savings in production rather than achieving lightweight construction. In another very recent study based on expert interviews [16], some experts were convinced that the same or even better weight could be achieved by sheet metal forming, but most of the experts saw an advantage in die casting, with the two main reasons being the lower specific weight of aluminium compared to steel and the lack of multiple joining or bonding surfaces. However, the same panel of experts, when asked about the environmental advantage of gigacasting vs. sheet metal forming, did not clearly favour gigacasting in terms of energy consumption and CO_2 emissions.

5.3. Comparative Summary

Gigacasting reduces non-material manufacturing costs by consolidating parts, eliminating many joining operations, reducing labour, and simplifying assembly. This makes it attractive for high-volume, low-variant EV platforms, especially in greenfield plants.

However, the total cost advantage is not automatic. Material cost, aluminium price, component mass, die cost, die lifetime, maintenance, depreciation, and capacity utilisation strongly affect the final result. The FEV benchmark shows that gigacasting has lower non-material costs than MMM but a higher total front-end cost once material costs are included. Thus, gigacasting should be described as having a manufacturing-cost advantage, not necessarily a total part-cost advantage. MMM remains more flexible and cost-effective for lower volumes, brownfield plants, and platforms requiring frequent design changes.

The sustainability advantage of gigacasting remains uncertain. Gigacasting can reduce part count, joining operations, and logistics complexity and potentially enable simpler aluminium recycling streams. However, aluminium has higher embodied CO_2 than steel, and HPDC is more energy-intensive than stamping.

Recent benchmark data show that gigacast front-end structures can have higher production-phase CO_2eq emissions than MMM equivalents, especially in regions with carbon-intensive electricity and aluminium production. The environmental outcome therefore depends mainly on aluminium carbon intensity, recycled content, electricity mix, component mass, casting yield, and actual vehicle-level weight reduction. MMM structures retain advantages through lower-carbon steel, mature recycling routes, thinner gauges, and better repairability. A full vehicle-level LCA is still needed before claiming a general sustainability benefit for gigacasting.

6. Discussion

In this review paper, we have assessed aluminium gigacasting and conventional MMM sheet-metal BIW manufacturing as competing vehicle-platform strategies rather than as isolated manufacturing processes. Recent reviews have addressed several important aspects of large-format casting technologies, including aluminium giga-casting alloys and applications [15], opportunities and challenges of ultra-large aluminium castings [27], broader trends in metal casting technology [28], Mg-alloy super-sized HPDC for automotive structural components [33], Al-Si castings in the context of vehicle electrification [34], and challenges for automotive aluminium HPDC components [38]. These contributions provide valuable material- and process-level knowledge, but they do not provide a consolidated technological comparison between aluminium gigacasting and conventional MMM sheet-metal BIW manufacturing. The added value of the present review is therefore its integrated product–process–factory perspective, through which gigacasting can be evaluated not only as a casting process but as a broader transformation in vehicle architecture, production organisation, cost structure, repairability, supply-chain configuration, and sustainability.

From this perspective, gigacasting represents a major technological shift in automotive manufacturing, particularly for electric vehicle (EV) platforms. By enabling the production of large, integrated aluminium components, it can reduce part count, shorten production cycles, simplify assembly, and lower non-material manufacturing costs. However, the technology is still maturing, and its large-scale adoption remains subject to technical, economic, and market-related uncertainties. Fluctuating EV demand, evolving incentive schemes, and unstable regulatory frameworks have led several OEMs to revise or postpone electrification investments [54]. This uncertainty also affects the supply chain, especially lower-tier suppliers that require long-term volume commitments to justify retooling for gigacasting.

The present review does not provide new mass-normalised stiffness or crashworthiness simulations. Such a comparison would require equivalent gigacast and MMM BIW architectures evaluated under identical boundary conditions, load cases, material models, defect assumptions, and mass constraints. Although recent studies address multidisciplinary optimisation of megacast components by considering stiffness, NVH, crash, castability, and weight minimisation [70], a direct mass-normalised comparison between gigacast and conventional MMM BIW structures is not yet available in the open literature. This remains an important topic for future research.

In Table 7, a synthetic overview of the comparison between gigacasting and MMM is provided.

A critical limitation is the relatively short life of gigacasting dies. Unlike conventional stamping tools, which can reach several million strokes, gigacasting moulds are typically limited to approximately 30,000–100,000 cycles. Their large size, high cost, and exposure to severe thermal and mechanical loading make maintenance, repair, and replacement major cost drivers. Future progress will depend on improved die materials, conformal cooling, additive-manufactured inserts, thermal management, and predictive maintenance strategies.

