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ARCHITECTURAL CAPITAL: A MODERN FRAMEWORK FOR ADDRESSING CONSUMER DISSATISFACTION AND UTILITY STAGNATION

Momchil R. Rusev

Abstract: This paper investigates a paradox of the early twenty-first century: despite rapid technological acceleration, consumer utility, satisfaction, and long-term sustainability have not increased proportionally. Building on Romer's theory of endogenous growth, the study introduces the concept of Architectural Capital (ArchCap) – a systemic property that captures the degree to which technological knowledge (ATech) is organised into a coherent, predictable, sustainable, and maintainable product architecture. ArchCap is operationalized through four analytical components: cognitive load, repairability and maintainability, total cost of ownership, and architectural coherence.

Empirical evidence shows that products with moderate technological density but high architectural capital – such as the Ford Model T, Volkswagen Beetle, FIAT 124/Lada 2101–2107, and early-generation iPhones – achieve higher real utility, lower ownership costs, and greater long-term sustainability than many contemporary devices with far higher ATech. These findings reveal a phenomenon of architectural entropy, in which escalating complexity nullifies a significant share of the value generated by technological knowledge.

The paper argues that architectural capital is the missing structural parameter in contemporary growth models and should be integrated into regulatory frameworks as a criterion for systemic sustainability, maintainability, and consumer safety. ArchCap is proposed as an analytical filter for evaluating innovations, public policies, and R&D strategies, ensuring that technological progress is translated into genuine economic and societal benefit.

Keywords: Architectural Capital; Architectural Integration; Endogenous Growth; Total Cost of Ownership (TCO); Architectural Entropy; Cognitive Load; Systemic Innovation; Regulatory Design

JEL codes: O31; O33; O38; L62; L15; L52; R41

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Introduction

Over the past two decades, technological industries have exhibited a clear paradox: despite accelerating technological progress, consumer utility, satisfaction, and perceived value are not increasing proportionally. In many sectors – automotive, household appliances, consumer electronics, and digital interfaces – users increasingly experience frustration, cognitive overload, and declining predictability, even as the number of available features grows. Eurostat data confirm that European households consistently spend more while obtaining nearly the same functional utility from many categories of goods (Eurostat, 2024; Dataset TEC00134).

This phenomenon is not nostalgia, but a structural signal. The underlying problem is architectural: the insufficient organisation and integration of existing technologies into coherent, predictable, sustainable, and repairable product systems. In other words, the issue is not the lack of technological knowledge (ATech), but the lack of architectural integration and architectural capital.

Everyday examples illustrate this clearly:

- vacuum cleaners requiring Wi-Fi to clean;
- washing machines offering 24 programmes while households typically use 3–4;
- cars in which adjusting the ventilation speed requires several steps through a touchscreen – distracting the driver – rather than an intuitive mechanical knob that can be operated without looking;
- smartphones whose interfaces change faster than users can learn them.

These symptoms reflect a pattern of *technological inflation*, where the accumulation of features outpaces the system's ability to integrate them into meaningful, long-term utility.

It should be noted that the historical examples included herein – ranging from the Ford Model T to the FIAT 124/Lada platform and early-generation iPhones – are not intended for a direct technological comparison with contemporary alternatives. Instead, they serve to illustrate how an optimal architectural configuration (High ArchCap) maximises systemic utility and product longevity based on the technology available at the time. The fact that some of these platforms remained in production for decades or continue to be operational today is a primary empirical indicator of their high architectural capital.

1. Historical Counterpoint: Periods When Architecture Dominated Technology

History offers multiple examples where architectural simplicity and systemic honesty produced mass utility. It is no coincidence that the *Ford Model T, Volkswagen Beetle*, and *FIAT 124/Lada 2101–2107* occupy leading positions among the best-selling vehicles of all time.

These systems share several architectural qualities:

- minimal internal complexity;
- clear, intuitive system logic;
- very low cognitive load;
- high repairability and maintainability (RE), mechanical robustness, and durability;
- harmonised engineering parameters;
- low total cost of ownership (TCO).

These products were not the most technologically advanced; they were the *best-assembled.* In the digital era, the early *iPhone* plays an analogous role: not the strongest hardware, but the most coherent architecture (Isaacson, 2011; IEEE Computer Society, 2010; IEEE Mobile Hardware Survey, 2010).

These examples confirm a universal principle: *architectural simplicity and coherence can outperform pure technological accumulation* across different technological epochs.

2. The Gap Between Technological Progress and Utility

Modern growth and innovation theories – including Romer's endogenous growth model – treat knowledge as the primary driver of productivity. Yet these models typically do not distinguish between:

- the *quantity of technological knowledge (ATech)* and
- the *quality of its systemic organisation into functional architectures.*
- This results in a widening gap between:
- the exponential growth of technological capabilities, and
- the linear or stagnating growth of user-perceived utility.

