

Modularity and Functional Design in Apple's Hardware and Software Architecture: Implications for Device Longevity, Supply Chains and Economic Performance

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Research Question: How does modular and functional design in Apple's hardware and software architecture enable device longevity, and what are the supply chain and economic implications?

Abstract

This research paper examines how modular and functional design within Apple's hardware and software architecture contributes to device longevity and explores the associated supply-chain and economic implications. The study first establishes the theoretical foundations of modular and functional design, highlighting their respective advantages and limitations in relation to flexibility, repairability, efficiency and user experience. It further considers the growing influence of sustainability initiatives and regulatory frameworks, including Extended Producer Responsibility and Ecodesign regulations, on product development decisions. Apple's design strategy is then analysed as a case study to assess how selective modularity and integrated hardware-software systems support long-term product relevance and operational efficiency. Findings suggest that Apple's contribution to device longevity emerges not solely from hardware modularity but also from software support and ecosystem integration. While these strategies can improve economies of scale and supply chain performance, they may also create tensions between performance optimisation, repairability and sustainability objectives

Key Words: Modular design, Functional design, Device longevity, Supply-chain efficiency, Apple ecosystem

Introduction

Modular design divides products or systems into smaller, independent units called modules, which can operate alone or collaboratively with other modules. This approach enhances adaptability and customisation, making it well-suited for industries such as manufacturing and software design (Ramalhete, 2017). Functional design creates functional architecture and solution concepts based on customer requirements to deliver the best possible user experience for products or services (Li, Li and Li, 2022). While modular and functional design pursue different objectives, both can influence device longevity through factors such as repairability, performance optimisation, software support and overall user experience. These design approaches can also influence supply chain efficiency, which refers to how effectively a company can deliver products or services while minimising costs.

Taking into account the rapid increase in e-waste – electronic waste is one of the leading contributors to global solid waste, with an estimated 62 million tonnes generated in 2022 (WHO, 2024) – governments across the globe have begun to hold manufacturers accountable by enforcing Extended Producer Responsibility (EPR) laws and other regulatory measures, applying pressure on companies to design products that extend product lifecycles and improve repairability. Apple dominates the industry with its elegant designs, strong interconnectedness among its devices, and long software lifecycles. While products like the Mac Pro are praised for their modularity and longevity, others, such as the iPhone, have occasionally faced criticism for repairability restrictions and tightly integrated designs that may limit upgrade flexibility and raise concerns about long-term sustainability (Feo, 2023). These trade-offs demonstrate the tension between performance optimisation and broader objectives involving functionality, accessibility and sustainability.

This research paper presents arguments about Apple’s use of modularity across various hardware designs and its unified software ecosystems to assist in longevity, supply-chain fluidity, and economic performance, while also recognising that these benefits are not consistent in all product lines, as Apple integrates modular aspects with intricately controlled design elements that can restrict external modifications and repairability. This research paper assesses both opportunities and challenges for Apple, providing a balanced overview.

Background

The concept of modular design in production can be traced back to Starr (1965), who proposed modular products as a novel approach to generating variety in manufacturing (Tseng, Wang and Jiao, 2018). Further research by Ulrich and Eppinger (2003) standardised modules as groups of components and described modularity as the process of breaking complex systems into logical parts that interact only within a narrow scope. It has grown into a wide range of practices instead of just one method. Consequently, the terms "module," "modularity," and "modularisation" have also become more varied and less clear over time due to their diverse usage. The literature indicates that concepts related to modular product design are applied across a wide range of industries and research contexts, leading to ambiguous interpretations and applications of the same terms (Bonvoisin et al., 2016). It is also said that modularity helps businesses reduce downtime and make repairs easier, manage materials and inventory more effectively, and take advantage of economies of scale by using uniform modules and interfaces (Gadde and Larsson, 2016). This all leads to better day-to-day efficiency and lower total cost of ownership. Product modularisation is a strategic approach that shapes product architecture in line with broader organisational goals, enabling mass customisation, environmentally friendly disposal strategies, and efficient teamwork within distributed organisational units. These components are grouped into modules on a common platform, allowing them to be applied across various product versions and supporting both cost savings and scalable customisation. Products can be assembled using ready-made modules, such as adding standard boards and cards to a PC, which are designed to be compatible and easily swapped.

