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Abstract

This report develops and evaluates a high-volume injection-moulded mobile phone case for the iPhone 16 Pro Max using Design for Manufacture and Assembly principles. Customer requirements were translated into measurable design targets using QFD, while DFMEA, PFMEA, DOE, CAD modelling and simulation were used to reduce design and process risk. Material selection identified ether-based TPU as the preferred option due to its balance of flexibility, impact resistance, durability, grip, mouldability, cost and recyclability. The manufacturing process proposed is a four-cavity moulding process and was assessed through manufacturing planning, cost analysis and sustainability review. Overall, the design provides a technically viable, cost-effective and manufacturable single-material product.

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1 Introduction

High-volume consumer products require repeatable, cost-effective manufacturing while maintaining dimensional accuracy, functional performance and acceptable surface quality. For injection-moulded polymer products, component and tooling design must be considered together because early decisions affect manufacturability, assembly efficiency, defect formation and production cost (Boothroyd, Dewhurst and Knight, 2011; Osswald and Menges, 2012).

This report develops and evaluates an injection-moulded mobile phone case for the iPhone 16 Pro Max. The case must provide impact protection, secure fit, full access to phone functions, ease of installation/removal and acceptable cosmetic quality. Thin-walled polymer parts are vulnerable to warpage, sink marks, weld lines, air traps, shrinkage variation and stress concentrations if material choice, wall thickness, gate location, cooling and mould layout are not optimised (Rosato, Rosato and Rosato, 2000; Osswald and Menges, 2012).

An integrated design and validation approach was applied. QFD translated customer needs into measurable engineering characteristics, while FMEA identified design and process risks before manufacture (Akao, 1990; AIAG and VDA, 2019). Autodesk Fusion 360 supported CAD modelling, plastics simulation and FEA, allowing filling behaviour, defect risk, stress and deformation to be assessed before tooling (Autodesk, 2026; Zienkiewicz, Taylor and Zhu, 2013). Granta EduPack supported material comparison against mechanical, thermal, manufacturing, cost and sustainability requirements (Ashby, 2017; ANSYS, 2021). Process planning, tooling, cost and sustainability were then considered to assess the suitability of the proposed design for high-volume manufacture.

2 Literature Review

The design of an injection-moulded mobile phone case requires early consideration of product performance, manufacturability, assembly efficiency, defect prevention and cost. The product must provide impact protection, dimensional accuracy, suitable appearance, reliable fit and low defect risk. This review therefore focuses on the design and validation methods most relevant to the development of a high-volume polymer mobile phone case.

2.1 Design for Manufacture (DFM) & Design for Assembly (DFA)

Design for Manufacture (DFM) aims to ensure that a product can be produced efficiently and consistently using the selected manufacturing process. For injection-moulded polymer components, this includes control of wall thickness, draft angles, ribs, radii, gate position, shrinkage and cooling behaviour, all of which influence mould filling, ejection, dimensional accuracy and defect formation (Boothroyd, Dewhurst and Knight, 2011; Osswald and Menges, 2012). Design for Assembly (DFA) focuses on simplifying assembly by reducing part count, improving handling and minimising secondary joining operations. This is relevant to the phone case because integrated snap-fit and retention features can reduce additional components, although these features must be designed to avoid weak sections, sink marks or stress concentrations.

2.2 Injection Moulding and Mould Design

Injection moulding is suitable for high-volume polymer products because it can produce complex, repeatable parts with short cycle times and low unit cost once tooling has been manufactured (Groover, 2020). However, the process is sensitive to material behaviour, melt temperature, mould temperature, gate location, injection pressure, cooling rate and part geometry. Poor control of these factors can cause short shots, sink marks, weld lines, air traps, uneven shrinkage and warpage (Rosato, Rosato and Rosato, 2000). Therefore, mould layout, runner design, gate position, cooling strategy, parting line and ejection must be considered alongside the product geometry.

2.3 Quality Function Deployment (QFD), Failure Mode and Effects Analysis (FMEA) & Design of Experiments (DOE)

Quality Function Deployment (QFD) is used to translate customer requirements into measurable engineering characteristics, allowing product expectations such as protection, grip, appearance, fit and affordability to be linked to technical requirements such as impact strength, wall thickness, shrinkage, surface finish and cost (Akao, 1990). Failure Mode and Effects Analysis (FMEA) support this by identifying possible design and process failures, their effects and the controls required to reduce risk. For this project, DFMEA and PFMEA are relevant to risks such as poor dimensional fit, cracked retaining features, short shots, sink marks, flashing, warpage and ejection damage (AIAG and VDA, 2019). Design of Experiment (DOE) then provides a structured method for investigating how process variables such as gate location, melt temperature, mould temperature, injection pressure and fill time affect moulding performance (Montgomery, 2017).

2.4 CAD, 3D Modelling and Simulation

CAD modelling allows the phone case geometry to be developed and refined before manufacture. Autodesk Fusion 360 provides an integrated CAD and analysis environment suitable for modelling the case, assessing manufacturability and carrying out simulation-based design checks. Plastics simulation can be used to predict filling behaviour, weld lines, air traps, sink marks and warpage before tooling is produced. Finite Element Analysis (FEA) can also be used to estimate stress and deformation around features such as corners, retaining lips and cut-outs (Zienkiewicz, Taylor and Zhu, 2013). However, simulation accuracy depends on material data, mesh quality, boundary conditions and loading assumptions, so results should be used to support design decisions rather than replace physical validation.

3 Definition of Customer Requirements

Customer requirements define the expected function, performance and constraints of a product and form the basis of the design specification (Pugh, 1991; Ulrich and Eppinger, 2004). These requirements may include measurable limits such as dimensions, mass, cost, impact resistance, durability and operating temperature. However, customers often describe desired outcomes rather than exact engineering values, so these needs must be translated into measurable technical specifications (Ulrich and Eppinger, 2004; ScienceDirect, 2018).

For this project, customer requirements were defined through market research, competitor benchmarking, Apple accessory guidance and practical operating conditions. Key requirements included impact protection, secure fit, ease of installation/removal, low weight, durability, visual quality, usability, cost and manufacturability. QFD was used to convert these needs into technical characteristics, while DFMEA identified design risks before manufacture. DOE was then used later in the project to support optimisation of variables such as wall thickness, gate position and processing conditions (Akao, 1990; Montgomery, 2017; Madhusudhan Chellappa, 2026)

3.1 Quality Function Deployment (QFD)

The mobile phone case was developed around the dimensional and functional requirements using Apple's published iPhone 16 Pro Max technical specification and Accessory Design Guidelines (Apple Inc, 2024; Apple Inc, 2026). This ensured that critical features such as the camera opening, buttons, charging port, speakers and external profile were considered from the beginning of the design process. Market research, competitor benchmarking and material limitations were also used to define the main customer and technical requirements.

QFD was used to translate these customer requirements, or demanded qualities, into measurable engineering characteristics (Erdil and Arani, 2019; Akao, 2024). The full QFD analysis is provided in [Appendix 1](#). The main customer requirements included impact protection, secure fit, ease of installation/removal, lightweight construction, comfortable grip, full phone functionality, good visual quality, durability, cost-effective manufacture, low defect risk and sustainable material/manufacturing choices.

These requirements were linked to technical characteristics such as impact strength, tear resistance, elongation at break, wall thickness, reinforced corners, dimensional tolerance, shrinkage and warpage control, port and button clearance, sink mark depth, surface finish, cycle time and scrap rate (Ulrich and Eppinger, 2004; Akao, 2024). The QFD showed that dimensional accuracy, impact performance, flexibility, tear resistance, fatigue resistance, wall thickness and corner reinforcement were the most influential design priorities.

The analysis demonstrated that the case should not simply maximise impact resistance, as this could increase bulk, weight, material usage and cost. Instead, the design must balance protection with slimness, flexibility, grip, visual quality and manufacturability. From a process perspective, the QFD also highlighted the importance of controlling shrinkage, warpage, sink marks, weld lines, gate location, fill balance, temperature, pressure and cycle time, as these directly affect product fit, appearance, defect risk and production cost. This provides the best balance between customer requirements, manufacturing efficiency and product performance.

3.2 Design Specification and Performance Attributes

The design specification converts the customer requirements identified through QFD, competitor benchmarking and material property analysis into measurable product targets, as shown in Tables 1–3.

The specification focuses on producing a lightweight, durable and injection-mouldable phone case that protects the device, fits securely, remains easy to install and remove, allows full phone functionality and can be manufactured cost-effectively with low defect risk (Pugh, 1991; Ulrich and Eppinger, 2004; Kent, 2016). To improve clarity, the specification is divided into three areas:-

- Material Requirements
- Geometry And Fit Requirements
- Manufacturing And Quality Requirements

The material requirements define the properties needed for the selected material, including flexibility, impact resistance, hardness, tear resistance, thermal behaviour and environmental durability (Ashby, 2017; Callister and Rethwisch, 2018).

Table 1 - Specification Material Requirements

Design Requirement	Target / Specification	Reason / Design Justification
Product material	Systematic selection process to identify correct material	Selected due to its balance of flexibility, impact resistance, tear resistance, grip, durability and injection mouldability.
Material hardness	Approx. Shore A 85–95	Provides sufficient flexibility for fitting/removal while maintaining stiffness and impact protection.
Density	Approx. 0.9–1.4 g/cm ³	Supports a lightweight design while maintaining suitable mechanical strength.
Impact resistance	>20 kJ/m ²	The case must absorb energy from drops and protect the phone from damage.
Tensile strength	Approx. 20–70 MPa	Ensures the case can withstand stretching, fitting/removal forces and repeated use without failure.
Elongation at break	>100, ideally >300%	Allows the case to flex during installation and removal without tearing or permanent damage.
Tear strength	>40 kN/m	Reduces the risk of splitting around thin sections, corners, buttons and port openings.
Flexibility	Flexible but shape-retaining	Allows easy installation/removal while maintaining a secure fit around the phone.
Young's modulus / stiffness	20 MPa – 3 GP	Prevents the case from being too rigid while still maintaining dimensional stability.
Grip / surface feel	Good tactile grip, non-slip surface	Improves user handling and reduces the chance of accidental drops.
Maximum service temperature	>60–80°C	Ensures the case remains stable in warm use conditions, such as pockets, cars or sunlight exposure.
Water absorption	<1%, ideally <0.5%	Maintains dimensional stability and prevents changes in feel, fit or performance due to moisture.
Chemical resistance	Resistant to skin oils, mild cleaning products and everyday contaminants	Ensures durability during normal use.
UV resistance	Moderate UV resistance preferred	Reduces discolouration, degradation or embrittlement from sunlight exposure.
Recyclability / sustainability	Recyclability preferred where available	Supports material efficiency and improved end-of-life options.
Material cost	£2–£8/kg	Maintains commercial viability for a high-volume consumer product.

The geometry and fit requirements define the dimensional, functional and ergonomic features needed for compatibility with the iPhone 16 Pro Max, including wall thickness, clearances, tolerances, surface finish and critical fit areas (Apple Inc, 2026 & 2026; Malloy, 2011).

Table 2 - Specification Geometry and Fit Requirements

Design Requirement	Target / Specification	Reason / Design Justification
Phone compatibility	iPhone 16 Pro Max	Defines the product envelope, geometry and all functional clearances.
Case mass	Approx. 44 g	Maintains a lightweight product suitable for everyday use and high-volume manufacture.
Nominal wall thickness	Approx. 2 mm	Balances flexibility, protection, material usage, cooling time and mouldability.
Drop protection requirement	Suitable for typical drop height of approx. 1.5 m	Provides a measurable performance expectation based on normal consumer use.
Dimensional tolerance	Approx. ± 0.2 – 0.5 mm depending on feature criticality	Ensures secure fit without excessive tightness, looseness or functional interference.
Critical fit tolerances	Tighter tolerance required around phone profile, buttons, camera and port openings	These areas directly affect fit, usability and customer satisfaction.
Camera opening clearance	To match Apple accessory geometry with suitable tolerance	Prevents obstruction of the camera, flash and sensors.
Button clearance / alignment	Aligned to Apple accessory design guidance	Maintains correct button operation and tactile response.
Charging port clearance	Sufficient clearance for cable access	Ensures the charging cable can be inserted without interference.
Speaker / microphone openings	Unobstructed and accurately aligned	Maintains acoustic performance and device functionality.
Corner protection	Reinforced corner geometry where possible	Corners are high-risk impact zones during drops.
Edge radius	Rounded edges where appropriate	Improves comfort, reduces stress concentration and improves mould flow.
Surface finish	Smooth, visually acceptable finish with controlled texture if required	Ensures an acceptable consumer appearance and feel.
Colour / appearance	Consistent colour and finish	Maintains product quality and reduces visual rejection risk.
Wall thickness	1.5–2.5 mm	Firm protection but remain thin and not bulky

The manufacturing and quality requirements define the process-related controls needed to ensure repeatable production, dimensional accuracy and acceptable visual quality during high-volume injection moulding. These requirements include shrinkage control, warpage limits, sink mark tolerance, production repeatability and inspection requirements (Osswald and Menges, 2012; Protolabs, 2020; British Plastics Federation, 2019).

Table 3 - Specification Manufacturing and Quality Requirements

Design Requirement	Target / Specification	Reason / Design Justification
Manufacturing process	Injection moulding	Suitable for high-volume production, repeatability, low unit cost and complex geometry.
Mould shrinkage allowance	Tooling/part geometry oversized according to selected TPU shrinkage rate	Compensates for material contraction after cooling to achieve final dimensional accuracy.
Thermal conductivity	0.15–0.4 W/m·K	Ensures the material can cool at a controlled rate during injection moulding, supporting stable cycle times and reducing the risk of uneven cooling, residual stress and warpage
Coefficient of thermal expansion	$<150 \times 10^{-6}/K$	Limits dimensional change caused by temperature variation, helping the case maintain a secure fit and reducing the risk of distortion during cooling and normal use.
Shrinkage	0.3–2.0%	Allows mould tooling and CAD dimensions to be compensated for material contraction after cooling, ensuring the final moulded part meets the required dimensional accuracy and fit.
Maximum allowable warpage	≤ 0.5 mm	Ensures the case remains flat, stable and able to fit securely after moulding.
Sink mark tolerance	≤ 0.025 mm or visually acceptable	Maintains external surface quality and reduces cosmetic defects.
Production repeatability	High repeatability required	Ensures all cases meet dimensional and visual quality requirements.
Quality inspection	Dimensional inspection, visual inspection and process monitoring	Confirms that the product meets specification before release.
Manufacturing process	High-volume injection moulding	To meet customer demand for high production volumes within their manufacturing facility
Surface quality	No major visible defects	To meet end user demands
Sustainability	Recyclable where possible, RoHS compliant and Low CO ₂ Footprint	To meet end user environmental expectations

The final material and process must therefore balance flexibility, impact resistance, tear resistance, tactile performance, dimensional stability and injection moulding suitability. These technical parameters ensure the case can meet customer requirements while remaining suitable for its intended operating environment.

3.3 Design Failure Modes and Effects Analysis (FMEA)

Design Failure Mode and Effects Analysis was used to evaluate potential risks in the mobile phone case design before manufacture, as shown in [Appendix 2](#). The purpose of the DFMEA was to identify how the product could fail to meet its design requirements, what effect those failures could have on the customer or product function, and what controls are required to reduce the risk (AIAG and VDA, 2019).

For this product, the DFMEA focused on material selection, hardness, flexibility, dimensional accuracy, wall thickness, corner protection, button and port alignment, camera clearance, surface finish and ease of assembly/removal. These areas are important because the case must protect the phone, fit securely, allow full device functionality and remain durable during repeated use.

Each failure mode was assessed using severity, occurrence and detection ratings to calculate a Risk Priority Number (RPN). This allowed the highest-risk issues to be prioritised. For example, incorrect material hardness could make the case too rigid to fit or too flexible to protect the phone effectively. Poor dimensional tolerance or excessive warpage could also lead to poor fit, loss of retention, button misalignment or customer dissatisfaction (AIAG and VDA, 2019; Madhusudhan Chellappa, 2026).