3. From Architectural Integration to Architectural Capital

To address this gap analytically, the present paper introduces the concept of *Architectural Capital (ArchCap)* – a systemic resource that explains how technological knowledge is transformed into real consumer and societal utility.

The relationship can be described as follows:

- *Architectural Integration (Arch)*: describes the engineering processes of assembling components.
- *Architectural Capital (ArchCap)*: captures the economic value generated by a well-assembled, coherent, sustainable system.

Thus, ArchCap bridges engineering practice and economic theory.

4. The Systemic Nature of Consumer Dissatisfaction

Consumer dissatisfaction is not an emotional or behavioural anomaly. It is a *systemic symptom of architectural deficit*, reflected in:

- increasing cognitive load (CLS);
- reduced predictability and reliability, architectural coherence (ACI);
- higher TCO;
- shorter product lifecycles;
- functional inflation with diminishing returns.

Poorly designed systems shift architectural complexity onto the user, increasing cognitive load and creating the illusion of 'user error' where the problem is fundamentally systemic (Norman, 2013).

In systemic terms*: technological capabilities expand, but architectural capital fails to integrate them into real, stable utility.*

5. Purpose of the Study

This article aims to:

1. operationalise ArchCap through four components (CLS, RE, TCO Ratio, ACI);
2. demonstrate the causal relationship between ArchCap and long-term utility;
3. show that architectural entropy can neutralise technological investments;
4. propose a regulatory and analytical framework that incorporates ArchCap into innovation policy.

6. Contribution

- The paper provides a structured analytical tool for understanding why historically successful systems delivered high utility with limited technology.
- It extends Romer's growth model by introducing a missing structural parameter linking knowledge to utility.
- It offers actionable insights for engineers, policymakers, technologists, and investors on how to reduce complexity, improve coherence, and increase the total social value of innovation.

Theoretical Framework and Literature Review

This section develops the conceptual basis the study and positions Architectural Capital (ArchCap) within existing economic and engineering theory. It synthesises insights from endogenous growth theory, the economics of knowledge, engineering design, modularity theory, and cognitive ergonomics. Its objective is to define ArchCap as a measurable systemic parameter that links technological knowledge (ATech) to real utility.

1. Knowledge and Endogenous Growth: Romer's Framework

Paul Romer's (1990) endogenous growth theory conceptualises knowledge as a non-rival input with increasing returns, capable of driving long-term growth. In this framework:

- ideas expand the production possibilities frontier;
- human capital accumulates through learning and innovation;
- technological knowledge (ATech) enables productivity gains.

However, Romer does not specify *how* technological knowledge becomes *usable* within complex systems. The theory treats knowledge as a homogenous input, abstracting from the architecture that embeds it in real products.

Thus, Romer provides:

- the *engine* (knowledge-driven growth),
- but not the *transmission system* (the architecture translating knowledge into utility).

This omission becomes critical in industries with escalating complexity, where misaligned architectures neutralise the potential of accumulated knowledge.

2. Architectural Thinking in Engineering and Design

Engineering science has long recognised the importance of architecture in complex systems. Baldwin & Clark's *Design Rules* (2000) demonstrates that modularity increases flexibility, reduces risk, and improves maintainability. Simon (1962) highlights the near-decomposability of complex systems as crucial for stability. Complex systems remain manageable and adaptive only when their architecture allows for near-decomposability into subsystems with limited interdependencies, making architecture a central determinant of system stability (Simon, 1962). Ashby's Law of Requisite Variety states that a system can remain stable and controllable only if its internal architecture provides sufficient variety to absorb and regulate external and internal complexity; otherwise, complexity overwhelms control (Ashby, 1956). Parnas' principle of information hiding shows that modular architectures protect systems from complexity and future change by isolating design decisions and preventing unnecessary propagation of complexity across subsystems (Parnas, 1972).

These works converge on the principle that *architecture determines system behavior* independent of component-level technological sophistication.

Key insights include:

- architecture governs interactions among modules;
- poorly designed interfaces cause cascading failures;

- complexity grows non-linearly with the number of components;
- design coherence determines maintainability and lifecycle costs.

However, engineering literature typically does not quantify the *economic* value created by coherent architecture. This is precisely where ArchCap contributes.

3. The Economics of Complexity and Consumer Frustration

Kahneman (2011) shows that human cognition operates under strict capacity limits, and that as informational and decision complexity increases, judgment quality and decision accuracy systematically deteriorate. Recent studies (Engström et al., 2005; Kahneman, 2011; Norman, 2013) show that cognitive overload reduces user performance, satisfaction, and productivity. Human cognition is subject to strict limits, whereby increased complexity and informational load systematically impair judgment and decision-making quality (Kahneman, 2011). In economics, Chobanova (2012) emphasises the role of knowledge organisation – not only knowledge quantity – in shaping functional outcomes and innovative capacity.