Conversely, using too many shared modules across different products can reduce overall performance, since these common components might not be the best fit for each specific product (Tseng, Wang and Jiao, 2018). Modularisation can sometimes work against design for manufacturing and assembly (DFMA), since adding more parts can increase the chances of assembly mistakes. There is no widely accepted measure of a product’s modularity, nor a standard methodology to guide designers in enhancing modularity (Bonvoisin et al., 2016). Creating modular systems from the start takes careful planning and some upfront investment. Standardised interfaces and interchangeable modules can complicate the early design process, especially when working with older components or existing systems (9altitudes, 2024). It is essential to track how modules depend on one

another. Although tools such as the Design Structure Matrix (DSM) can help identify and reduce these dependencies, residual links between modules can still create unexpected maintenance issues or integration problems.

Functional design is an approach that focuses on how a system works first, before considering how it looks or how much it costs. It begins with a clear understanding of users' needs, preferences, and behaviour, enabling designers to develop interfaces and features that reflect user expectations (JD, 2025). An effective functional design system simplifies tasks and processes, enabling users to accomplish their objectives more easily by prioritising key requirements such as weight reduction, power efficiency, and overall effectiveness, often resulting in closely integrated system structures, unlike modular design, where components operate independently (Höltkä, Suh and De Weck, 2005). While this level of integration can enhance efficiency and ease of use, it conflicts with modularity by relying on coupled components rather than independent units. The interfaces required to enable this decoupling can introduce performance losses and increase material or resource use, creating a tension between the two approaches. There is an effort to optimise performance by heavily integrating components; on the other hand, there is an emphasis on flexibility by keeping components loosely separated. These objectives cannot be maximised simultaneously, requiring designers to make compromises between functionality and modularity continually.

The way product components and functions are assembled plays a significant role in a product's development, lifecycle, and its sustainable dimensions (economic, ecological, and social). This directly shapes a product's supply chain performance (Bonvoisin et al., 2016). A supply chain is the entire system of interrelated processes and entities that convert raw materials into finished goods and supply them to customers. It runs all the way back to resource extraction, manufacturing and assembly of components, logistics/transport to eventual retail sales, and delivery to the end consumer (McKinsey & Company, 2022). Modular design categorises all the elements of various products into variant and common modules that build up the core platform. In this way, it is possible to design large assortments of high-demand products by realising economies of scale (Tseng, Wang and Jiao, 2018). Functional design, on the other hand, serves to address increasingly specialised customer demands and can profoundly affect manufacturing output and product quality. However, its emphasis on tightly integrated systems may also create greater supplier dependencies and increase production complexity (Li, Li and Li, 2022). Despite pursuing different objectives, both approaches can influence supply-chain performance. Modular design can improve flexibility and scalability through standardisation, while functional design can enhance efficiency by optimising product performance and aligning systems with user requirements.

However, these design decisions are not always driven solely by the objective of maximising efficiency or profitability. Manufacturers are increasingly subject to legal and regulatory obligations that encourage the development of longer-lasting systems and seek to reduce the environmental impact of electronic waste in support of broader sustainability agendas. Extended Producer Responsibility (EPR) is a policy model that holds producers accountable for their products throughout their lifecycle, including the post-consumer phase. This specially formulated environmental policy strategy shifts the responsibility for disposing of end-of-life products from local governments and taxpayers to manufacturers who put the products on the market (UNEP, 2024). The Ecodesign for Sustainable Products Regulation (ESPR) is another regulation that aims to significantly improve the sustainability of products placed on the European market by improving their circularity, energy performance, recyclability and durability (European Commission, 2024). Such regulatory frameworks encourage longer device lifecycles, increased repairability, and reduced e-wastage, whilst also contributing to the 12th Sustainable Development Goal (SDG): "Ensure sustainable consumption and production patterns" (UN, 2025).

Apple Case Study

Modular and functional design isn't just theory; it has been implemented by several companies worldwide for decades, with one of the largest and most popular being Apple. Apple has consistently adopted a hybrid design strategy, combining modular structures for manufacturing and development with tightly integrated systems to maximise performance and user experience in a bid to maintain market leadership, product longevity, and supply chain efficiency. This case study aims to analyse the aforementioned and understand how it has contributed to the company's competitive advantage.