The DFMEA identified controls such as material verification, supplier datasheets, CAD tolerance checks, design reviews, prototype testing, drop testing, dimensional inspection, FEA and mould-flow simulation. Significant Characteristics (SC) were assigned where features affected fit, protection, durability or function, while Critical Characteristics (CC) were used more selectively where failure could create a safety issue or prevent normal phone operation (AIAG and VDA, 2019; Autodesk, 2026).

Overall, the DFMEA improves design robustness by identifying weaknesses early and linking them to corrective actions before tooling and production begin. This reduces the risk of costly design changes and improves the likelihood that the final case will meet customer requirements for protection, fit, usability, appearance and durability.

4 Material Selection

Material selection used the design specification, QFD outputs and performance requirements to compare candidate materials against mechanical, thermal, manufacturing, cost and sustainability constraints. Following recognised selection practice, materials were screened against functional and processing requirements before final justification (Ashby and Johnson, 2014; Ashby, 2017). Primary properties were those directly linked to performance; secondary properties addressed commercial and environmental suitability.

4.1 Primary Material Properties

The primary requirements in Tables 4-9 define the material performance needed for a protective phone case. Physical properties such as density, shrinkage and moisture absorption influence weight, fit and environmental stability (Ashby, 2019; Granta EduPack; Osswald & Menges, 2012). Mechanical properties such as tensile strength, modulus, impact resistance, hardness, elongation and tear resistance control protection, flexibility and repeated installation/removal.

Table 4 - Physical Properties Requirements

Physical Property	Suggested Target / Range	Why it Matters
Density	0.9–1.4 g/cm ³	A lower density ensures the phone case remains lightweight, improving user comfort and portability while maintaining sufficient material integrity.
Water Absorption	<1%, ideally <0.5%	Low water absorption is critical for maintaining dimensional stability and preventing swelling, which could affect fit and long-term performance.
Transparency	Optional (clear/semi-clear)	Transparency enables aesthetic versatility for consumer preferences, particularly in premium or display-focused products.
Shrinkage	0.3–2.0%	Material shrinkage directly affects dimensional accuracy, influencing fit, warpage, and manufacturability during injection moulding.

Mechanical properties such as tensile strength, Young's modulus, impact resistance, hardness, elongation and tear resistance are critical to protection, flexibility and durability. The material must absorb impact, resist cracking and allow repeated installation and removal without permanent deformation or tearing (Ashby, 2019; Callister and Rethwisch, 2018; ASTM International)

Table 5 - Mechanical Properties Requirements

Mechanical Property	Suggested Target / Range	Why it Matters
Young's Modulus	20 MPa – 3 GPa	Controls stiffness of the case, balancing flexibility for impact absorption with rigidity for structural support.
Tensile Strength	20–70 MPa	Ensures the material can withstand everyday stresses without permanent deformation or failure.
Elongation at Break	>100% (ideally >300%)	High elongation improves flexibility and energy absorption during drops, reducing risk of cracking.
Impact Strength	>20 kJ/m ²	Critical for protecting the device from damage during accidental drops or impacts.
Hardness	Shore A 85–95 / Shore D	Determines tactile feel, scratch resistance, and ability to absorb shocks.
Flexural Modulus	50 MPa – 2.5 GPa	Influences bending stiffness, affecting how the case fits and feels during handling.
Tear Strength	>40 kN/m	Prevents tearing in high-stress regions such as corners and button cut-outs.
Abrasion Resistance	High	Ensures durability against wear from daily handling and pocket storage.
Fatigue Resistance	Good/Excellent	Allows repeated flexing without failure, important for installation/removal cycles.

Thermal behaviour affects service performance and injection moulding stability (Osswald and Menges, 2012; Ashby, 2019).

Table 6 - Thermal Properties Requirements

Thermal Property	Suggested Target / Range	Why it Matters
Max Service Temperature	≥60–80°C	Ensures the case maintains structural integrity in elevated temperatures (e.g., cars, charging conditions).
Glass Transition Temperature	Avoid operating near T _g	Prevents softening or embrittlement that could compromise protection and fit.
Thermal Conductivity	0.15–0.4 W/m·K	Allows moderate heat dissipation from the device while maintaining user comfort.
Coefficient of Thermal Expansion	<150 × 10 ⁻⁶ /K	Reduces dimensional changes with temperature, maintaining fit and minimising warpage.
Melt Processing Temperature	Material dependent	Must align with injection moulding capabilities for manufacturability.
Mould Shrinkage	Low/moderate	Influences dimensional accuracy and defect formation.

Electrical insulation is required around an electronic device (Callister and Rethwisch, 2018; Groover, 2020).

Table 7 - Electrical Properties Requirements

Electrical Property	Suggested Target / Range	Why it Matters
Electrical Resistivity	High (insulating)	Prevents electrical conduction, protecting internal electronics.
Dielectric Strength	Moderate/High	Ensures safe insulation performance around electronic devices.
Static Tendency	Low / antistatic optional	Reduces dust attraction and improves user experience.

Aesthetic and manufacturing properties, including surface finish, colourability, texture, mouldability, cooling rate, cycle time and defect risk, determine both customer perception

and high-volume production viability (Osswald & Menges, 2012; Ashby, 2019; Autodesk Fusion 360)

Table 8 - Aesthetic / Surface Properties Requirements

Aesthetic / Surface Property	Suggested Target / Range	Why it Matters
Scratch Resistance	Moderate/High	Maintains visual quality over product lifespan.
UV Resistance	Good/Excellent	Prevents degradation and discolouration over time.
Colourability	Good	Enables product differentiation and branding.
Gloss/Matte Capability	Good	Supports varied consumer preferences.
Fingerprint Resistance	Useful	Enhances perceived product quality.
Chemical Resistance	Good	Ensures durability against oils, sweat, and cleaning agents.

Table 9 - Manufacturing Considerations

Manufacturing Considerations	Suggested Target / Range	Why it Matters
Process Compatibility	Injection Mouldable	Essential
Thin-wall mouldability	Good at 1.5-2.5mm wall thickness	Product specification
Melt flow index	Medium/high depending on material	Filling thin sections
Weld-line sensitivity	Low preferred	Strength and visual defects
Warpage tendency	Low preferred	Defects probability
Sink-mark tendency	Low preferred	Visual quality
Cooling time	Low/Moderate	Cycle time and cost
Surface Finish Quality	Good/Excellent	Consumer product appearance

4.2 Secondary Material Properties

Secondary requirements in Tables 10 and 11 assess the commercial and environmental viability of each candidate. Sustainability factors included recyclability, embodied energy, carbon footprint, lifecycle impact and end-of-life route, while cost factors included raw material price, tooling investment, processing cost, volume and scrap/rework risk. These criteria ensured the final selection was not only technically suitable but also commercially scalable and environmentally defensible (Ashby, 2012; European Commission, 2020; Groover, 2020).

Table 10 - Sustainability Considerations for Mobile Phone Case

Sustainability Considerations	Suggested Target / Range	Why it Matters
Recyclability	Prefer Thermoplastic (TPU, PC, ABS & PCS	Environmental Conscience
Embodies Energy	Low preferred	Sustainability Scoring
CO ₂ Footprint	Low preferred	Environmental Conscience
Recycled Content Availability	Desirable	Sustainability Justification
Bio Based Content	Optional	Could compare but not essential
Toxicity / RoHS compliance	Required	Consumer Electronics Accessory

Table 11 - Cost Considerations for Mobile Phone Case

Cost Consideration	Suggested Target / Range	Why it Matters
Material Cost	Ideally £2-£8/Kg, Premium grades may exceed this	Consumer Product Price
Processing Cost	Low/Moderate	High/Volume Production
Tooling suitability	Good for Steel Moulds	High Volume Durability
Scrap/Regrind Potential	Good	Waste Reduction

4.3 Material Screening and Selection

Granta EduPack was used to screen candidate materials against the property ranges in the design specification (ANSYS, Inc., 2021). The process moved from broad material families to a smaller shortlist using mechanical, thermal, manufacturing, cost and sustainability filters, consistent with Ashby's staged selection method (Ashby, 2017) Shown in Figure 1.

Material Selection Strategy for Injection Moulded Mobile Phone Case

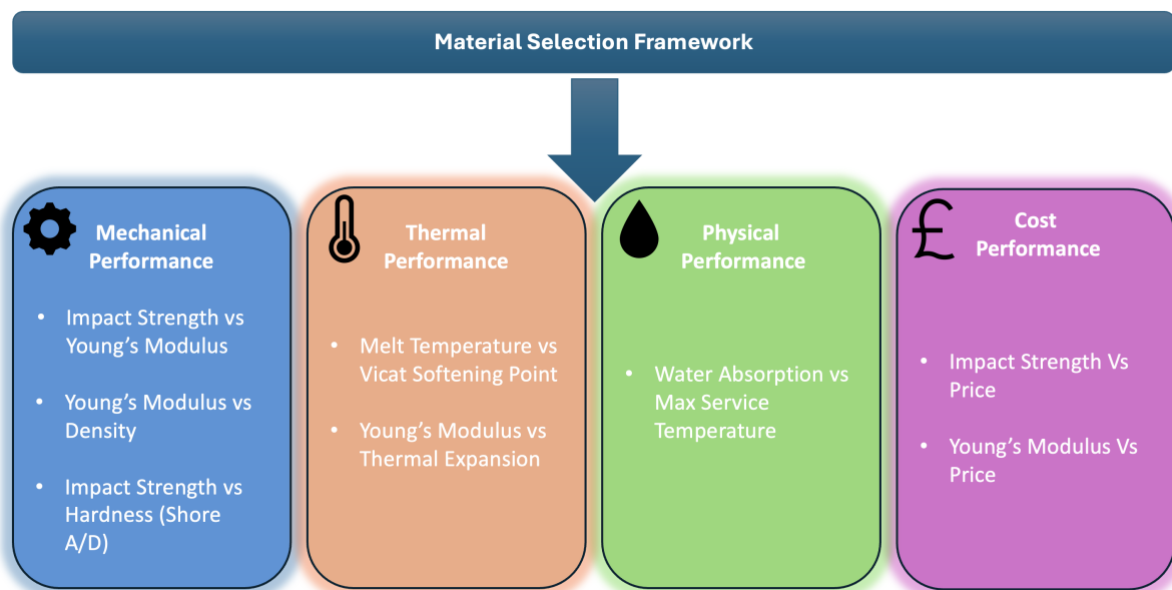


Figure 1 - Material Selection Framework

Mechanical screening prioritised impact strength, modulus, hardness, elongation and tear resistance. Processing screening considered melt temperature, shrinkage, thermal expansion, service temperature and water absorption (Ashby, 2017; Callister and Rethwisch, 2018; ASTM International, 2023a; ASTM International, 2023b; ASTM International, 2023c).

The final comparison reviewed cost, embodied energy, carbon footprint and recyclability. The charts showed that polymer materials provided the best balance of flexibility, manufacturability, comfort and cost; composites and metals were rejected because they failed to meet this balance despite some isolated property advantages (Ashby, 2012; Ashby, 2017; European Commission, 2020a).

Table 12 - Material Selection Methodology

Stage	Chart	Justification
1	Impact strength vs Young's modulus	To identify materials that balance energy absorption (drop protection) with sufficient stiffness to maintain structural integrity.
2	Young's modulus vs Density	To compare stiffness-to-weight efficiency, ensuring the case remains lightweight while still providing rigidity.
3	Melt temperature vs Vicat softening point	To assess processing temperature requirements alongside thermal performance during service.
4	Young's modulus vs Thermal expansion coefficient	To evaluate dimensional stability, ensuring the case resists warping and maintains fit under temperature changes.
5	Impact strength vs Price	To determine the most cost-effective materials that still provide adequate impact protection.
6	Young's modulus vs Price	To compare stiffness performance against material cost for economically viable production.
7	Impact strength vs Hardness (Shore A)	To assess how softer, elastomeric materials balance surface compliance with impact resistance.
8	Impact strength vs Hardness (Shore D)	To compare tougher, more rigid polymers in terms of their resistance to impact and surface damage.
9	Water absorption vs Maximum service temperature	To evaluate environmental durability, particularly resistance to moisture and elevated temperature conditions.
10	Embodied CO ₂ vs Embodied Energy	To evaluate the environmental impact of material production by comparing manufacturing energy demand with associated carbon emissions.
11	Price vs Recyclability	To assess the trade-off between mechanical protection performance and environmental impact, ensuring the selected material achieves adequate impact resistance while minimising carbon emissions.

The methodology of material property comparison decisions outlined in Table 12 were devised to reduce candidate materials to fully applicable choices. Some comparisons can be seen in Figures 2-5.