These findings align with the central proposition of the present study:

Utility depends not on the technological frontier itself, but on the quality of its architectural embedding.

Thus, technological progress does not automatically generate proportional gains in consumer welfare.

4. Defining Architectural Capital (ArchCap)

Architectural Capital is defined as: *the systemic value created when existing technological components are assembled into a coherent, predictable, low-friction, sustainable and repairable product architecture.* In this paper, sustainability is used as a system-level property referring to long-term functional viability and lifecycle stability, while maintainability and repairability denote specific engineering attributes related to serviceability.

ArchCap differs from ATech in several ways:

Dimension	**Technological Knowledge (ATech)**	**Architectural Capital (ArchCap)**
Nature	Component-level or algorithmic knowledge	System-level organisation and integration
Returns	Potentially high, but unstable	Stable, compounding, utility-generating
Risks	Obsolescence, feature inflation	Architectural entropy
Value Realisation	Requires integration	Converts ATech into real utility

ArchCap is operationalsed through *four analytical components:*

1. *Cognitive Load of the System (CLS)* – the total mental effort required for operation, troubleshooting, and learning.
2. *Repairability and Maintainability (RE)* – accessibility, durability, maintainability, and lifecycle continuity.
3. *Total Cost of Ownership (TCO Ratio)* – direct and indirect long-term costs borne by the user.
4. *Architectural Coherence Index (ACI)* – the internal logic, predictability, and consistency of subsystem interactions.

Together, these parameters capture the systemic qualities that determine real-world utility.

5. ArchCap as the Missing Parameter in Growth Models

By integrating ArchCap into the endogenous growth framework, we obtain:

- a mechanism explaining why technological progress sometimes yields stagnant utility;
- a structural explanation of *architectural entropy*;
- a bridge between engineering design and macroeconomic outcomes.

ArchCap transforms Romer’s abstract knowledge into a concrete, measurable economic resource.

It also provides a foundation for evaluating innovation policies and regulatory standards.

6. Synthesis

The theoretical analysis demonstrates that:

1. Knowledge is necessary, yet insufficient, for utility.
2. *Architecture determines utility, costs, and sustainability in complex machines and systems.*
3. Romer’s growth model can be extended through ArchCap.
4. Engineering theories of modularity provide a basis but do not address economic value realisation.
5. Contemporary regulation requires architecture-oriented analytics.

Therefore, *ArchCap is proposed as a new systemic parameter* – a bridge between endogenous growth theory, knowledge economics, engineering design, and regulatory policy.

Methodology and Research Design

The purpose of the methodology is to operationalise the concept of Architectural Capital (ArchCap) and to establish a structured analytical pathway for evaluating the relationship between technological knowledge (ATech), product architecture, and realised utility. Given the interdisciplinary nature of the study – spanning economics, engineering, consumer behaviour, and regulatory analysis – the methodological design integrates qualitative and quantitative components.

1. Conceptual Operationalisation of ArchCap

ArchCap is operationalised through a framework composed of four analytical dimensions. For analytical clarity, each dimension is subsequently referenced using its acronym (CLS, RE, TCO, ACI):

1. *Cognitive Load of the System (CLS)* – architectural attributes capturing the mental effort required to operate, maintain, and learn a system. Indicators include number of steps for key operations, interface consistency, error rates, recovery time, and intuitive discoverability.
2. *Repairability and Maintainability (RE)* – serviceability-related attributes assessing structural accessibility, part modularity, repair pathways, component durability, and compatibility across generations. Includes regulatory proxies such as Right-to-Repair indices and EcoDesign requirements.
3. *Total Cost of Ownership (TCO Ratio)* – lifecycle cost attributes reflecting long-term consumer costs, including maintenance, depreciation, consumables, energy use, and forced obsolescence. The TCO Ratio compares purchase price to lifetime value delivered.
4. *Architectural Coherence Index (ACI)* – structural alignment attributes capturing the predictability and consistency of interactions between subsystems. Includes dependency minimisation, interface clarity, and harmonised parameter behaviosr.

Together, these dimensions capture the cognitive, serviceability, economic, and structural qualities through which Architectural Capital translates technological knowledge into stable real-world utility.

These dimensions collectively form the *ArchCap Systemic Map*, which is used as the primary analytical instrument throughout the present study.

2. Analytical Approach

The research design employs a *comparative multi-case methodology*, structured within three categories:

1. *High-ArchCap historical systems.* Examples: the Ford Model T, Volkswagen Beetle, FIAT 124/Lada 2101–2107. These products provide reference points for architectural simplicity and coherence.
2. *Modern systems with high ATech but low ArchCap.* Examples: selected modern vehicles, home appliances, and consumer electronics exhibiting functional overload, increased CLS, or reduced repairability.
3. *Hybrid systems where architecture amplifies technology.* Example: the early-generation iPhone (2007–2013), where architectural integration compensates for moderate hardware specifications.