Apple uses elements of modular design to deliver incremental innovations continuously. With recent advances in Computer-Aided Design (CAD), modular design has seen exponential adoption due to the ability to simulate parts and modules with high accuracy and precision (Bi, 2021). Apple has divided many standardised parts into individual components, such as displays, processors, batteries and camera systems, which can be designed and developed separately before assembly into a final product (Zivkovic, 2026), although these components are not always independently upgradeable or replaceable from a consumer perspective. This approach allows Apple to accelerate product development by reusing technologies and design architectures across product families, including software interfaces and internally developed processor technologies, enabling the company to respond more rapidly to changing technological and consumer demands without restarting the design process entirely.

Although Apple incorporates certain modular elements within its products, the company generally limits user-level modularity in favour of highly integrated systems that prioritise performance, compactness and ecosystem consistency. While this approach can improve efficiency and usability, it may also reduce repairability and upgrade flexibility, demonstrating the trade-off between modular and functional design principles discussed previously.

The best implementation of modularity can be observed in the Mac Pro line. Apple's interest in modular computing dates back to 1985, when Joseph Friedman and John Fitch first led the development of a modular Macintosh project codenamed “Jonathan” (Chu, 2019). Although the project was eventually discontinued, viewed as a future concept rather than an immediate practical direction, it reflected Apple's early exploration of modular architecture. Over time, Apple shifted toward a workflow-centric approach to designing the Mac Pro to accommodate the growing diversity of professional skills and specialisations, a challenge that previous models had faced due to the classic functional and modular design trade-off discussed earlier. This led Apple to label the Mac Pro as “The most configurable Mac ever” in 2019 (Chu, 2019). The Mac Pro represents one of Apple's clearest examples of practical modularity, as users can replace or upgrade specific components rather than replacing the entire system. This can extend device longevity by reducing long-term ownership costs and allowing devices to adapt to changing professional requirements. Consequently, modular architecture can improve both product lifespan and resource efficiency.



Figure 1: Prototype of Apple's "Jonathan" modular Macintosh concept

The philosophy of functional design is evident in the way Apple integrates usability, durability, and aesthetics into a single user experience. Instead of treating design as an aesthetic issue, Apple makes the user the central focus of the process, so that every interaction is intuitive and even highly complicated operations take the slightest mental effort (Aksu, 2024). It is one of the reasons for the high brand loyalty to Apple products: users not only like the appearance of the items but also appreciate the impression that they are specifically designed to be functional and durable. Apple's software ecosystem also contributes to device longevity through extended operating system support and interconnected features that keep devices functionally relevant for longer. Consequently, longevity is influenced not only by hardware durability but also by continued software compatibility and performance. Meanwhile, its design philosophy has an effective human-centred aspect, particularly through its convenient features, including VoiceOver, Switch Control, and AssistiveTouch, which make technology more inclusive (Dey, 2024). In that manner, Apple's combination of selective modularity and highly integrated hardware-software architecture demonstrates how functional design can enhance performance and user experience while also contributing to longer device lifecycles.

Supply Chain and Economic Implications

Apple's use of selective modularity and integrated functional design extends beyond product engineering, with broader implications for both supply chain management and economic performance. While previous sections demonstrated how Apple's design architecture supports product development and longevity, these same design decisions also influence production efficiency, supplier coordination and long-term cost structures. Standardised technologies and shared product architectures can reduce operational complexity by enabling components and systems to be utilised across multiple product lines. This may create economies of scale, in which increasing production volumes lower average unit costs and improve efficiency across manufacturing and distribution processes.

Apple's investment patterns further demonstrate the long-term economic implications of the strategy. Although implementing modular and integrated systems requires substantial upfront investment in research and development, such expenditure can contribute to long-term efficiency gains. As shown in Figure 2, Apple's research and development expenses for the twelve months ending March 31, 2026, were \$40.038B, a 22.86% year-over-year increase (Macrotrends, 2026). Rather than reflecting investment in modularity alone, these expenditures support broader technological development, including reusable processor architectures, software integration and internal design systems that can later be utilised across multiple products. Such investments may initially increase production costs, but they can reduce development time and improve scalability over the long term by allowing technologies to be repeatedly adapted rather than recreated.