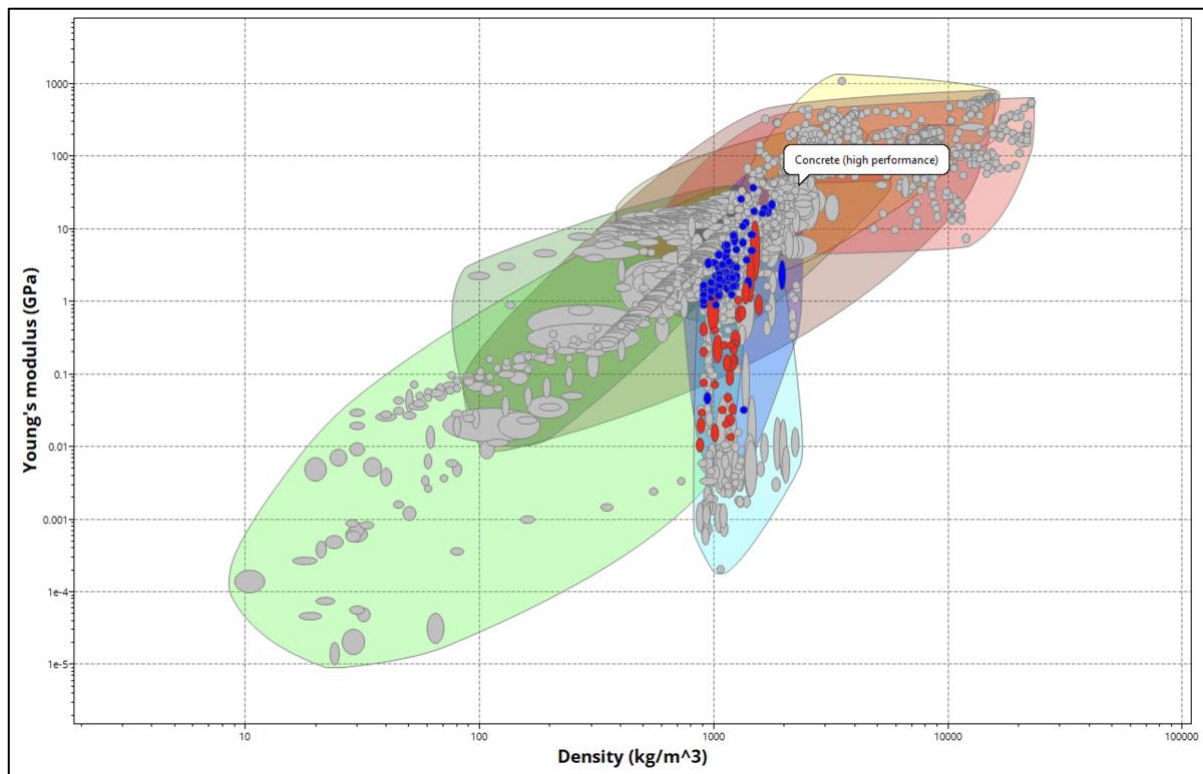


Figure 2 – Strength vs Density Comparison Chart

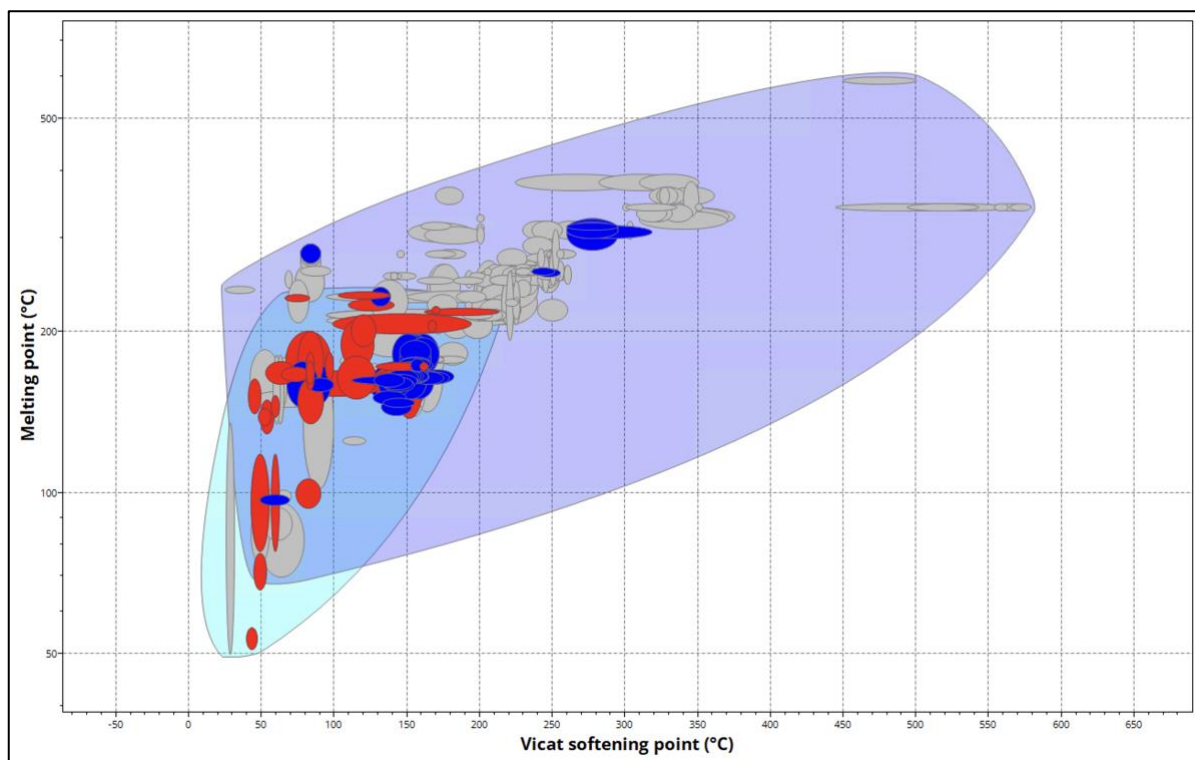


Figure 3 – Melt Temp vs Softening Temp Comparison Chart

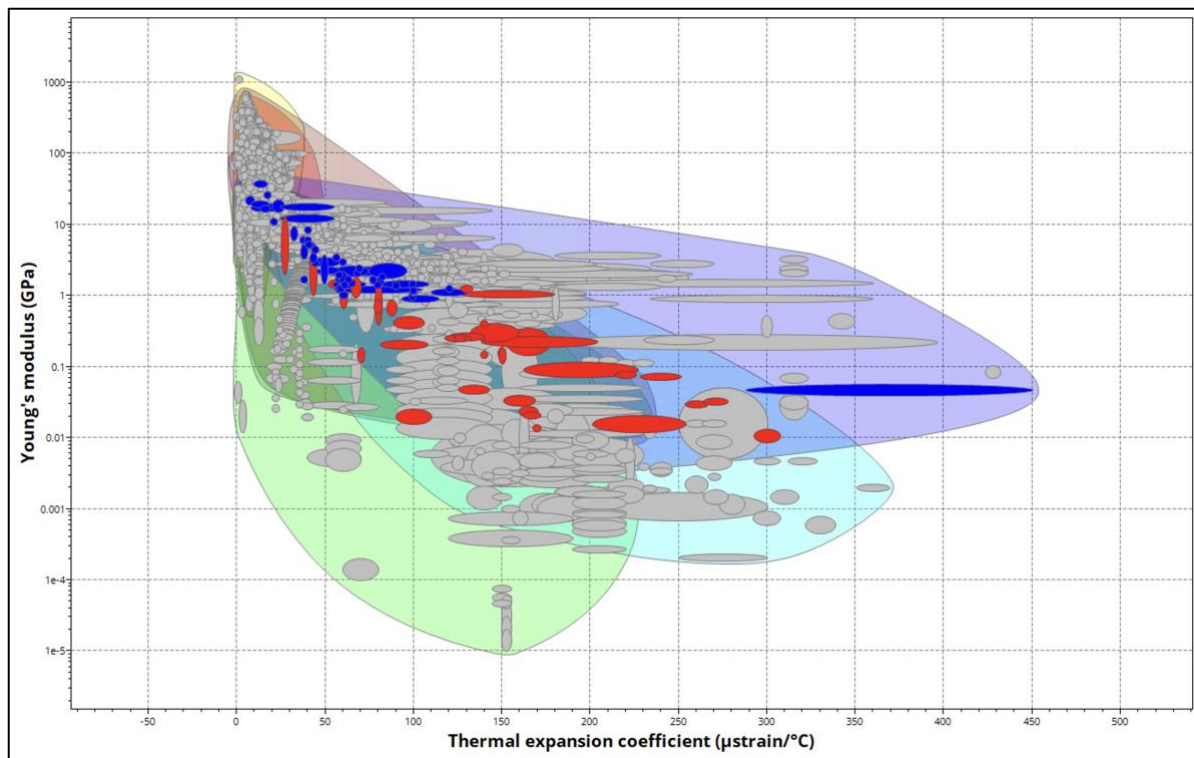


Figure 4 – Strength vs Thermal Expansion Property Comparison Chart

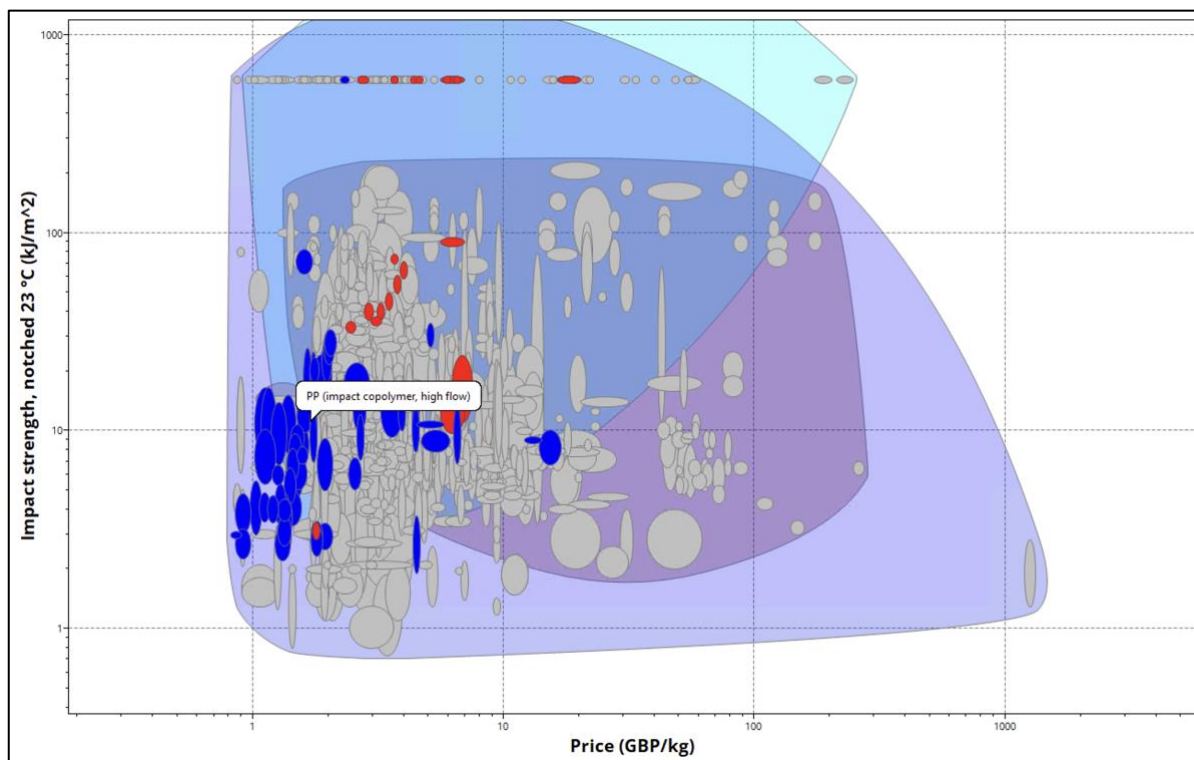


Figure 5 – Impact Strength vs Price Property Comparison Chart

4.4 Material Choice Justification

The final selection compared the remaining polymer candidates against the design specification, QFD priorities and sustainability requirements. Sustainability comparisons were charted in Figures 6 and 7.

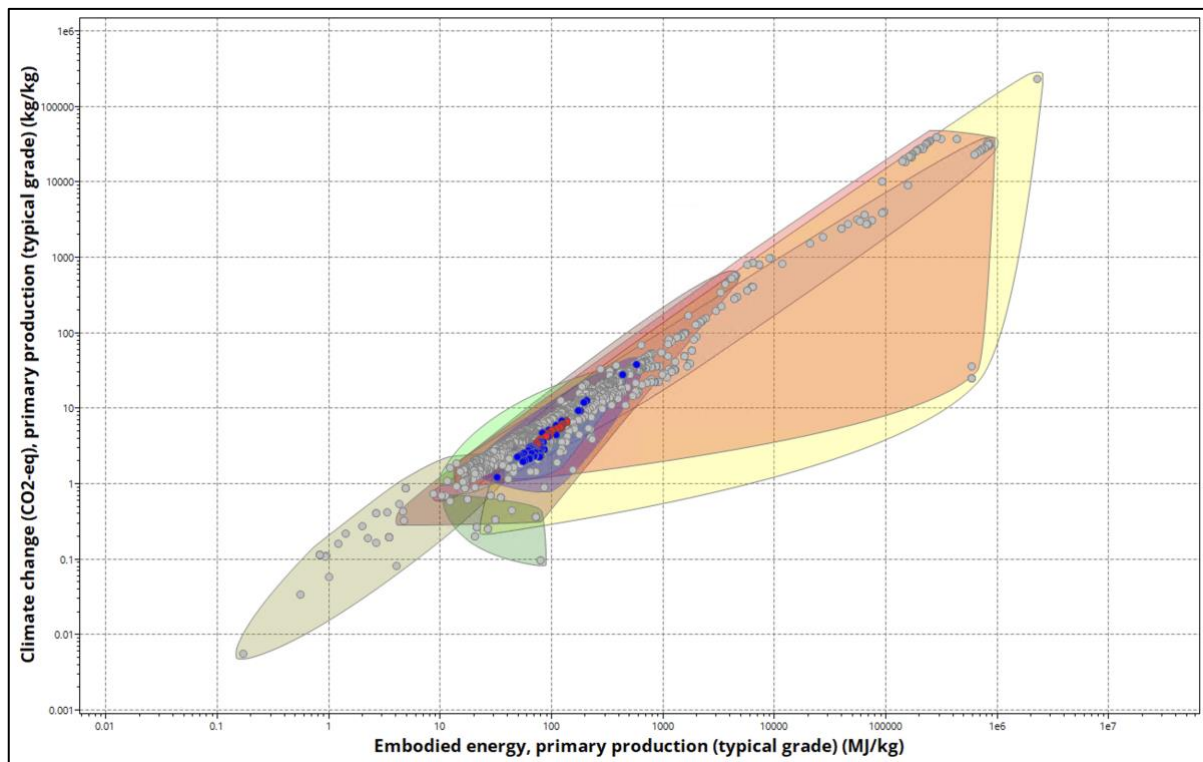


Figure 6 – Embodied Energy vs Carbon Footprint Comparison Chart

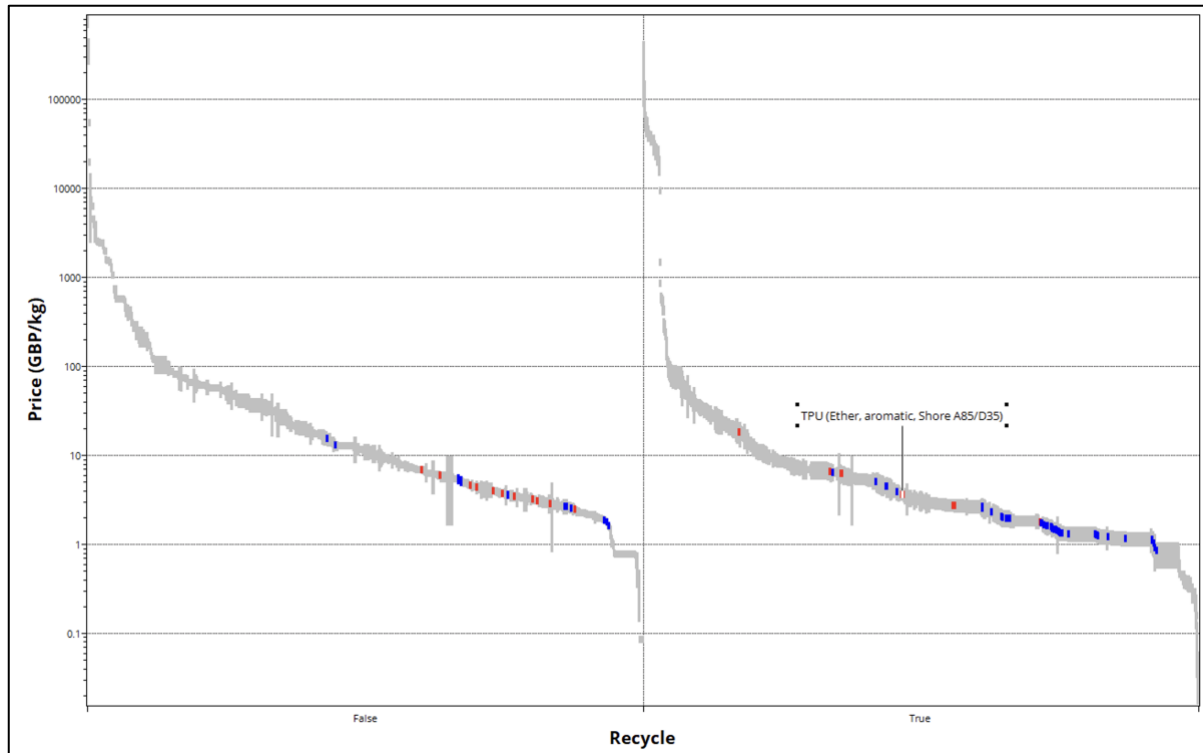


Figure 7 – Recyclability vs Price Comparison Chart

Thermoplastic polyurethane, specifically an ether-based TPU grade with suitable Shore hardness, was selected because it provides the best balance of impact resistance, flexibility, durability, grip, tear resistance, environmental resistance and injection moulding capability (BASF, 2022; Covestro, 2016; Lubrizol, 2026; Special Chem, 2025). TPU also supports the DFM/DFA strategy by allowing the case to be produced as a single injection-moulded component, avoiding secondary bonding, over-moulding or multi-material assembly. Although a multi-material case could improve isolated properties, it would increase tooling complexity, cost, defect risk and end-of-life separation difficulty.

5 Design and Development

The design and development stage considered both the mobile phone case geometry and the injection moulding requirements needed for high-volume manufacture. The aim was to ensure that the final product met the functional requirements of the iPhone 16 Pro Max while remaining suitable for repeatable, cost-effective and low-defect production. For an injection-moulded polymer component, product geometry, material behaviour, mould layout, gate location, shrinkage and cooling must be considered together because early design choices strongly influence manufacturability, dimensional accuracy and defect formation (Boothroyd, Dewhurst and Knight, 2011; Osswald and Menges, 2012).