This comparative structure enables the identification of causal mechanisms, not merely correlations.

3. Data Sources

The study draws from multiple categories of sources:

- *Official data* from UNECE, Eurostat (Dataset TEC00134), OECD, FAA, ISO.
- *Engineering documentation* from automotive and electronics manufacturers (e.g., Avtoexport USSR, 1977).
- *Peer-reviewed literature* on design theory, cognitive ergonomics, and modularity.
- *Industry datasets* (IEEE Mobile Hardware Survey, Consumer Reports, IFixit Repairability Index).
- *Empirical tests and secondary analyses*, including historical measurements of braking performance and contemporary testing of upgraded components (2020–2025).
- *Model-based estimations* for TCO and CLS derived from validated frameworks.

All data sources are triangulated to increase validity and reduce measurement bias.

4. Comparative Architecture Analysis (CAA)

Ulrich (1995; Ulrich & Eppinger, 2016) formalises the concept of product architecture and introduces systematic methods for mapping functional elements to physical components, making explicit interdependencies, coupling, and architectural trade-offs, as well as allowing for their analysis.

To assess the architectural structure of systems, the study introduces the *Comparative Architecture Analysis (CAA)* method, which includes:

- *functional decomposition* of the system;

- *interface mapping* between components;
- *complexity profiling* (number of components, number of interaction pathways);
- *cognitive-path count* for core operations;
- *modularity vs. coupling index* analysis;
- *failure-mode mapping* (how local failures propagate).

CAA allows for systematic comparison across systems with different historical origins and technologies.

5. CLS, RE, TCO, and ACI Measurement Procedures

(1) CLS Measurement

CLS is measured through:

- step-count analysis for key tasks,
- interface consistency scoring,
- interaction predictability,
- user error frequency, and
- redundancy of pathways.

A lower CLS score indicates a more efficient, user-friendly architecture.

(2) RE Measurement

RE evaluates:

- physical accessibility of components,
- number of modules requiring removal for common repairs,
- availability of spare parts,
- sustainability of materials, and
- lifetime repair cost.

Higher RE indicates structural support for long-term utility and reduced environmental impact.

(3) TCO Ratio Calculation

TCO Ratio includes:

- purchase cost,
- maintenance over lifecycle,
- consumables,
- energy use,
- degradation curve, and
- forced obsolescence for reasons related to architecture.

Systems with a high TCO Ratio relative to utility exhibit signs of architectural entropy.

(4) ACI Scoring

ACI scores the internal logic of the system through:

- consistency of subsystems,
- alignment of mechanical and digital interfaces,
- predictability under stress, and
- internal conflict resolution (absence of contradictory behaviours).

High ACI indicates stability, predictability, and reduced error propagation.

6. Validity and Reliability

The methodology ensures:

- *construct validity*, by grounding ArchCap in established engineering and economic theories;
- *internal validity*, through cross-case triangulation;
- *external validity*, using historically and globally recognised systems;
- *reliability*, by defining repeatable measurement criteria for CLS, RE, TCO, and ACI.

7. Limitations

As with many interdisciplinary frameworks, the ArchCap model has limitations:

- some measures (e.g., CLS) involve subjective components;
- repairability data varies across industries;
- long-term TCO is sensitive to context;
- architecture scoring depends on system documentation.

Nevertheless, the triangulated design mitigates most risks.

8. Summary

The methodology provides a robust analytical structure for evaluating Architectural Capital across diverse systems. It establishes measurable parameters, standardises comparison, and ensures that results are interpretable within both engineering and economic frameworks.

Architectural Capital: Mechanism and Systemic Function

This section explains how Architectural Capital (ArchCap) transforms technological knowledge (ATech) into real, long-term consumer and societal utility. While ATech expands the frontier of what is technologically possible, ArchCap determines how much of this potential becomes accessible, predictable, sustainable, and economically meaningful.

The mechanism is presented in four stages, corresponding to the four analytical components of ArchCap: cognitive load (CLS), repairability and maintainability (RE), total cost of ownership (TCO Ratio), and architectural coherence (ACI), which together determine the sustainability and realised utility of the system.

1. Stage 1: Technological Knowledge (ATech)

Technological knowledge provides the *building blocks* for innovation – algorithms, mechanical components, materials, sensors, interfaces, and software modules. However, in complex systems, knowledge alone does not determine utility.

ATech contributes to utility only when:

- it is *accessible* to the user,
- it interacts *predictably* with other components,
- it does not introduce *excessive cognitive or operational burden*, and
- it supports a *manageable and sustainable lifecycle*.