The benchmark in [17] supports a balanced interpretation of gigacasting. The aluminium giga-cast baseline showed clear advantages in part consolidation and selected stiffness metrics, but advanced steel alternatives remained competitive in mass, crash-performance targets, cost, and production-phase CO_2 emissions. This reinforces the main conclusion of the present review: gigacasting should be evaluated against optimised next-generation MMM architectures, not only against conventional baseline designs.

Defect control remains a key challenge. Large-scale HPDC is sensitive to porosity, shrinkage cavities, oxide inclusions, cold flakes, residual stresses, and dimensional distortion, all of which are critical for BIW crashworthiness, fatigue resistance, and structural integrity. Vacuum-assisted HPDC, optimised gating, solidification simulation, real-time process monitoring, and stricter melt-quality control are therefore essential to ensure repeatable part quality.

Repairability is another relevant barrier. Conventional MMM architectures allow localised repair or replacement of individual panels and subcomponents, whereas damaged gigacast structures may require larger-section replacement. This affects repair cost, insurance cost, and sustainability. Segmented repair zones, bolted modules, hybrid castings, and predefined fracture-control areas may mitigate this disadvantage, but they also reintroduce some modularity, interfaces, and assembly complexity. Their adoption will therefore depend on whether reduced repair and insurance risk compensates for the loss of part-consolidation benefits.

Gigacasting also reshapes the supply chain by shifting emphasis from stamped steel parts and sheet-metal subassemblies toward aluminium alloys, foundry expertise, giga-presses, large dies, and advanced quality-control systems. A reliable supply of high-quality, low-defect aluminium, preferably with increasing recycled content, is essential for both cost competitiveness and environmental performance.

This transition is closely linked to Industry 4.0 and sustainability trends. Digital twins, casting simulation, AI-based die design [71], process monitoring, and data analytics can reduce scrap and improve process robustness, while environmental targets require cleaner electricity, energy-efficient furnaces, low-carbon aluminium, and closed-loop recycling strategies.

Table 7. Comparative overview of aluminium alloy gigacasting and conventional multi-material mix sheet-metal BIW manufacturing.

Aspect	Gigacasting	Conventional MMM Sheet Metal
Part Count	Very low for integrated modules; many components consolidated into one	High; dozens to hundreds of stamped, extruded, or joined parts
Assembly Complexity	Reduced; fewer joining operations, fixtures, and robots, but still requires mechanical joining to the rest of the BIW	High; many welding, riveting, adhesive bonding, and assembly stations
Cycle Time	Typically <100–150 s per large casting, followed by trimming, inspection, machining, and handling	Longer multi-step process chain; equivalent assemblies may require up to ~30 min, although operations parallel
Production Volume Suitability	Best for high-volume, low-variant, dedicated EV platforms	Suitable across a wider range of volumes; especially advantageous for high-mix, lower-volume, or frequently updated platforms
Tooling Cost and Lifespan	Very high initial tooling cost; die life typically ~30,000–100,000 shots, with strong dependence on cooling, inserts, alloy, and maintenance	Lower tooling risk and longer tool life; stamping tools can reach several million strokes
Repairability	Limited; large-part replacement often required, although segmented repair strategies are emerging	High; localised repair or replacement of panels and subcomponents is generally possible
Flexibility and Adaptability	Low to moderate; design changes usually require expensive mould modification, but common platforms may reuse major castings	High; modular tooling and part-level changes support frequent design updates
Defect Sensitivity	High; porosity, oxide bifilms, shrinkage, cold flakes, warpage, and local property variation are critical	Moderate; main risks include formability defects, springback, weld fatigue, joint defects, and corrosion at interfaces
Dimensional Accuracy	Requires tight process control; sensitive to thermal gradients, die temperature, solidification, and post-casting distortion	Managed through mature multi-stage tolerance strategies and distributed correction points
Weight Reduction Potential	Reported at ~7–20% when optimised, but uncertain and sometimes offset by larger wall thicknesses	Moderate to high through AHSS, UHSS, tailored blanks, HFQ®, hot stamping, and local material optimisation
Crash Performance	Potentially high, dependent on defect control, local ductility, fracture design, and process-aware crash simulation	Predictable through tailored crumple zones, material grading, and modular reinforcements
Sustainability Potential	Uncertain; favourable only with low-carbon aluminium, high-quality recycled feedstock, clean electricity, high yield, and real mass reduction	Often lower material CO_2 per kg, mature steel recycling, and better repairability; multi-material separation can remain challenging
Digital Integration	High; relies strongly on casting simulation, digital twins, sensors, AI-based process control, and NDT	Moderate to high; increasingly digitalised but supported by mature forming and assembly know-how
Supply Chain	Requires high-quality aluminium supply, large HPDC capability, giga-presses, die specialists, and foundry expertise	Mature and diversified supply base for steel/aluminium sheets, stampings, joining, and subassemblies