5.1 Mobile Phone Case Design and Development

The mobile phone case was designed around the iPhone 16 Pro Max, with the primary requirement being a secure fit while maintaining full access to the camera, buttons, charging port and speaker openings. Autodesk Fusion 360 was used to develop a scaled CAD model based on published device dimensions, allowing the internal profile, wall thickness, corner radii, cut-outs and edge clearances to be defined before simulation and validation (Apple Inc, 2024; Apple Inc, 2026; Autodesk, 2026).

A small retaining lip was incorporated around the outer edge of the case to provide a snap-on function and improve device retention. Corner radii and the raised camera protection feature were also included to help distribute external loads and reduce localised stress during impact and handling simulations. The design process therefore balanced fit, protection and geometry while also considering manufacturability through subsequent simulation work.

The final CAD model provided the basis for material selection, injection moulding simulation, finite element analysis and manufacturability review. This ensured that the case was designed not only to meet functional requirements, but also to support practical high-volume production by injection moulding (Malloy, 2011; Boothroyd, Dewhurst and Knight, 2010).

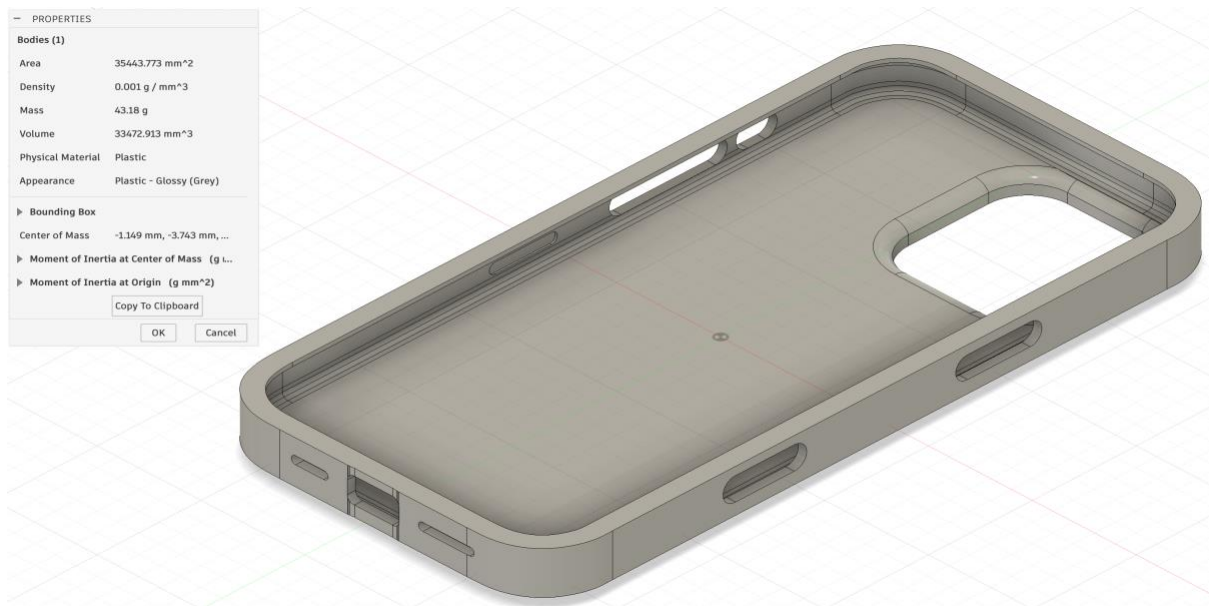


Figure 8 - 3D CAD model of iPhone Pro Max Mobile Phone Case

5.2 Injection Mould Design and Development

Although a full injection mould design is outside the main scope of this report, the key tooling requirements were considered to ensure that the proposed phone case could be manufactured effectively at high volume. Injection moulding was selected because it is suitable for producing repeatable, thin-walled polymer components with good dimensional accuracy and low unit cost once tooling has been produced (Groover, 2020; Bryce and Society of Manufacturing Engineers, 1998; Kazmer and Carl Hanser Verlag, 2016).

The main mould design considerations included tool material primary and secondary properties as outlined in Tables 13 and 14.

Table 13 - Mould Primary Properties

Requirement	Why?
High hardness and wear resistance	The mould must withstand repeated opening, closing, injection, packing and ejection cycles without excessive wear. This is critical if the tool is expected to last hundreds of thousands to millions of cycles.
Dimensional stability under heat and pressure	TPU injection moulding involves repeated heating and cooling, as well as injection and packing pressure. The mould must maintain cavity accuracy, so the phone case remains dimensionally consistent.
High compressive strength	The mould must resist clamping force and injection pressure without deformation, especially around thin walls, corners, gates, ribs and detailed features.
Good thermal conductivity	Efficient heat transfer allows the mould to cool the TPU consistently, reducing cycle time, shrinkage variation, warpage and surface defects.
Good machinability / polishability	The mould must be accurately machined to produce the phone geometry, button details, camera opening and surface finish required.
Resistance to fatigue and thermal cycling	The mould experiences repeated heating and cooling, so the material must resist cracking, distortion and long-term degradation.
Corrosion resistance where required	TPU grades and moulding environments can introduce moisture, additives or degradation products. Corrosion resistance helps maintain surface quality and dimensional accuracy over time.

Table 14 - Mould Secondary Property Requirements

Requirement	Why it matters
Cost effectiveness	The mould material must balance initial tool cost against tool life. A cheaper steel may reduce upfront cost but wear faster.
Availability and supply reliability	Common tooling steels are easier to source, heat treat, repair and replace.
Heat treatment compatibility	The material should be capable of hardening or nitriding where increased surface wear resistance is needed.
Repairability / weldability	Useful if the mould requires modification after trials or if local damage occurs during production.
Sustainability	Steel is energy-intensive to produce, but long tool life, recyclability and reduced scrap rates improve the overall sustainability case.
Surface finish retention	Important for achieving consistent visual quality on the phone case, especially if a textured or polished finish is required.
Compatibility with cooling channels	The material must allow accurate machining of cooling channels without compromising strength or corrosion performance.

A corrosion-resistant stainless mould tool steel, such as 420 stainless steel, was selected because it provides suitable hardness, wear resistance, polishability and dimensional stability during repeated injection, cooling and ejection cycles. Whilst it is more expensive than traditional high strength steel, the corrosion resistance elements negate cooling water used in service, and the hard wearing properties extend the life span of the tooling to more than 1 million shots per mould (Fictiv, 2022; Fictiv, 2023).

In addition to material primary and secondary properties cavity layout, sprue and runner sizing, gate location, cooling, shrinkage allowance and dimensional control, were additional careful considerations in decision making of the mould design (Bryce and Society of Manufacturing Engineers, 1998; Kazmer and Carl Hanser Verlag, 2016; Osswald, Turng and Gramann, 2002).

A four-cavity mould was selected to improve production output and reduce energy use per part. Based on a simulated part mass of 44 g and TPU density of 1.15 g/cm³, the estimated part volume was 38.3 cm³ per cavity, giving a total product shot volume of approximately 153.2 cm³ for four cavities before runner, sprue and gate volume (Autodesk, 2026). These tooling decisions provide a justified preliminary mould-design basis and demonstrate that manufacturability was considered alongside product geometry (Goodship, Arburg and Rapra Technology Limited, 2004; Groover, 2020).

Table 15 - Mould Dimension Calculations

Dimension / feature	Formula used	Working	Calculated answer
Single case shot volume	Volume = mass ÷ density	44 g ÷ 1.15 g/cm ³	38.3 cm ³ per case
Four-cavity part volume	Total volume = part volume × number of cavities	38.3 × 4	153.2 cm ³
Total mould flow rate	Total flow rate = four-cavity volume ÷ fill time	153.2 cm ³ ÷ 1.0 s	153.2 cm ³ /s
Sprue small diameter (D _{small})	D _{small} = Total Shot volume against Anticipated Fill time.	Using the Injection Moulding Spure Diameter Selection chart	0.55 mm
Sprue large diameter (D _{large})	D _{large} = small diameter + 2 × sprue length × tan taper angle	0.55 + 2 × 50 × tan 1.5°	3.17 mm
Runner diameter	Runner diameter = 3 × nominal wall thickness	3 × 2.0 mm	6.0 mm
Runner length	Balanced layout estimate = Main runner 80 mm + four branch runners 4 × 50 mm	80 mm + 4 × 50 mm	280 mm
Shrinkage oversize factor	Mould dimension = final part dimension ÷ (1 – shrinkage fraction)	Final dimension ÷ (1 – 0.01)	Final dimension ÷ 0.99 (Mould cavity approx. 1.01% Oversized)
Oversize for 2mm wall	(Wall thickness ÷ Final Dimension) – 2.0	(2mm ÷ 0.99) – 2.0	+0.02mm

5.3 Design for Manufacture/Assembly (DFM/DFA) considerations

Building on the preliminary mould-design decisions, DFM and DFA principles were central to the final product strategy. A possible alternative would be a multi-material case, such as a rigid polycarbonate backplate combined with a softer TPU or TPE rim. This could improve stiffness, grip and impact absorption, but it would also increase tooling complexity, cycle time, process-control requirements and assembly risk. Additional operations such as over-moulding, bonding or mechanical clipping would increase cost and create further opportunities for defects. From a DFM perspective, a single-material TPU design is more suitable for high-volume injection moulding because it simplifies material handling, moulding, quality control and recycling. It also avoids defects linked to poor adhesion, misalignment, secondary assembly and inconsistent bonding (Boothroyd, Dewhurst and Knight, 2010; Malloy, 2011; Osswald and Menges, 2012).

From a DFA perspective, the preferred design is a one-piece case with integrated retention features like the small lip around the rimmed edge of the case to give a secure snap-on feature. TPU provides enough flexibility for the phone to be inserted and removed without cracking, while still offering sufficient elastic recovery to retain the device during use. This removes the need for separate clips, bonded layers or additional components (Boothroyd, Dewhurst and Knight, 2010).

Overall, the selected single-material injection-moulded TPU case provides the best balance between product performance, manufacturability, assembly simplicity, cost control and sustainability. It supports high-volume production while reducing unnecessary process complexity and defect risk.

6 Manufacturing Process Planning

Value Stream Mapping (VSM) was used to define the proposed production flow for the high-volume manufacture of the TPU mobile phone case, as shown in Figure 9. The VSM identifies the movement of material and information through key stages including material receipt, raw material storage, internal transport, injection moulding, quality inspection, finished goods storage and dispatch (Rother and Shook, 1999; Womack and Jones, 2003).

The VSM highlighted waste, delay and inefficiency before production. This supports Lean Manufacturing principles by focusing on improved flow, reduced handling, lower inventory, improved machine utilisation and fewer defects. The map also includes a rework/recycling route, allowing for excess mould material and defective mouldings to be redirected for reuse where material quality permits. This supports both cost reduction and waste minimisation (Liker, 2004; George, 2011).

Value Stream Map of Facility and Facility Flow

Material and information flow for a four-machine injection moulding cell producing mobile phone cases

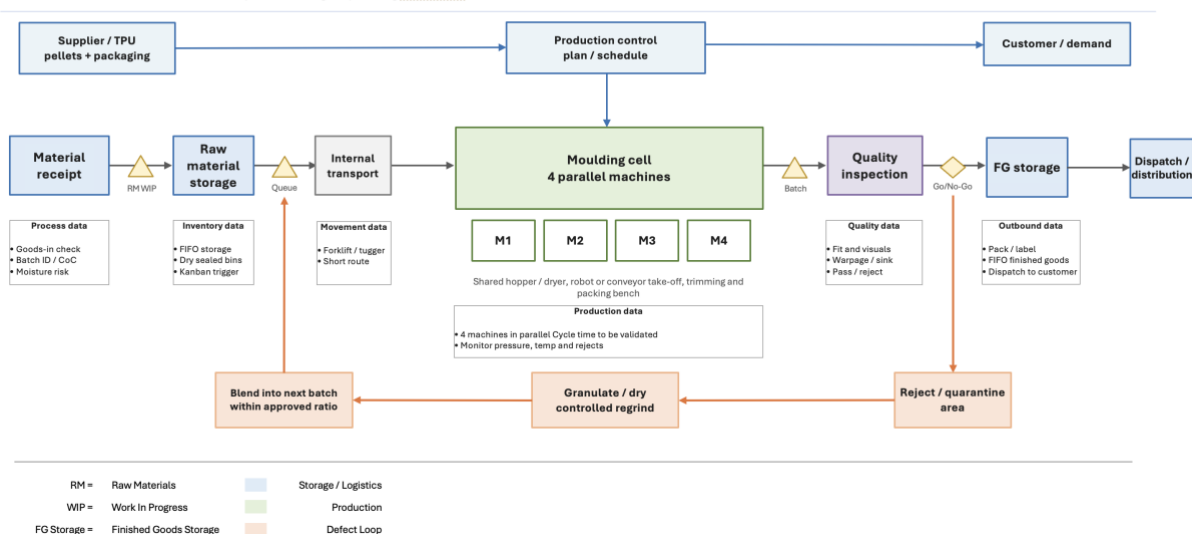


Figure 9 - Production Process VSM (Lean Principles)

Following the VSM, a Process Failure Mode and Effects Analysis was completed, as shown in [Appendix 3](#). The PFMEA evaluates each process stage against possible failure modes, causes, effects and controls. For this project, the analysis considers material receipt, storage, transport, injection moulding, inspection, rework/recycling and dispatch. This helps reduce process risk, improve repeatability and increase the likelihood of producing consistent, defect-free components during high-volume manufacture.

7 Simulation and Validation

Simulation and validation were used to reduce design risk before physical tooling by assessing moulding behaviour, predicted defects, deformation and stress in Fusion 360. The results support decision-making but require physical trial validation (Autodesk, 2026; Zienkiewicz, Taylor and Zhu, 2013).

7.1 Design of Experiments (DOE)

A DOE approach was used after CAD modelling and TPU selection to compare gate location, gate number, melt temperature, mould temperature, fill time and injection pressure against filling behaviour, weld lines, air traps, sink marks, shrinkage, warpage, flow front temperature and end-of-fill solidification. Four initial gate arrangements were compared while keeping melt and mould temperatures constant so that gate effects could be isolated. Multi-gate options improved flow balance and temperature retention by reducing flow length but introduced additional flow fronts and a higher weld-line risk (Montgomery, 2017; Autodesk, Inc., 2025).

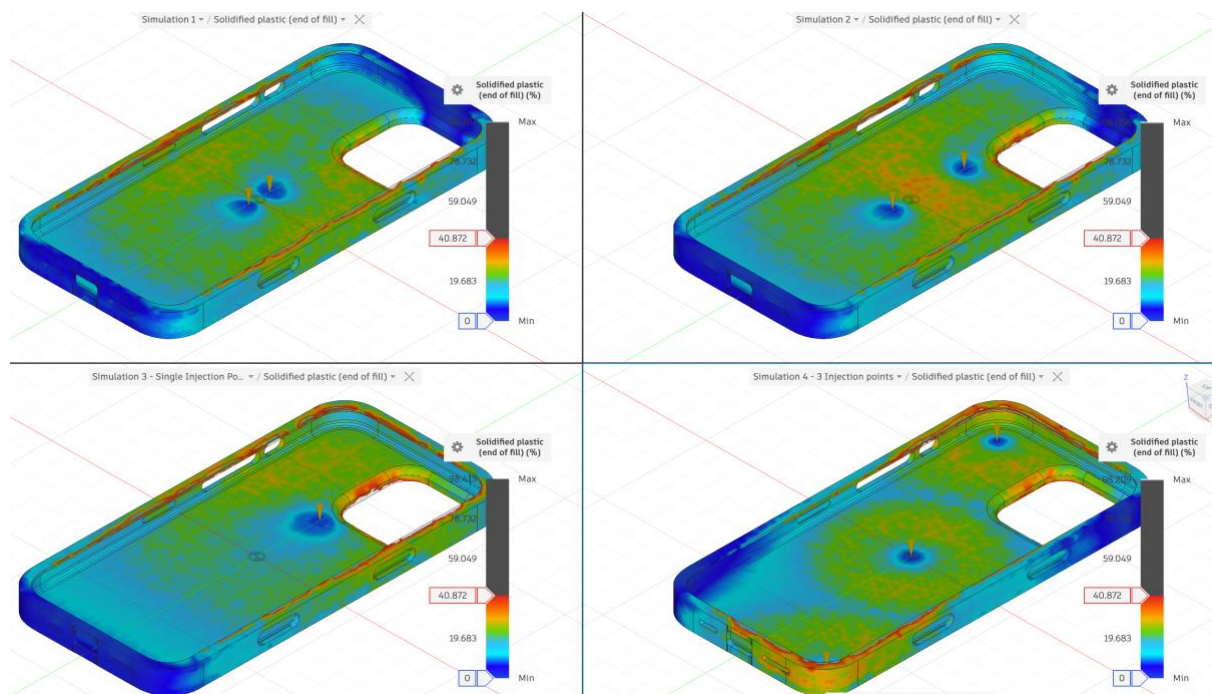


Figure 10 – Four-way comparison of solidified at end of fill metric from different gate locations

Because visible weld lines conflicted with the surface-finish requirement, the final design used a single gate. This created a longer flow path and greater risk of end-of-fill solidification, sink

marks and shrinkage, so later DOE work balanced melt/mould temperature, pressure and fill time to maintain full fill and packing while keeping the process as cool as practicable. The selected process window therefore balanced visual quality, dimensional control and manufacturability (Osswald and Menges, 2012; Rosato, 2000; Protolabs, 2020).