Without proper architectural organisation, accumulated ATech may lead to diminishing returns, cognitive overload, and rising TCO – phenomena described in this paper as *architectural entropy*.

The proposed theoretical framework can be synthesised through the conceptual model presented in Figure 1. The model illustrates the role of Architectural Capital (ArchCap) as a moderating factor that determines the extent to which technological knowledge (ATech) is transformed into real utility and sustainable endogenous growth.

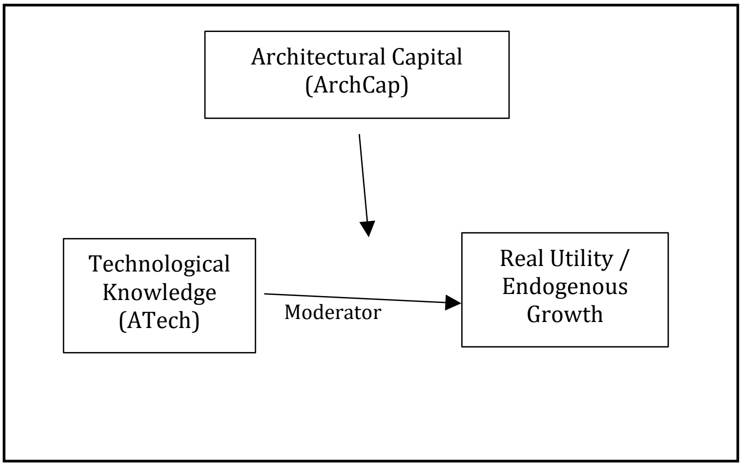

Figure 1. Conceptual mechanism of Architectural Capital as a moderator between technological knowledge (ATech) and realised utility

2. Stage 2: Architectural Integration (Arch)

Architectural Integration is the engineering process through which technological components are assembled into a system. It includes decisions about:

- system structure;
- modularity and component boundaries;
- interface design;
- control logic consistency;
- interaction pathways between subsystems;
- repairability and maintainability;
- maintainability and lifecycle alignment.

Good architectural integration minimises unnecessary coupling, maintains internal logic, and reduces friction – whether mechanical or cognitive. Poor integration amplifies complexity and increases error propagation.

Arch is necessary but not entirely sufficient. It provides the *engineering substrate* upon which architectural capital is built.

3. Stage 3: Architectural Capital (ArchCap)

Architectural Capital is the *value added* when architectural integration is executed with systemic coherence, user-centered logic, sustainability, and long-term lifecycle efficiency. It determines how effectively ATech is converted into real-world outcomes.

The core proposition:

ArchCap moderates the relationship between ATech and utility.

High ArchCap:

- increases utility without requiring constant technological escalation;
- stabilises product behaviour;
- reduces user errors and frustration;
- lowers the cognitive burden;
- extends product lifespan;
- reduces TCO;
- amplifies maintainability and repairability;
- strengthens the "spillover of benefits" at macroeconomic level;
- enhances long-term system sustainability.

Low ArchCap:

- neutralises technological improvements;
- increases feature-based inflation;
- raises costs for users and society;

- accelerates depreciation and waste;
- increases cognitive friction and maintenance costs;
- lowers productivity.

In this sense, ArchCap acts as an economic multiplier that determines how much of the technological frontier translates into actual welfare.

4. Stage 4: Realised Utility

Realised utility is the final outcome experienced by consumers, organisations, and society. It depends on:

- predictability;
- ease of operation;
- maintenance simplicity;
- lifecycle duration;
- sustainability;
- the total cost of ownership (TCO);
- reliability under stress;
- cognitive comfort.

Utility increases when ArchCap effectively harmonises technological components and decreases when architectural entropy dominates.

5. Systemic Mechanism: How ArchCap Works

The overall mechanism can be expressed as:

Technological Potential (ATech) → Architectural Integration (Arch) → Architectural Capital (ArchCap) → Realised Utility

Key causal pathways include:

1. *Cognitive Load Pathway (CLS → Utility).* Lower CLS increases usability, reliability, and safety. Empirical evidence demonstrates that increased visual and cognitive load in real-world tasks directly degrades performance and safety, even in otherwise technically adequate systems (Engström et al., 2005).
2. *Repairability & Maintainability Pathway (RE → Utility).* Maintainable and repairable architectures reduce TCO, extend lifecycle value, and contribute to long-term system sustainability.
3. *Cost Pathway (TCO Ratio → Utility).* Efficient architectures lower lifetime financial burden.
4. *Coherence Pathway (ACI → Utility).* Coherent systems reduce internal conflict, errors, and unpredictable behaviour.