Strategically, gigacasting is best suited to dedicated, high-volume, low-variant EV platforms with large underbody or front/rear structural modules, where part consolidation can reduce joining operations, assembly complexity, handling, and factory footprint. However, no universal production-volume threshold can be defined. The break-even depends on vehicle architecture, part size, annual volume, programme stability, aluminium cost, die life, casting yield, factory strategy, and regional electricity mix. Conventional MMM sheet-metal manufacturing remains preferable for lower-volume or high-variant programmes, brownfield factories, frequent design updates, or cases where repairability, modularity, existing assets, low-carbon aluminium supply, or casting quality control are critical constraints. These conditions are summarised in Table 8.

Table 8. Decision matrix for selecting gigacasting or conventional MMM sheet-metal BIW manufacturing.

Decision Factor	Conditions Favouring Gigacasting	Conditions Favouring Conventional MMM Sheet-Metal Manufacturing
Production volume and programme stability	High and stable annual volumes, long production runs, low variant complexity, and limited geometry changes, allowing giga-presses, dies, trimming, and inspection systems to be amortised.	Low-to-medium volumes, uncertain demand, frequent facelifts, short product cycles, or multiple body variants, where modular tooling is less risky.
Vehicle architecture and size	Dedicated EV platforms, especially medium-to-large vehicles, with large front or rear underbody modules suitable for structural integration and joining reduction.	Small or highly cost-sensitive vehicles, multi-energy platforms, or architectures shared across ICE, HEV, and EV variants, where modularity is valuable.
Factory and supply-chain context	Greenfield plants or major factory redesigns, with access to large HPDC machines, die maintenance expertise, suitable aluminium alloys, and integrated inspection capability.	Brownfield plants with existing press shops, body shops, joining lines, skilled labour, and validated sheet-metal supplier networks.
Cost and environmental conditions	Scenarios where joining, handling, fixtures, robots, and floor-space costs dominate, and where low-carbon or recycled aluminium and high casting yield are available.	Regions or programmes where aluminium is expensive or carbon-intensive, advanced steels are locally available, or existing assets reduce investment needs.
Performance, repairability, and validation	Designs that exploit integrated load paths, high torsional/bending stiffness, and reduced joint count, supported by NDT, defect-sensitive simulation, and validated repair procedures.	Applications requiring modular crash management, easy sectional repair, mature fatigue/crash validation, and high tolerance to late design changes.

In summary, gigacasting is a powerful enabler of next-generation vehicle manufacturing, but it should not be considered automatically cheaper or more sustainable than conventional solutions. It reduces process complexity and non-material manufacturing costs, but total cost and CO_2eq footprint remain strongly affected by aluminium price, aluminium carbon intensity, component mass, die life, and casting yield. Conventional sheet-metal forming will therefore remain important where flexibility, repairability, structural tailoring, or lower production volumes are priorities.

The most realistic future is likely a hybrid one, in which gigacasting and MMM architectures coexist according to platform strategy, production scale, repairability constraints, and sustainability targets. Within this perspective, hybrid gigacasting should not be seen merely as a compromise that reduces part consolidation but also as an additional design tool for reaching a system-level optimum between integration, structural performance, manufacturability, repairability, and cost. In a longer-term perspective, this hybridisation may not be limited to the coexistence of casting and sheet-metal assemblies but may also include more advanced material concepts, such as locally reinforced or functionally graded metallic structures, where composition, microstructure, and mechanical properties are tailored to the local structural function [72].

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Abbreviations

The following abbreviations are used in this manuscript:

AHSS	Advanced High-Strength Steel
AI	Artificial Intelligence
BIW	Body-in-White
CAPEX	Capital Expenditure
CO_2eq	Carbon Dioxide Equivalent
EV	Electric Vehicle
HPDC	High-Pressure Die Casting
LCA	Life Cycle Assessment
MMM	Multi-Material Mix
MUSD	Million US Dollars
NDT	Non-Destructive Testing
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
SPR	Self-Piercing Riveting
UHSS	Ultra-High-Strength Steel

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