7.2 Finite Element Analysis

FEA evaluated mechanical performance under representative assembly/removal and in-service loads. The aim was to confirm that the TPU case could flex sufficiently during fitting and removal, while retaining enough stiffness to hold the phone securely and resist everyday compression, grip and impact loading (Zienkiewicz, Taylor and Zhu, 2013; Autodesk, 2026).

7.2.1 Assembly / Removal of phone case

Assembly and removal loads were applied to the front retaining edge, clip-on surround, corners, rear internal panel and inner side walls, as these features control elastic deformation during fitting/removal. The simulations shown in Figures 11-14 checked for excessive stress, cracking or permanent distortion and supported the one-piece TPU design without separate clips, bonded layers or additional components (Malloy, 2011; Zienkiewicz, Taylor and Zhu, 2013).

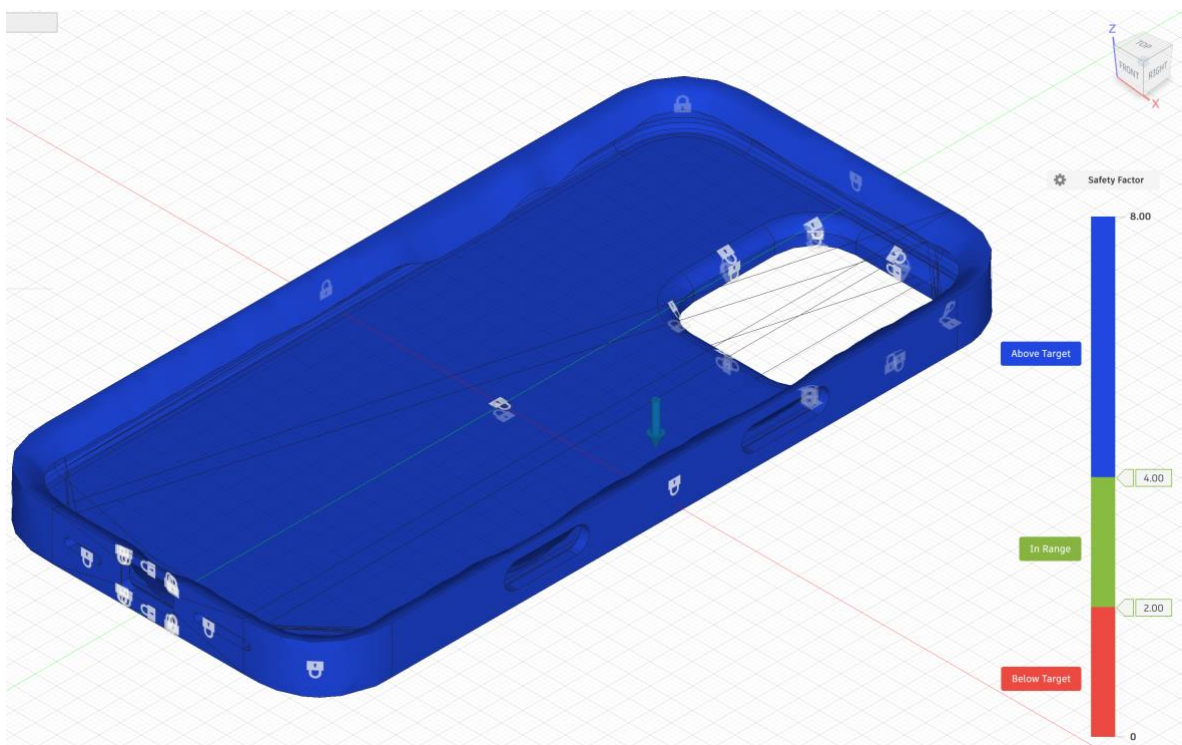


Figure 11 - Removal loading applied to front-facing retaining edge

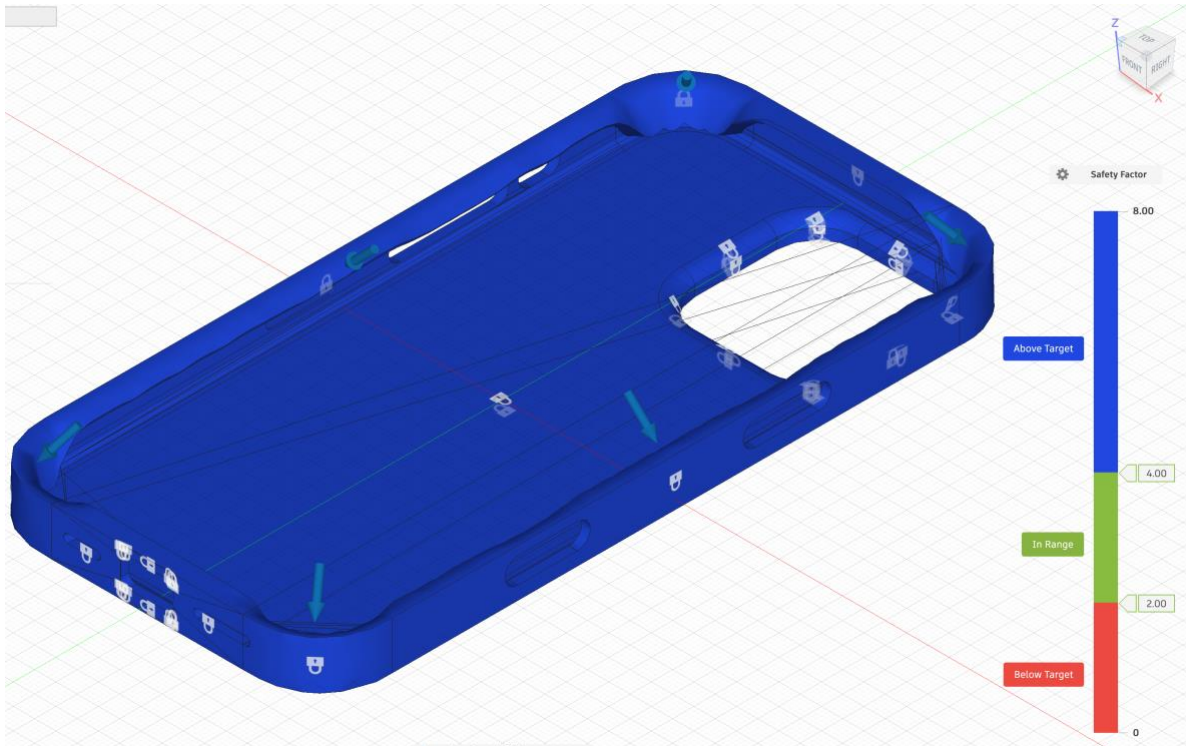


Figure 12 – Loading force applied to clip-on surround and corner regions

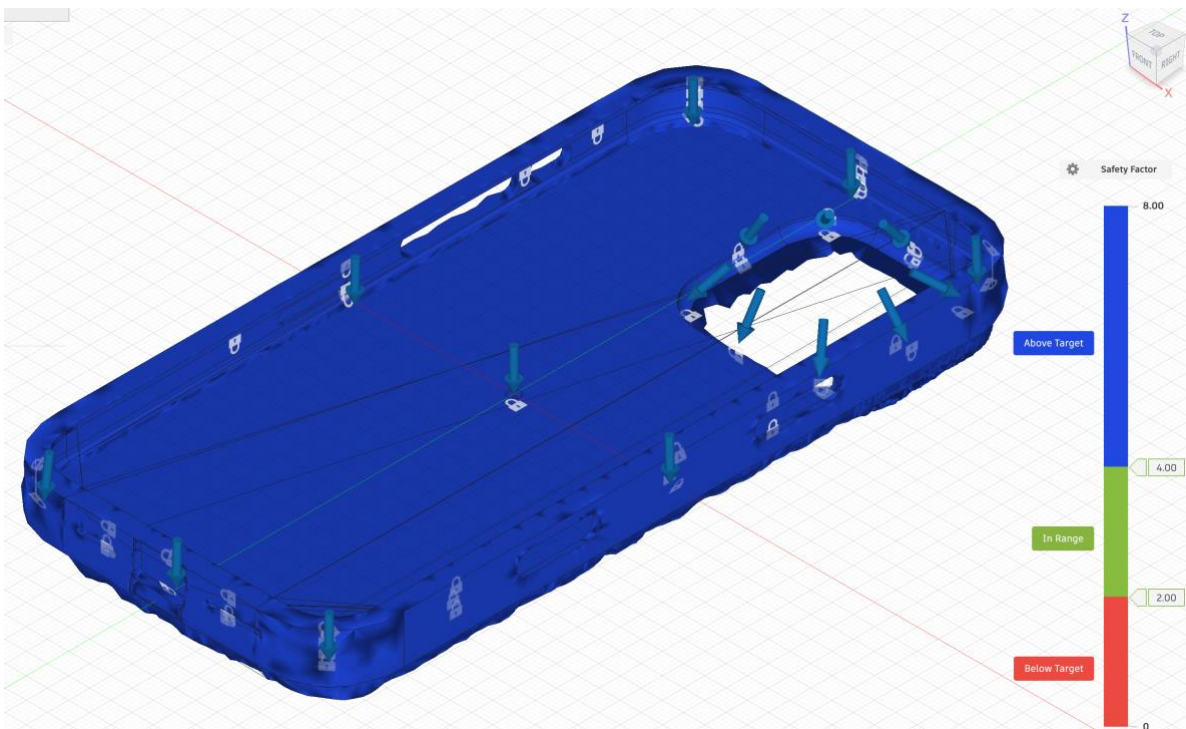


Figure 13 - Rear internal panel: downward load into the case, representing the phone being pressed into position

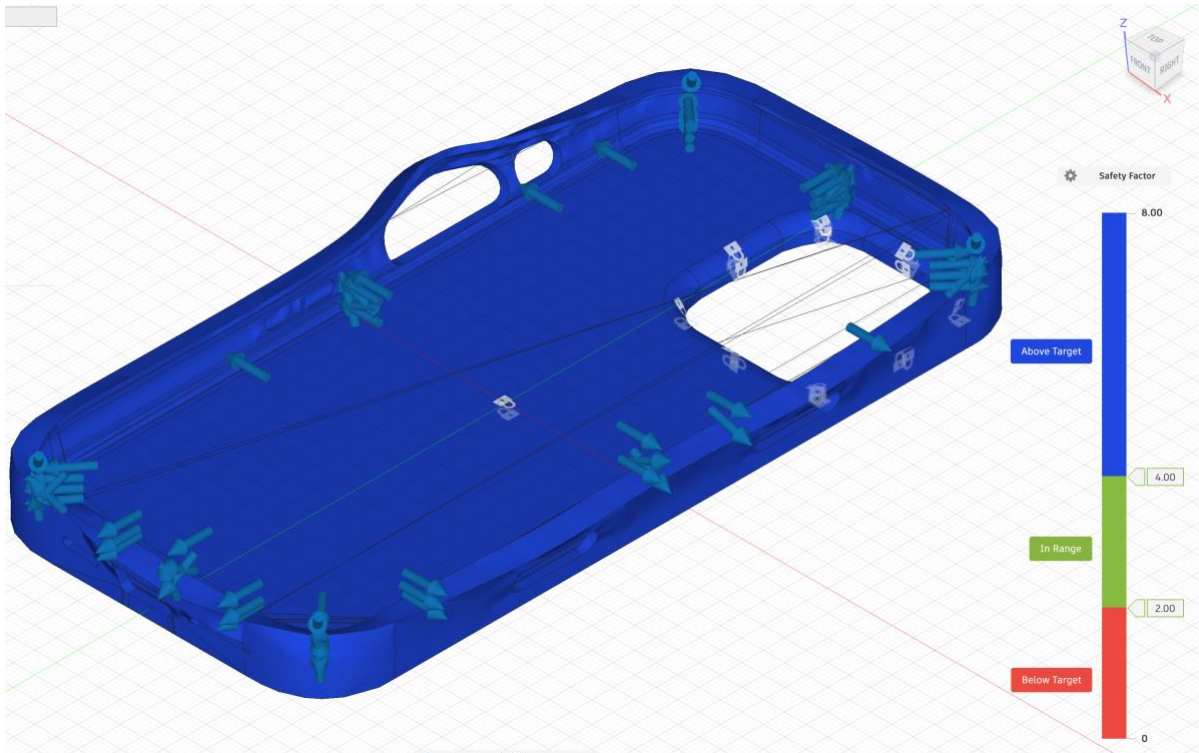


Figure 14 - Four inner corners & Long inner side walls: downward and slightly outward loading, representing corner stretching as the phone enters the case

7.2.2 In-service / day-to-day loading

In-service FEA represented pocket compression, gripping, cut-out loading and corner impact. Pocket loading used an adapted static compression equation, with body mass from 50-130 kg giving approximately 491-1,275 N full body-weight force. Load transfer factors were then applied to represent light contact through to severe pocket loading.

Equation 1 – Static Compressive Load Calculation

$F = mgk$		
F	= Force measured in Newtons	
m	= mass	50 – 130kg
g	= gravity	9.8 m/s ²
k	= proportion of body weight transferred through the phone	0.1 Light contact / 1.00 Full body weight equivalent

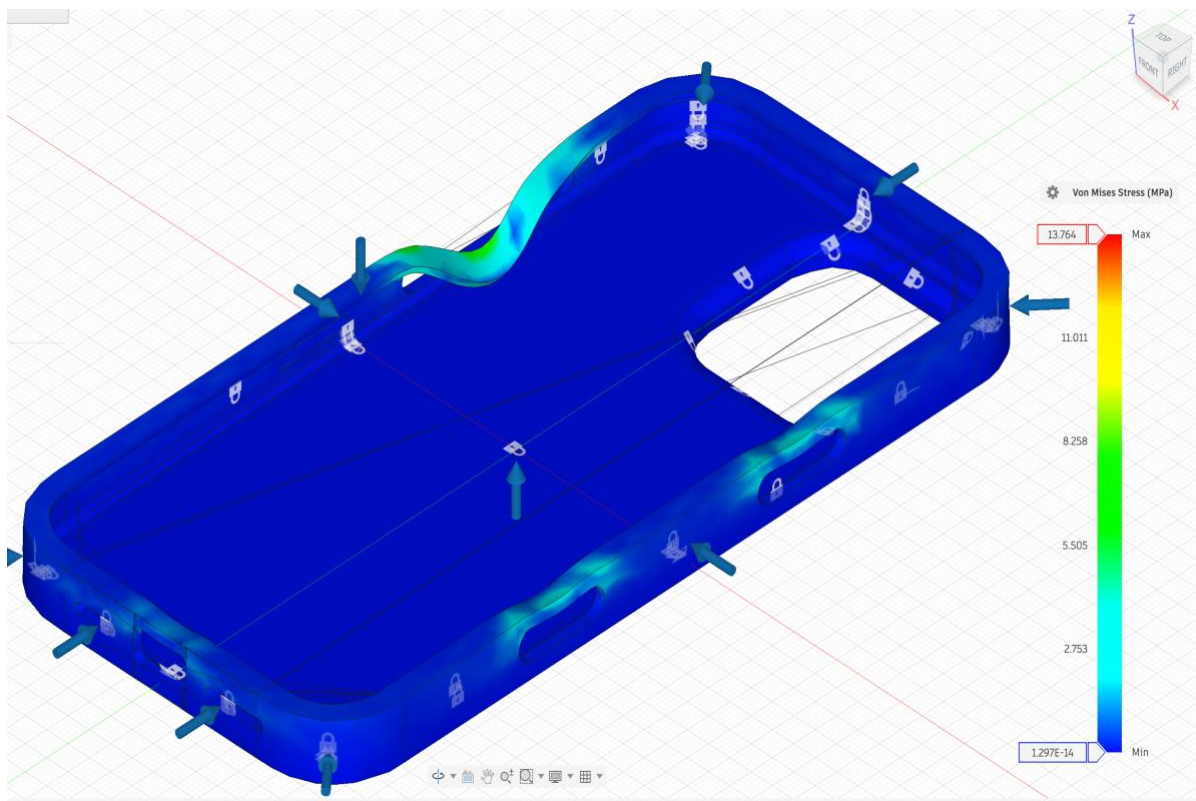


Figure 15 - All outside surface to simulate compressive loading of pocket use

Drop loading used a simplified work-energy method to estimate average impact force rather than exact peak force, allowing comparison between hard and softer impact surfaces 3,375 – 7,759N. Corner regions were prioritised because they are most likely to strike the floor during accidental drops, while apertures can create local stress concentrations. Overall, FEA supported the TPU geometry but identified the need for physical testing around corners, retaining lips, button openings, camera cut-out and charging port (Zienkiewicz, Taylor and Zhu, 2013).