6. Summary

The mechanism presented in this chapter demonstrates how the four components of Architectural Capital – CLS, RE, TCO Ratio, and ACI – work together to transform technological potential into real consumer and societal value.

In systems with high ArchCap:

- technological complexity becomes *manageable*,
- user experience becomes *predictable*,
- costs become *sustainable*, and
- product lifecycles become *longer and more efficient*.
- In systems with low ArchCap:
- technological innovation fails to create proportional value,
- leading to stagnation of utility despite rapid technological progress.

Empirical Analysis

The purpose of the empirical analysis is to demonstrate that Architectural Capital (ArchCap) is not an abstract construct but a measurable systemic property that consistently manifests across industries and technological eras.

Three empirical domains are examined:

1. *historical systems with exceptionally clean architectures*,
2. *modern systems with high ATech but low ArchCap*, and
3. *hybrid cases where architecture amplifies or suppresses usefulness*.

The evidence collectively supports the hypothesis that ArchCap, not ATech alone, determines real utility.

1. Historical Examples of Architectural Coherence

Ford Model T, Volkswagen Beetle, FIAT 124/Lada 2101–2107

The most successful automobiles of the 20th century share a common architectural philosophy, despite emerging from different industrial contexts:

- minimal internal complexity,
- clear, intuitive control logic,
- low cognitive load,
- *high maintainability and mechanical robustness*,
- harmonised engineering parameters, and
- low total cost of ownership (TCO).

The reason for their longevity is not advanced technology, but *exceptional architectural* *clarity* – high ArchCap with moderate ATech.

For example, the Beetle used a very limited number of components compared to modern cars, yet its architectural ordering (Baldwin & Clark, 2000) ensured extraordinary maintainability and reliability.

The same logic applies to the *FIAT 124/Lada 2101–2107*, whose platform remained usable and affordable for decades due to a combination of:

- very high Architectural Coherence (ACI),
- low CLS (cognitive load),
- low cost of parts,
- excellent mechanical predictability, and
- *durability and ease of repair even in low-infrastructure environments.*

These cars remained functional across generations because their architecture minimised hidden complexity while maximising real user utility and operational resilience.

2. The Lada Paradox: High ArchCap Compensating for Low ATech

A central empirical finding of this study is the so-called *Lada paradox*:

A 55-year-old design, with almost no modern electronics, achieves braking performance comparable to regulatory thresholds for modern cars.

(1) Verified historical performance

The official factory specification booklet *"Lada 1500"* (Avtoexport USSR, 1977) documents that *VAZ-2103* met all braking requirements of its time using:

- original asbestos brake pads,
- period-appropriate all-season tires, and
- a hydraulic braking layout without any electronic assistance.

This historical data provides a reliable baseline.

(2) Comparison with today's regulatory test

When these values are translated to today's *UN R13-H Type-0* test – *the same regulatory dry-braking test applied to all new cars in the EU today* – the original VAZ-2103 *still meets the minimum standard*.

Moreover, because Lada's braking system is architecturally clean and mechanically symmetric, it would also pass the remaining dry-braking subtests under the same conditions.

(3) Updated consumables: further improvement

Independent enthusiast tests (2020–2025), and theoretical calculations made by M. Rusev, (2026) show that a VAZ-2103 equipped with:

- *modern non-sport premium tires,* and
- contemporary brake pads
- achieves braking distances around *39–44 m*, which:
- are *far below the minimum threshold* of UN R13-H, and
- fall *close to the real-world average* of mass-market vehicles sold in 2025 (typically 36–42 m on dry asphalt).

This does not imply technological equivalence with 2025 vehicles.

(4) The paradox

A 55-year-old braking architecture – without ABS, ESC, sensors, or software – can still perform at a level close to modern normative expectations *due to its architectural purity*:

- predictable hydraulic behaviour,
- optimal mechanical leverage,
- symmetric force distribution, and
- minimal internal friction and complexity.

(5) Regulatory implication

The Lada paradox exposes a systemic blind spot:

Regulations reward the presence of technologies (ATech), not the quality of architecture (ArchCap).

Thus, high-ArchCap systems remain invisible in normative frameworks, while low-ArchCap systems can pass by accumulating components.

3. Case Study: The Early iPhone as an Architecture-Dominated Innovation

Early generation iPhones (2007–2013) illustrate a different dimension of ArchCap, *software–hardware coherence*.

Key architectural characteristics:

- extremely low cognitive load;
- highly coherent interface structure;
- minimal internal complexity for the user;
- predictable system behaviour;
- tight hardware-software synchronisation;
- robust construction relative to competitors;

- competitive pricing for the value offered;
- extendability through the App Store ecosystem.

Notably:

The hardware of early iPhones was not the strongest in the industry (IEEE, 2010),

yet their architectural excellence produced superior real-world utility, leading to market dominance.