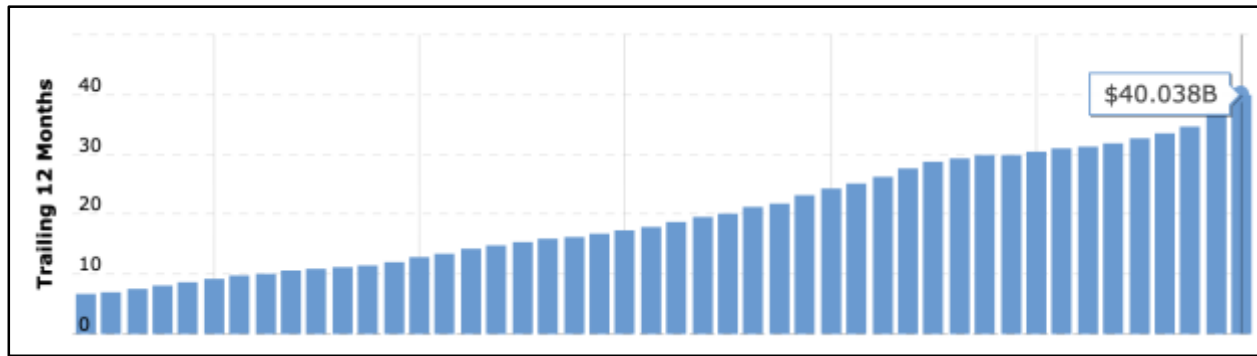


Figure 2: Apple Research and Development Expenses 2012-2026

Apple’s supply chain has also benefited from a high degree of vertical coordination and component standardisation. Reusable technologies such as internally designed processors and shared software architectures reduce supplier complexity and create more efficient production networks. As product lines increasingly share technologies and operating systems, Apple can coordinate procurement and manufacturing more effectively while reducing dependence on entirely separate development pathways. This can increase supply chain resilience by allowing faster adaptation to changes in market demand and production disruptions. Studies of Apple's global value chain suggest that the company relies heavily on coordinated supplier relationships and extensive technological integration to maintain efficiency across large-scale operations (Miller and Venugopalan, 2025).

That said, these strategies also generate economic and sustainability concerns. While integrated hardware and software ecosystems create stronger customer retention and encourage repeat purchases, they may simultaneously reduce repairability and increase dependence on proprietary components. Consumers embedded in Apple’s ecosystem often continue purchasing complementary products and services, thereby strengthening recurring revenue streams and brand loyalty. Yet critics argue that highly integrated systems may contribute to concerns regarding planned obsolescence and restrictions on independent repairs. Consequently, Apple’s design philosophy reflects a continuing trade-off between economic efficiency and broader sustainability objectives. Future regulation surrounding right-to-repair initiatives and circular economy frameworks may increasingly pressure companies to balance performance optimisation with greater modular accessibility and long-term product sustainability.

Conclusion

This research paper examined how modular and functional design principles in Apple's hardware and software architecture contribute to device longevity, while also assessing the resulting supply chain and economic implications. The study explored the theoretical foundations of modular and functional design and evaluated the advantages and limitations associated with each approach. It further considered the influence of sustainability concerns and regulatory frameworks, including Extended Producer Responsibility and Ecodesign initiatives, which increasingly encourage manufacturers to prioritise durability, repairability and responsible production practices.

The findings suggest that Apple's approach does not rely entirely on modularity but instead follows a hybrid strategy that combines selective modular elements with highly integrated hardware-software systems. While modularity can support longevity through component reuse, adaptability and more efficient development

processes, Apple's strongest contribution to device longevity appears to emerge from its integrated software ecosystem and extended operating system support, which allow devices to remain functionally relevant over longer periods. Consequently, longevity is influenced not only by physical hardware characteristics but also by continued software compatibility and ecosystem functionality.

The paper also found that these design strategies have broader implications for supply chain management and economic performance. Reusable technologies and coordinated design architectures can contribute to economies of scale, streamline manufacturing processes and support long-term operational efficiency. However, the same tightly integrated systems that enhance performance and strengthen consumer retention may also reduce repairability and create concerns regarding sustainability and consumer accessibility. Therefore, in answering the research question, Apple's modular and functional design architecture enables device longevity only to a certain extent, as its benefits are ultimately balanced against trade-offs involving flexibility, repairability, and long-term sustainability.

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