Equation 2 - Simplified Work-Energy Calculation

$$F_{avg} = \frac{mgh}{d}$$

F_{avg}	= Force Average
m	= mass 227g + 44g = 271g iPhone 16 Pro Max + Mass of TPU mobile Phone Case (Apple Inc 2024, Fusion 360)
g	= gravity 9.8 m/s ²
h	=height 1 meter
d	= stopping distance 0.5mm (concrete) / 5mm Carpeted Flooring

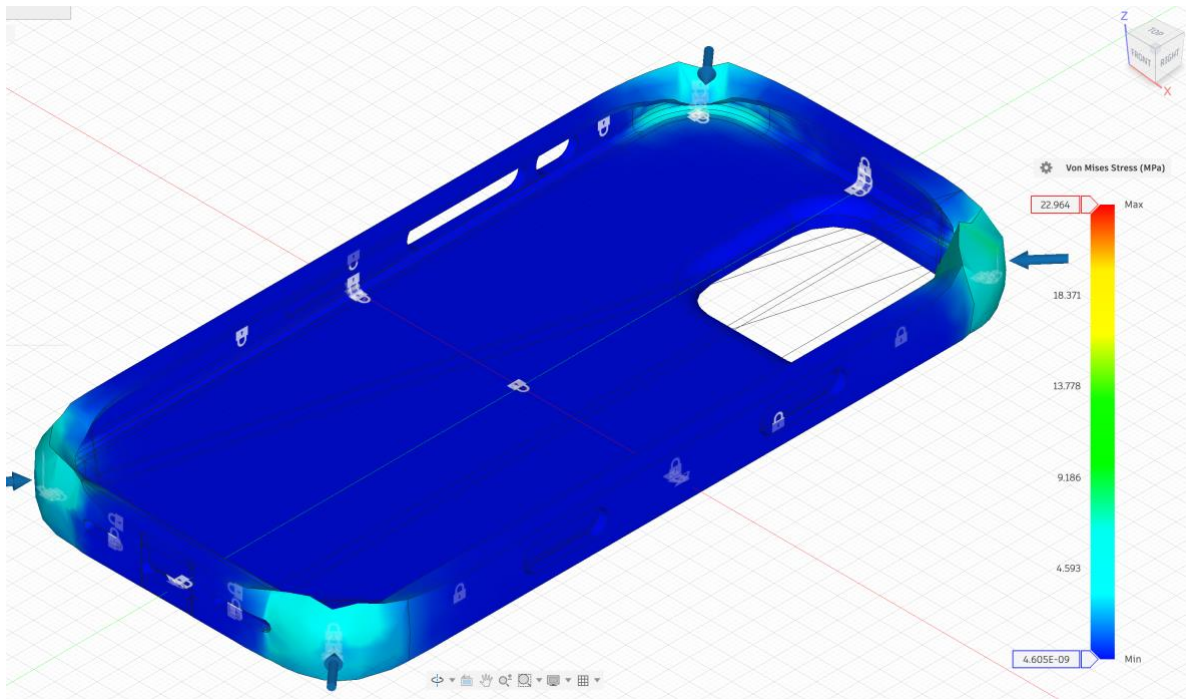


Figure 16 - Four outside corners: impact and drop loading on a hard floor like concrete.

8 Cost Calculation Analysis

The cost analysis is based on the production cell defined in Section 6 – Manufacturing Process Planning. This consist of four injection moulding machines, each with a four-cavity mould, giving 16 active cavities. The model assumes two 8-hour shifts per day and 25 employees, equivalent to 200 labour hours illustrated in Table 16 (Groover, 2020; British Plastics Federation, 2019).

Table 16 - Assumed Employee Numbers and Labour Hours

Role	Staffing Assumption	Hours Per Person/Day	Total Labour Hours/Day
Injection Moulding Operators	2 per shift × 2 shifts = 4	8	32
Material Handling	1 per shift × 2 shifts = 2	8	16
Finished Product Handling	1 per shift × 2 shifts = 2	8	16
Packaging	1 per shift × 2 shifts = 2	8	16
Distribution	1 per shift × 2 shifts = 2	8	16
Engineering: Mechanical, Electrical, Systems/PC&A	3 per shift × 2 shifts = 6	8	48
Supervisor	1 per shift × 2 shifts = 2	8	16
Manager	1 per shift × 2 shifts = 2	8	16
Admin/Support Staff	2 x day staff	8	16
Procurement/Sales	1 x day staff	8	8
Total	25 employees	—	200 labour hours/day

The assumptions for the cost analysis are outlined in Table 17. These combine academic sources, tooling and moulding references, material cost data, market assumptions, UK labour/operating costs and Fusion 360 process outputs, including fill time, injection pressure, mould temperature and melt temperature (Office for National Statistics, 2025a; Office for National Statistics, 2025b; Made-in-China, 2025; BlueBee, 2025; Rutland Plastics, 2026).

Table 17 - Assumptions used in Time and Cost Analysis

Item	Assumption Used	Justification
Part Mass	44 g per case	From Fusion 360 model.
Mould Material	Stainless steel mould, S136 or equivalent	Stainless steel has been selected to improve resistance to corrosion within cooling channels and maintain mould condition over repeated production cycles. S136 stainless steel is also associated with high tool life in injection moulding applications (Fictiv, 2022; Fictiv, 2023).
Mould Cavities	4 cavities per mould	Proposed multi-cavity mould, producing 4 cases per machine cycle.
Number Of Moulding Machines	4 injection moulding machines	Production layout includes 4 moulding machines operating in parallel.
Total Cavities In Operation	16 active cavities	4 machines × 4 cavities per mould.
Machine Cycle Time	35 seconds per mould cycle	Cycle time is based on 1.85s fill time+12s packing time+8s cooling time+14s ejection and tool reset time = Giving the assumption for a TPU phone case as 35s (Kariminejad et al., 2021; PlastFabWorks, 2026).
Shift Pattern	2 × 8-hour shifts	Morning and afternoon shift pattern.
Facility Operating Time	06:00–22:00	16 available operating hours per day.
Daily Available Time	960 minutes/day	16 hours × 60 minutes.
Setup Time	120 minutes/day	Allows for mould change, purging, parameter setup and first-off inspection.
Net Production Time	840 minutes/day	960 minutes – 120 minutes setup.
Daily Batch Quantity	23,040 cases/day	Based on 4 machines, each running a 4-cavity mould for one full 16-hour production day including setup.
UK Manufacturing Wage	£21.84/hr	Based on UK earnings assumptions informed by ONS average earnings data and converted to an hourly rate using a 37.5-hour working week (ONS, 2026).
Labour Overhead Rate	25%	Allows for employer overheads such as National Insurance, pension, holiday, administration and indirect employment costs. Employer National Insurance is 15% before other employment on-costs are considered (Department for Energy Security and Net Zero 2026; HMRC, 2026).
Labour Requirement	25 Employees	Outlined in Table 16
Machine Cost	£90,000 per machine	Assumed injection moulding machine capital cost for a suitable production cell.
Total Machine Cost	£360,000	4 machines × £90,000.
Energy / Utilities Overhead	£312,724/year	Variable cost of approx. 16% of overall Manufacturing costs
Rent / Facility Overhead	£195,451/year	Fixed Cost of approx. 10% of overall Manufacturing Costs
Machine Service Life	12 years	Assumed service life for production equipment.
Annual Operating Hours	4,000 hr/year	Approximate two-shift manufacturing operation.
Equipment Overhead Rate	60%	Allows for maintenance, utilities, floor space, insurance and indirect support.
TPU Material Cost	£4.00/kg	Mid-range industrial TPU resin assumption. (Farr, 2025; Made-in-China, 2026)
Material Allowance	+10%	Allows for runner, sprue, purge and scrap.
Tool Cost	£45,000 per stainless steel mould	Increased from the previous tool-cost assumption to reflect the higher cost of stainless-steel tooling. (Get It Made, 2025; BEC Group, n.d.; Rutland Plastics, n.d.)
Total Tool Cost	£180,000	4 stainless steel moulds × £45,000.
Tool Life	1,000,000+ shots per mould	S136 stainless steel tooling is commonly associated with 1,000,000 shots or more, supporting the use of stainless steel for a high-volume production mould (Fictiv, 2022; Fictiv, 2023).
Selling Price	£3.75 per case	Wholesale distribution selling price.

8.1 Time Analysis Calculations

At a 35 second cycle time, including setup allowance, the four-machine cell can produce 23,040 phone cases per day, as shown in Tables 18 and 19.

Table 18 - Time Analysis Calculations

Calculation	Formula Used	Substitution	Answer
Cycle time	$T_c = T_o + T_h + T_t$	Given cycle time	35 sec/cycle
Cycle time conversion	$T_c \div 60$	$35 \div 60$	0.583 min/cycle
Daily available time	$16 \text{ hr} \times 60$	16×60	960 min/day
Net production time	Available time – setup time	$960 - 120$	840 min/day

Table 19 - Production Quantity Calculations

Calculation	Formula Used	Substitution	Answer
Hourly cycle rate per machine	$R_c = 60 \div T_c$	$60 \div 0.583$	102.9 cycles/hr
Daily cycles per machine	Net production time $\div T_c$	$840 \div 0.583$	1,440 cycles/day
Daily cases per machine	Cycles $\times$ mould cavities	$1,440 \times 4$	5,760 cases/day
Total daily production	Cases per machine $\times$ machines	$5,760 \times 4$	23,040 cases/day
Average production time per piece, including setup	$T_p = T_b \div Q_b$	$960 \div 23,040$	0.0417 min/case
Average production time per piece	0.0417×60	—	2.50 sec/case
Average hourly production rate	$R_p = 60 \div T_p$	$60 \div 0.0417$	1,440 cases/hr

8.2 Cost Analysis Calculations

Tables 20-24 calculate material, labour, equipment, operating and tooling costs before combining them into the total manufacturing cost per case in Table 25 (Neagu, 2022; Ferreira, 2024; Chan, 2026).

Table 20 - Material Cost Per Piece Calculations

Calculation	Formula Used	Substitution	Answer
Part mass in kg	$44 \text{ g} \div 1000$	$44 \div 1000$	0.044 kg
Base material cost	Mass $\times$ material cost/kg	$0.044 \times \text{£}4.00$	£0.176/case
Material allowance	Base material cost $\times$ 10%	$\text{£}0.176 \times 0.10$	£0.0176/case
Total material cost per piece	Base cost $\times$ 1.10	$\text{£}0.176 \times 1.10$	£0.1936/case

Table 21 - Labour Cost Rate Calculations

Calculation	Formula Used	Substitution	Answer
Hourly wage rate	RH	Given	£21.84/hr
Labour overhead rate	RLOH	Given	25%
Labour cost rate per employee	$CL = RH \div 60 \times (1 + RLOH)$	$21.84 \div 60 \times 1.25$	£0.455/min
Number of employees	—	Given	25 employees
Total labour cost rate	$CL \times \text{employees}$	$\text{£}0.455 \times 25$	£11.375/min

Table 22 - Equipment Cost Rate Calculations

Calculation	Formula Used	Substitution	Answer
Initial equipment cost	IC	Given	£360,000
Machine service life	N	Given	12 years
Annual operating hours	H	Given	4,000 hr/year
Equipment overhead rate	RQH	Given	60%
Base equipment cost rate	$IC \div (60 \times N \times H)$	$360,000 \div (60 \times 12 \times 4,000)$	£0.125/min
Equipment cost rate with overhead	$C_{eq} = IC \div (60NH) \times (1 + RQH)$	0.125×1.60	£0.200/min

Table 23 - Work Cell Operating Cost Rate Calculations

Calculation	Formula Used	Substitution	Answer
Labour cost rate	CL	From Table 21	£11.375/min
Equipment cost rate	C_{eq}	From Table 22	£0.200/min
Work cell operating cost rate	$C_o = CL + C_{eq}$	$11.375 + 0.200$	£11.575/min

Table 24 - Tooling Cost Per Piece Calculations

Calculation	Formula Used	Substitution	Answer
Tool cost per mould	—	Given	£45,000
Number of moulds	—	4 machines × 1 mould each	4 moulds
Total tooling cost	Tool cost × number of moulds	£45,000 × 4	£180,000
Tool life per mould	—	Given	1,000,000 shots
Cavities per mould	—	Given	4 cavities
Cases produced per mould life	Shots × cavities	1,000,000 × 4	4,000,000 cases/mould
Total cases over tooling life	Cases per mould × 4 moulds	4,000,000 × 4	16,000,000 cases
Tooling cost per piece	Total tool cost ÷ total cases	£180,000 ÷ 16,000,000	£0.0113/case

Table 25 - Total Cost Per Piece Calculations

Cost Element	Formula Used	Substitution	Answer
Material cost per case	Cm	From Table 24	£0.1936/case
Operating cost per case	Co × Tp	£11.575 × 0.0417	£0.4827/case
Tooling cost per case	Ct	From Table 21	£0.0113/case
Energy / utilities cost per case	Annual energy cost ÷ annual production quantity	£312,724 ÷ 5,760,000	£0.0543/case
Rent / facility cost per case	Annual rent cost ÷ annual production quantity	£195,451 ÷ 5,760,000	£0.0339/case
Total manufacturing cost per case	Cpc = Cm + CoTp + Ct + Cu + Cr	£0.1936 + £0.4827 + £0.0113 + £0.0543 + £0.0339	£0.7758/case

8.3 Revenue and Profitability Calculations

Tables 26 and 27 estimate revenue, profit and annual financial performance.