This demonstrates:

- *ArchCap amplifies ATech, and*
- *ATech cannot compensate for poor ArchCap.*

4. Modern Examples of High ATech but Low ArchCap

Across contemporary industries, we observe products with:

- high technological density,
- but declining real usefulness.
- Typical symptoms include:
- car dashboards requiring multi-step screen navigation for basic functions,
- software interfaces that require training,
- electronically fused modules that degrade maintainability,
- unpredictable interactions between subsystems, and
- regressions introduced by over-the-air updates (IEEE, 2021).

These effects demonstrate *architectural entropy*: as complexity grows, coherence deteriorates, reducing utility despite higher ATech.

5. TCO Evidence: Why Architecture "Wins"

Eurostat household expenditure data (2022–2024) shows a clear pattern:

Products with higher systemic complexity have *higher TCO*, even when purchase prices are similar.

Examples include home appliances, consumer electronics, and automobiles. When complexity exceeds architectural capacity to integrate it, users incur:

- higher maintenance costs,
- more frequent repairs or replacements, and
- shorter product life cycles.

Thus:

ArchCap reduces TCO and increases long-term utility.

6. Summary of Empirical Findings

Across all cases, the following regularities emerge:

1. *High ATech ≠ high utility* (Eurostat, 2022–24).
2. Architectural clarity strongly shapes real-world performance (Baldwin & Clark, 2000).
3. Historical products with low ATech but high ArchCap exhibit exceptional longevity and accessibility (ACEA, 2021).
4. Contemporary regulations fail to detect architectural deficits (UN R13-H, 2022).
5. ArchCap acts as a *moderator* linking knowledge (ATech) to real utility (Romer, 1990).

Conclusion: Architectural Capital is the structural variable that determines how effectively technological knowledge is transformed into real usefulness.

Discussion

This section directly addresses the key conceptual and methodological questions raised by reviewers, clarifying the mechanisms through which Architectural Capital (ArchCap) influences technological usefulness, economic performance, and long-term societal outcomes.

The discussion is organised around four analytical dimensions: (1) value erosion, (2) the incentive structure of firms, (3) the relationship between ArchCap and endogenous growth, and (4) the distinction between ArchCap, ATech, and related concepts.

1. What Value Is "Nullified" by Low Architectural Capital?

One of the central reviewer questions concerns the nature of the value that is "nullified" or eroded when ArchCap is low.

The evidence and theory developed in this paper allow us to distinguish *three layers of value erosion*.

(1) Erosion of Long-Term Consumer Value

When the internal architecture of a system becomes fragmented or overloaded with poorly integrated features, several predictable mechanisms emerge:

- cognitive load increases,
- error rates rise,
- reliability declines,

- maintainability decreases,
- the life cycle shortens, and
- total cost of ownership (TCO) increases.

Under these conditions, consumers may pay more for a product whose real utility stagnates or even decreases relative to earlier generations.

Thus, *the private value of technological progress is partially nullified*.

(2) Erosion of Macro-Economic Value

Low ArchCap produces structural inefficiencies at the societal level:

- households lose time in troubleshooting, training, and service interactions;
- productivity declines due to unnecessary complexity;
- capital depreciates faster;
- infrastructure absorbs higher maintenance burdens;
- consumer budgets are strained by higher TCO.

Collectively, these factors suppress the positive spillovers that endogenous growth theory expects from technological knowledge (Romer, 1990).

Hence, *low ArchCap weakens the macro-economic returns of innovation.*

(3) Erosion of Environmental and Resource Value

Architectural decay also accelerates resource consumption:

- shorter product life cycles generate more waste,
- repairs are superseded by replacements,
- modularity declines, and
- upgrades become impossible.

This undermines circular-economy objectives and reduces sustainability.

(4) Market and Asset Value Erosion

A final layer, rarely addressed in the literature, concerns the *market value of the products themselves*.

Low ArchCap leads to:

- rapid price depreciation,
- lower resale value,
- shrinking brand loyalty, and
- reduced willingness to buy from the same manufacturer.

Thus, architectural deficits weaken future demand, reducing firms long-term value capture as well.

2. Why Firms Have Weak Incentives to Maximise Architectural Capital

From the perspective of micro-economic incentives, firms rarely have strong motives to invest in high ArchCap voluntarily.

Several structural reasons explain this:

(1) Feature Inflation is More Profitable in the Short Run

Adding new components, modes, or software layers:

- increases perceived innovation,
- accelerates product cycles,
- drives repeat purchases,
- allows higher price points, and
- creates marketing advantages.

By contrast, architectural simplification:

- is invisible at the point of sale,
- requires deeper expertise, and
- reduces the need for frequent upgrades.

Thus, firms optimise for *ATech accumulation*, not *architectural coherence*.