Table 26 - Revenue and Profit Calculations

Calculation	Formula Used	Substitution	Answer
Selling price per case	—	Given	£3.75/case
Daily production quantity	—	From Table 16	23,040 cases/day
Daily revenue	Quantity sold × selling price	23,040 × £3.75	£86,407.50/day
Daily production cost	Quantity × cost per piece	23,040 × £0.7758	£17,874.43/day
Daily gross profit	Revenue – total cost	£86,407.50 – £17,874.43	£68,533.07/day
Profit per case	Selling price – cost per piece	£3.75 – £0.7758	£2.9742/case

Table 27 - Annual Production and Cost Calculations

Calculation	Formula Used	Substitution	Answer
Hourly Production Rate	—	From Table 16	1,440 cases/hr
Annual Operating Hours	—	Given	4,000 hr/year
Annual Production Quantity	Hourly rate × annual hours	1,440 × 4,000	5,760,000 cases/year
Annual Revenue	Annual quantity × selling price	5,760,000 × £3.75	£21,600,000/year
Annual Production Cost	Annual quantity × cost per piece	5,760,000 × £0.7758	£4,468,608/year
Annual Gross Profit	Annual revenue – annual production cost	£21,600,000 – £4,468,608	£17,131,932/year
Annual Fixed And Variable Overheads	Energy/utilities + rent/facility	£312,724 + £195,451	£508,175/year
Gross Profit After Fixed Overheads	Gross profit – fixed overheads	£17,131,932 – £508,175	£16,623,757/year

8.4 Break Even Point

Table 28 presents the break-even calculation. The machine and tooling investment is recovered after approximately 352,423 cases, equal to 15.29 production days at the planned output rate and £1,321,586.25 of sales.

Table 28 – Break-even Point

Calculation	Equation Used	Working	Answer
Machine investment	Given fixed capital cost	—	£360,000
Tool investment	Given fixed capital cost	—	£180,000
Energy / utilities overhead	Annual overhead cost	—	£312,724/year
Rent / facility overhead	Annual fixed overhead cost	—	£195,451/year
Total fixed and overhead cost	Machine + tooling + utilities + rent	$£360,000 + £180,000 + £312,724 + £195,451$	£1,048,175
Selling price	Market research	—	£3.75/case
Manufacturing cost per case	From revised Table 25	—	£0.7758/case
Contribution per case	Selling price – manufacturing cost per case	$£3.75 - £0.7758$	£2.9742/case
Break-even quantity	$QBE = \text{total fixed and overhead cost} \div \text{contribution per case}$	$£1,048,175 \div £2.9742$	352,423 cases
Break-even sales revenue	Break-even quantity x selling price	$352,423 \times £3.75$	£1,321,586.25
Break-even time	$QBE \div \text{daily production quantity}$	$352,423 \div 23,040$	15.29 production days

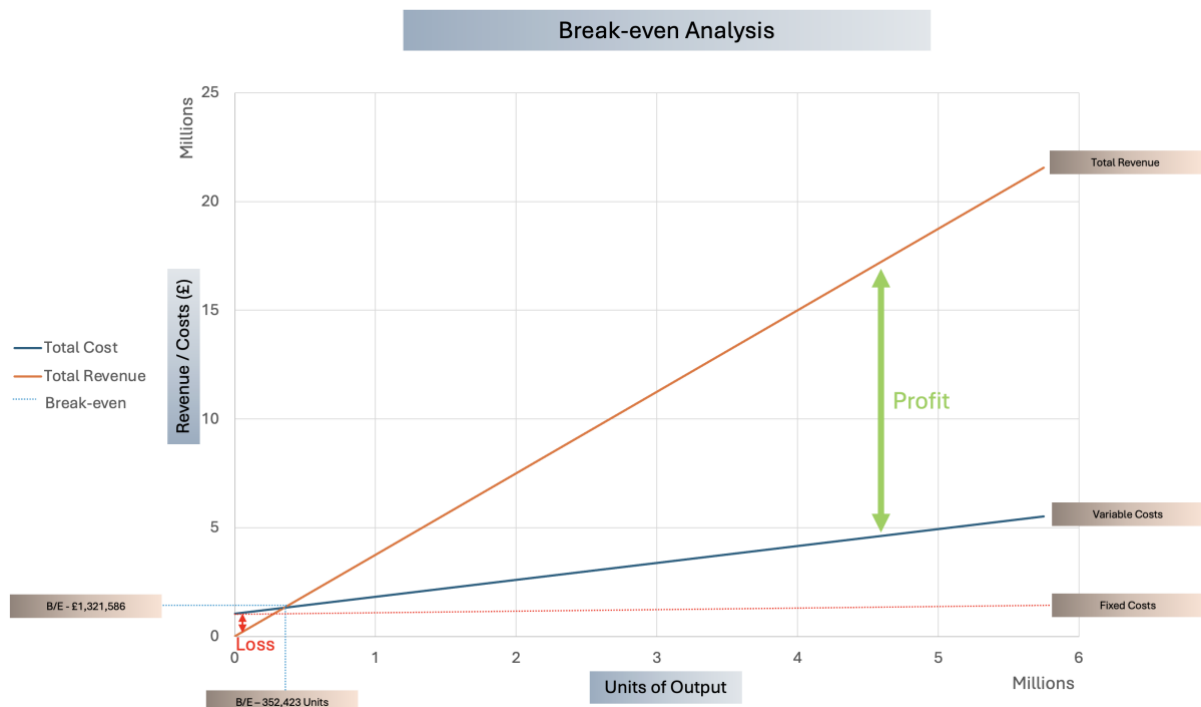


Figure 17 - Break-even illustration

9 Sustainability Considerations

Sustainability was considered from material selection through manufacture and end-of-life, rather than only as a recycling issue. Ether-based TPU is fossil-fuel derived, so its extraction and production are not fully sustainable; however, it was selected because renewable or natural alternatives did not meet the required combination of flexibility, impact resistance, durability, cost and injection moulding performance (Ashby, 2012; European Commission, 2020a; Plastics Europe, 2024).

Its main sustainability advantage is that it is a thermoplastic, meaning clean production scrap can be remelted and reprocessed where quality permits. The production process layout shown in [Section 6](#) therefore includes a rework/recycling loop for sprues, runners, cold slugs and suitable defective parts, supporting the reduce, reuse and recycle principles while reducing material waste and cost. Further reductions can be achieved by controlling melt temperature, cooling efficiency, cycle time and defect formation, as these directly affect energy use and scrap rate (British Plastics Federation and Plastics Europe, 2026; WRAP, 2022; Tangram Technology Ltd., 1999).

The facility could also improve operational sustainability through renewable or hybrid electricity supply, electrically powered handling equipment and Lean flow to reduce movement and inventory. At end-of-life, the case should be mould-marked with <TPU> and recycling code <7>. TPU does not have a dedicated recycling stream like PET, but the combined marking helps recyclers identify the product as a single-material TPU component suitable for mechanical recycling by sorting, shredding and reprocessing (ISO, 2011; ISO, 2016; GWP Group, 2023; Recycle Now, 2025).

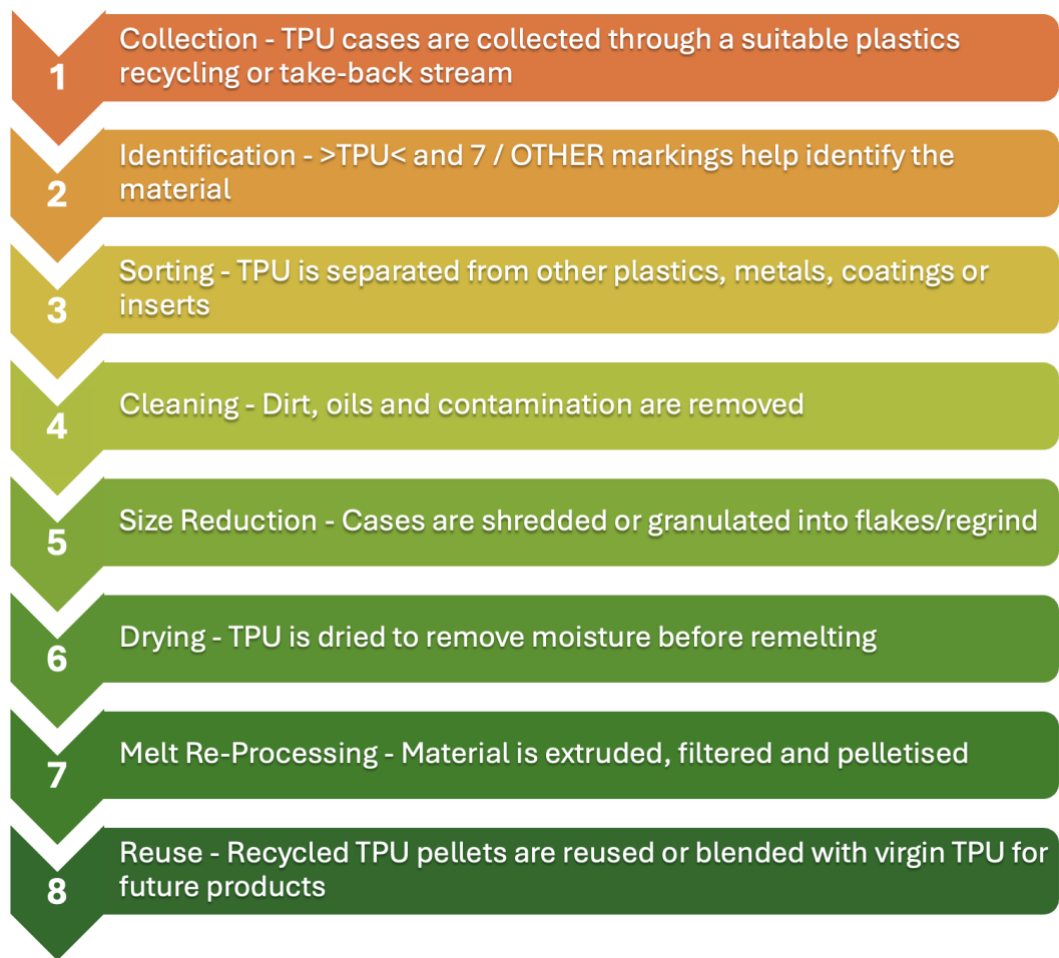


Figure 18 - Mechanical Recycling Process for TPU Products

10 Discussion and Recommendations

Ether-based TPU was selected because it provides the required balance of flexibility, impact resistance, tear resistance, grip, durability and injection moulding suitability. It meets the design specification, QFD and material selection outputs while supporting DFM/DFA through a single injection-moulded component. This avoids bonding, insert moulding, multi-shot moulding and mechanical assembly, reducing tooling complexity, cycle time, cost, energy demand, defect risk and end-of-life separation issues (BASF, 2022; Covestro, 2016; Special Chem, 2025; Boothroyd, Dewhurst and Knight, 2010).

A higher-specification design could use a rigid polycarbonate backplate with a softer TPU/TPE/TPO rim or local ribs/bumper pads, but this would increase process control, inspection, energy use and recycling difficulty. FEA indicated that the case was structurally robust under assembly, removal and in-service loading, suggesting that further material reduction may be possible. Although a 1.50 mm wall showed potential during DOE, 1.75 mm was retained as a conservative margin against repeated flexing, fatigue, TPU relaxation and loss of fit.

Initial production trials should therefore use the 1.75 mm wall before any further weight-reduction study. The moulding process was optimised around 30°C mould temperature, 235°C melt temperature, 1.85 s fill time and approximately 12 s packing time. This enabled full fill through a single gate while maintaining visual quality and dimensional control. The single gate avoids visible weld lines but requires close control of temperature, pressure, fill and packing to limit sink marks, warpage and end-of-fill defects. Predicted shrinkage was below 1%, so the mould cavity was oversized by +0.02 mm, although this must be confirmed through production trials.

Further optimisation should focus on labour efficiency, automation, cell layout, material use, runner/sprue reduction, purge control and scrap reduction. Offshore production may reduce labour cost but would increase transport distance, logistics complexity and embodied emissions. Six Sigma monitoring and operator training are recommended to improve dimensional control, defect prevention, safety, troubleshooting and continuous improvement.

11 Conclusions

The product, mould and production process were developed together to create a functional, manufacturable mobile phone case suitable for high-volume injection moulding. Ether-based TPU was selected because it provides the best balance of flexibility, impact resistance, tear resistance, grip, durability, cost and moulding performance. The single-material, single-component design supports DFM/DFA by reducing process complexity, avoiding assembly operations and improving manufacturing efficiency.

The four-cavity mould and four-machine production cell provide a high-capacity manufacturing approach, while the single-gate strategy improves visual quality by avoiding visible weld lines. DOE supported full cavity filling and dimensional control, although physical trials are required to validate shrinkage, sink marks, warpage, cooling time and long-term performance. FEA indicated that the case is structurally robust, but the 1.75 mm wall thickness was retained as a conservative choice against repeated flexing, fatigue and loss of fit.

Sustainability was considered through material selection, single-material construction, reduced assembly, potential recyclability, scrap reduction and Lean manufacturing principles. The design supports reduce, reuse and recycle principles by minimising material use, allowing suitable scrap recovery and avoiding bonded or over-moulded material combinations that complicate end-of-life handling.

The cost analysis indicates strong commercial potential, with low estimated manufacturing cost compared with the proposed selling price. However, the financial results remain an early projection and should be expanded to include packaging, transport, warehousing, tooling maintenance, quality losses, marketing, retailer margins and offshore manufacturing comparisons. Overall, the proposed TPU case meets the functional, manufacturing, cost and sustainability objectives. The next stage should be prototype testing and controlled production trials to confirm dimensional accuracy, process stability, durability and actual manufacturing cost.

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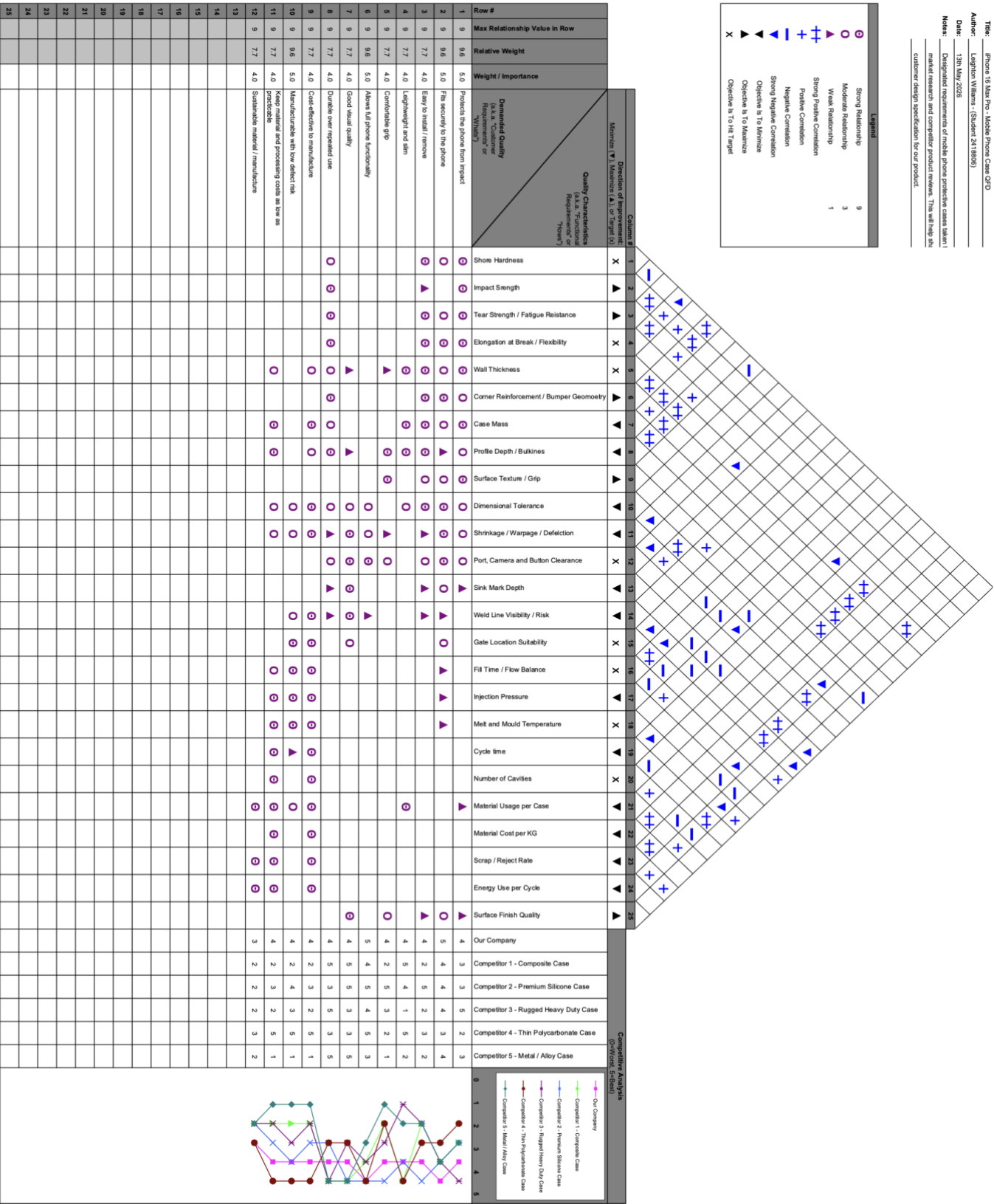
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13 Appendices

13.1 Appendix 1 – Quality Function Deployment (QFD)



13.2 Appendix 2 – Design Failure Modes and Effects Analysis (DFMEA)

DESIGN FAILURE MODE AND EFFECTS ANALYSIS (DFMEA)																
Item:	Injection moulded mobile phone protective case – Product Design				Responsibility:	Design / Manufacturing Engineering				DFMEA-IP-60K-001						
Model:	iPhone 16 Pro Max protective case				Prepared by:	Leigh Williams				DFMEA Product design						
Core Team:	Design, Process, Quality and Manufacturing Engineering				Page:	1 of 1				Scope: iPhone mobile phone case project						
DFMEA Date (Orig):	23/05/2026				Revision:	A				Prepared for:						
Function / Requirement	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Class	Potential Cause(s) / Mechanism(s) of Failure	Occ	Current Control / Detection Method	Det	RPN	Recommended Action(s)	Responsibility and Target Completion Date	Actions Taken	Sev	Occ	Det	RPN
Material selection	Incorrect material grade selected; hardness outside target range	Case may be too rigid to install/remove or too soft to protect/restrain shape; customer dissatisfaction	8	SC	Material screening incomplete; supplier data not verified; Shore hardness and elongation not balanced against impact requirement	4	Granta/CTIS material screening; supplier datasheet review; QFD trial	5	160	Define approved material grade and Shore hardness range; require CoC; test Shore samples	Materials Engineer / Design Engineer – before design freeze	Approved TPU grade and hardness range added to specification; incoming CoC and hardness checks defined	8	2	3	48
Dimensional accuracy / phone fit	Case inner dimensions too tight or too loose after moulding	Poor fit, case ditches, excessive assembly force, buttons/port/camera misalign	9	CC	Incorrect phone datum dimensions; inadequate shrinkage compensation; tolerance stack-up not completed	4	CAD model based on iPhone 16 Pro Max geometry; design review; prototype fit check	4	144	Complete tolerance stack-up; add shrinkage compensation; create go/no-go fit gauge and first article inspection plan	Design Engineer / Quality Engineer – before tool release	Tolerance stack-up completed; fit gauge and first-article dimensional check added	9	2	2	36
Wall thickness strategy	Wall thickness uneven or outside design target	Sink marks, warpage, poor tactile quality, longer cycle time, weak thin areas	8	SC	Shimness requirement over-prioritised; rib/boss/corner not balanced; poor transition radii	4	CAD section checks; DPM review; Fusion plastics simulation	5	160	Set nominal wall thickness and minimum thick section before tool release	Design Engineer – before CAD freeze	Wall thickness rules added to CAD checklist and simulations sign-off	8	2	3	48
Corner impact protection	Corner bumper/rib geometry provides insufficient energy absorption	Reduced drop protection; local cracking/heating; failure to meet customer impact requirement	9	CC	Corner geometry too thin; material damping not considered; drop test cases not reviewed	3	FEA load assumptions; QFD impact requirement; prototype drop/jumping review	5	135	Define minimum corner thickness/radius; review FEA stress areas; conduct simple drop validation on prototype samples	Design Engineer – before design validation	Minimum corner bumper rule and prototype drop check added to validation plan	9	2	3	54
Button features	Buttons covers too stiff, too soft or mispositioned	Difficult button actuation; reduced user experience; customer complaints/returns	7	SC	Button web thickness too high/low; incorrect datum; shrinkage/warpage not allowed for	4	CAD overlay; prototype functional check; dimensional inspection	5	140	Specify button actuation feel target; tune button web thickness; include functional phone fit test	Design / Quality Engineer – before design freeze	Button actuation check and sample phone validation added	7	2	3	42
Port/speaker/camera openings	Cut-outs misaligned, too small or sound restriction; camera obstruction; poor user functionality	Charging/accessory interference; reduced drop protection; local cracking/heating; failure to meet customer impact requirement	9	CC	Incorrect datum; tolerance not allocated; shrinkage ignored; tool matching tolerance not considered	4	CAD overlay with phone geometry; dimensional inspection; functional fit check	4	144	Apply tighter tolerances to CTR cut-outs; add functional gauge; verify with sample phone and cable/accessories	Design / Quality Engineer – before design freeze	Functional gauge and accessory clearance checks included in control plan	9	2	2	36
Depth angle / demoulding design	Insufficient draft or undercut areas cause deformation during ejection	Distortion, tearing, ejection marks, poor fit or tool damage	8	SC	Aesthetic surfaces prioritised over demoulding; draft omitted on thin walls; undercuts not reviewed	3	DPM review; toolmaker review; first-of visual and dimensional check	5	120	Add draft where practical; review undercuts; position ejection ways from cosmetic/critical surfaces	Tooling Engineer / Design Engineer – detailed tool design	Draft/undercut review added to tool design checklist	8	2	3	48
Gate location design	Gate location causes weak weld line or cosmetic mark in critical area	Visible blemish, weak point near line or cosmetic mark in critical area	8	SC	Gate chosen for tooling convenience; flow fronts meet across high-stress area; long flow path	4	Fusion filling simulation; mould design review; visual review of fill pattern	5	160	Move gate to lower-risk edge; assess weld-line location; use balanced runner/gate strategy for multi-cavity mould	Tooling / Process Engineer – before mould manufacture	Gate location and weld-line sign-off added to simulation review	8	2	3	48
Surface texture / grip design	Texture too smooth, too aggressive or inconsistent with material	Poor grip, poor tactile quality, scratches/contamination more visible	6		Texture not specified; mould finish not matched to TPU grade; no tactile benchmark	4	Design review; competitor/product benchmarking; prototype feel review	6	144	Specify mould texture/finish standard; approve texture plate/sample; define visual/tactile acceptance criteria	Design / Quality Engineer – before production release	Texture sample approval and visual standard added	6	2	4	48
Aesthetic design requirements	Sink-prone decorative features or sharp transitions designed into case	Visible sink/flow marks; perceived low quality; increased reject rate	7		Local mass build-up; sudden section changes; decorative detail not reviewed for mouldability	5	DPM review; Fusion sink-mark data review	5	175	Reduce thick decorative sections; blind transitions; include sink-mark acceptance criteria and simulation check	Design Engineer / Quality Engineer – before tool release	DPM checklist updated for sink-prone features	7	3	3	63
Assembly/removal durability	Case permanently deforms or tears during repeated installation/removal	Loss of retention; poor fit over time; customer complaint/return	8	SC	Material fatigue/tear strength not considered; clip lip too thin; high strain around corners	4	FEA assembly/removal load case; prototype fatigue test; material data review	5	160	Review high-strain areas; increase radii/thickness; specify repeated fit/removal cycles	Design Engineer – before validation	Repeat installation/removal validation added to test plan	8	2	3	48
Sustainability / end-of-life design	Material/design choice prevents practical recycling or increases waste	Poor sustainability performance; higher material cost/waste; weak alignment with project objectives	5		Unclear recycling route; multi-material design selected; excessive scrap due to design complexity	3	Material selection review; DPM/DFEA review; cost and sustainability comparison	6	90	Prioritise single-material TPU solution where feasible; reduce unnecessary mass; improve recyclability and scrap regain strategy	Design / Manufacturing Engineer – before final concept	Single-material DPA strategy and waste reduction notes added	5	2	4	40
Class SC – Significant Characteristic Class CC – Critical Characteristic																

13.3 Appendix 3 – Process Failure Modes and Effects Analysis (PFMEA)

PROCESS FAILURE MODE AND EFFECTS ANALYSIS (PFMEA)											
Item: Injection moulded TPU mobile phone protective case – manufacturing process			Responsibility: Design / Manufacturing Engineering			FMEA number: PFMEA-IP-6M-001			PFMEA		
Model: iPhone 16 Pro Max protective case			Prepared by: Leighton / Project Team			FMEA Type: Manufacturing process			Manufacturing process		
Core Team: Design, Process, Quality and Manufacturing Engineering			Page: 1 of 1			Scope: Mobile phone case project					
FMEA Date (Orig): 05/06/2026			Revision: B			Prepared for:					
Function / Requirement	Potential Failure Mode	Potential Effect(s) of Failure	Sev Class	Potential Cause(s) / Mechanism(s) of Failure	Occ Method	Current Control / Detection	Det RPN	Recommended Action(s)	Target Completion Date	Action Taken	Sev Occ Det RPN
Material receipt and storage	Wrong TPU grade or contaminated material loaded	Incorrect hardness/flow behaviour; poor fit, weak parts, cosmetic defects or scrap	8	Material mix-up; poor labelling; contaminated bags; unapproved supplier	4	Goods-in inspection; batch labels; material CoC; stores	5	Barcode/batch verification before loading; approved material list; quarantine non-conforming material	Process Engineer / Production – before production	Batch verification and quarantine route added	8 2 3 48
Material drying	TPU moisture content too high before moulding	Splay, bubbles, poor surface finish, degraded mechanical properties	8	Dryer temperature/time incorrect; hopped left open; dryer fault; no dew-point verification	5	Drying set-up sheet; operator check; visual inspection	5	Add dryer temperature/dew-point monitoring; SCAADA alarm for dryer deviation; record drying time and batch release	Process Engineer / Production – before SOP	Dryer monitoring and alarm limits added to control plan	8 2 3 48
Machine set-up	Incorrect process recipe selected on injection moulding machine	Short shot, flash, warpage, sink marks, dimensional variation	9	Operator select wrong recipe; uncontrolled manual changes; poor version control	4	Machine set-up sheet; first-off approval	5	Use locked approved recipe in BPCS/SCADA; password control for critical parameters; electronic change log	Process Engineer / Production – before release	Recipe lock, change log and first-off sign-off added	9 2 2 36
Melt temperature control	Melt temperature outside approved process window	Material degradation/burn marks or high viscosity/short shot; inconsistent dimensions	8	Heater band fault; incorrect barrel settings; thermocouple fault; poor alarm response	4	Machine temperature controllers; operator checks; first-off inspection	4	Set high/low temperature alarms in SCAADA/BPCS; trend barrel zones; require alarm acknowledgement and escalation	Process / Maintenance Engineer – before SOP	Temperature alarms and trend checks added	8 2 2 32
Mould temperature control	Mould temperature too high/low or uneven	Warpage, shrinkage variation; sink marks; poor surface quality; long cycle time	9	Chiller/controller fault; blocked cooling channel; incorrect setpoint; unbalanced cooling	5	Mould temp controller; first-off simulation review	5	Monitor mould inlet/outlet temperatures and flow; SCAADA alarm on deviation; planned cooling channel cleaning	Process / Tooling / Maintenance – during tool proving	Mould temperature/flow monitoring and PM task added	9 3 3 81
Injection pressure / speed	Injection pressure or speed too low/high	Short shot, burn marks, flash, high residual stress or dimensional instability	8	Incorrect setting; hydraulic/servo issue; gate restriction; operator adjustment outside window	5	Machine pressure display; first-off inspection; trial settings	4	Define process window; BPCS limit alarms for pressure/speed; trend peak injection pressure and reject correlation	Process Engineer – during mould trial	Pressure/speed limits and trend review added to control system	8 2 2 32
Packing pressure and hold time	Insufficient or excessive packing/holding	Sink marks, voids, flash, over-packed areas; poor dimensional stability	9	Poor process window; gate freeze not established; recipe drift; pressure sensor fault	5	Trial shot inspection; dimensional checks; visual inspection	5	Conduct DOE/process window study; set packing/hold limits; alarm on pressure deviation; verify gate freeze time	Process Engineer / Quality – before production approval	DOE/process window and packing pressure limits added	9 3 3 81
Cooling time / cycle time	Part ejected before sufficient cooling	Warped or distorted case; ejector marks; poor fit; increased scrap	8	Cycle time reduced to increase output; mould temp high; insufficient cooling capacity	4	Cycle time setting; first-off dimensional check; operator visual inspection	5	Lock minimum cooling time in recipe; SCAADA alarm if cycle time below approved minimum; verify part temperature at ejection	Process / Production Engineer – before ramp-up	Minimum cooling time alarm and ejection temperature check added	8 2 3 48
Venting and air escape	Poor venting causes burns, incomplete fill or trapped air	Burn marks, weak areas, poor surface finish, scrap	7	Blocked vents; inadequate vent design; contamination build-up; high injection speed	4	Visual inspection; tool maintenance; mould trial review	6	Define vent cleaning PM; inspect vents at set intervals; add burn-mark defect trigger for tool inspection	Tooling / Maintenance – during SOP	Vent cleaning schedule and trigger criteria added	7 2 3 42
Multi-cavity balance	Cavity-to-cavity variation in fill, pressure or cooling	Inconsistent dimensions/appearance; one cavity produces repeated rejects	8	Unbalanced runner; varying gate size; cooling imbalance; blocked gate/runner	4	First-off inspection by cavity; visual inspection; simulation	5	Conduct identification; SPC by cavity; balance runner gate size; alarmship rule for repeat cavity defects	Tooling / Quality / Process – tool proving	Cavity ID and SPC-by-cavity control added	8 2 3 48
Ejection system	Ejector pins damage, mark or distort the case	Cosmetic defect; poor fit; tearing/creasing; scrap	8	Ejection force too high; ejector timing wrong; insufficient draft; part sticks to tool	4	First-off visual/dimensional inspection; toolmaker review	5	Optimize ejector timing/speed; check ejector pin locations; add mould release maintenance standard if needed	Tooling / Process Engineer – during tool trial	Ejection settings and tooling checklist updated	8 2 3 48
Deburring / trimming	Burns, flash or sharp edges remain after trimming	Poor feel; phone scratching risk; cosmetic rejection; customer complaints	7	Tool wear; poor clamping; manual trimming variation; no defined flash limit	5	Operator trim; visual inspection; general visual inspection; occasional dimensional checks	4	Define flash/burr acceptance limit; provide trim fixture and edge-vel check; inspect after-of-process	Production / Quality / Tooling – before launch	Flash limit, trim fixture and edge-vel introduced	7 3 2 42
In-process quality inspection	Dimensional or cosmetic defects not detected	Non-conforming cases shipped; repeated customer complaints	8	Sampling frequency too low; unclear CTQ list; gauge not calibrated; operator fatigue	4	Operator screen alarms; production log; supervisor support	6	Create CTQ control plan; calibrated gauges; sampling frequency; detect phone standard; escalation for trends	Quality Engineer – before SOP	CTQ control plan, calibrated gauges and defect phone standard added	8 2 3 48
Control system alarm management	SCADA/BPCS alarm ignored, disabled or not escalated	Process drifts outside limits; quality defects continue until inspection catches item	8	Alarm overload; unclear response actions; permissive not configured; poor shift handover	3	Alarm response matrix; critical alarm require acknowledgement; consider interlock/permissive for critical deviations	144	Define alarm response matrix; critical alarms require acknowledgement; consider interlock/permissive for critical deviations	Process / Controls Engineer – before SOP	Alarm response matrix and critical parameter acknowledgement added	8 2 3 48
Packaging and storage	Good part scratched, discoloured or poor protected quality; customer contaminated after moulding	Scratch marks; cosmetic defects; return	5	Stacked while warm; abrasive packaging; contamination; poor handling	4	Basic packaging standard; operator handling practices	5	Allow cooling before stacking; use protective packaging; define clean handling/storage standard	Production / Logistics – before launch	Cooling-before-packaging and protective packaging standard added	5 2 3 30