(2) High ArchCap Reduces Planned Obsolescence

Products that are:

- durable,
- maintainable,
- repair-friendly, and
- software-stable

extend their life cycle, decreasing revenue from replacements.

Hence, high ArchCap may be *privately costly yet socially beneficial*.

Empirical evidence from Clark and Fujimoto (1991) shows that product architecture and cross-functional coordination, not technological intensity, determine development speed, quality, and production costs. Organisations evolve through established routines that favour local optimisations, often at the expense of long-term architectural coherence (Nelson & Winter, 1982).

(3) Low ArchCap Increases Consumer Lock-In

Complex or proprietary architectures:

- bind consumers to original parts and services,
- increase switching costs, and
- reduce interoperability.

This creates *dependency lock-in*, a rational micro-incentive that opposes architectural clarity.

(4) Regulators Reward Components, Not Architectures

As shown in the Lada paradox case, regulatory frameworks:

- require the presence of technologies (e.g., ABS),
- but do not evaluate architectural coherence.

Thus, firms comply by *adding components* rather than *improving the architecture*, reinforcing systematic bias toward low ArchCap.

3. How ArchCap Expands the Theory of Endogenous Growth

Endogenous growth theory (Romer, 1990) treats knowledge (ATech) as the primary driver of productivity and long-run growth.

However, it assumes implicitly that knowledge is *effectively absorbed* into economic structures.

ArchCap fills this theoretical blind spot.

ArchCap as a Moderator Variable

This paper conceptualises ArchCap as a *moderating variable*, determining the degree to which ATech is translated into:

- consumer utility,
- productivity gains,
- lower TCO,
- higher societal spillovers, and
- sustainable economic growth.

Crucially, this role of ArchCap aligns with established innovation theory.

Henderson & Clark (1990) distinguish between component innovation and architectural innovation, showing that changes in system architecture – rather than in individual components – are the most difficult to implement, yet generate the highest and most persistent value. Architectural innovation requires reconfiguring relationships among existing components, challenging established routines, knowledge structures, and coordination mechanisms.

This insight explains why ArchCap does not accumulate automatically alongside technological progress. While component-level innovations (new features, faster processors, additional sensors) are relatively easy to introduce and market, architectural improvements demand deep systemic reorganisation. They require coordination across engineering, design, production, and organisational boundaries – precisely the type of change firms tend to avoid due to cost, risk, and institutional inertia.

From the perspective of endogenous growth, ArchCap therefore acts as a conversion efficiency parameter. When ArchCap is high, technological knowledge generates strong spillovers, stable productivity gains, and durable increases in welfare. When ArchCap is low, a growing share of ATech is absorbed by complexity management, coordination failures, cognitive overload, and rising maintenance costs, leading to diminishing returns at both the micro- and macroeconomic levels.

In this sense, architectural innovation represents the highest-leverage but most underprovided form of innovation in modern economies. Markets and organisations systematically favour incremental, component-based technological accumulation, even though long-term growth and welfare depend disproportionately on architectural coherence.

By integrating ArchCap into endogenous growth theory, the present framework explains why knowledge accumulation alone is insufficient. Sustainable growth requires not only more technology, but architectural structures capable of absorbing, stabilising, and translating that technology into real economic value.

4. Distinguishing ArchCap from Related Concepts

It is important to clarify what ArchCap *is not*, in order to avoid confusion with adjacent terms.

(1) ArchCap ≠ Technological Density

Technological density (ATech) tallies components.

ArchCap evaluates the *quality of their integration*.

(2) ArchCap ≠ UX or UI Design

UX is one subset of architectural clarity, but ArchCap includes:

- internal mechanical ordering
- Subsystem coordination,
- maintainability,
- modularity,
- cognitive load, and
- long-term resilience.

(3) ArchCap ≠ Modularity Alone

Classic modularity theory (Baldwin & Clark, 2000) focuses on design structure.

ArchCap incorporates economic and system-level outcomes.

(4) ArchCap ≠ Regulatory Compliance

Regulations define minimal technical thresholds.

ArchCap defines systemic quality beyond compliance.

5. Synthesis

The above discussion shows that:

1. Low ArchCap erodes private, macro-economic, environmental, and market value.
2. Firms have weak natural incentives to increase ArchCap and often benefit from architectural entropy.
3. ArchCap moderates the relationship between knowledge accumulation and real utility, expanding the endogenous growth framework.
4. ArchCap is distinct from, and complementary to, ATech, modularity, UX, and regulatory requirements.

Thus, ArchCap emerges as a *foundational explanatory and policy-relevant variable,* essential for understanding why technological progress often fails to deliver proportional increases in utility or welfare.

Regulatory Implications

The empirical and theoretical analysis presented in this paper shows that low Architectural Capital (ArchCap) generates systemic frictions – higher TCO, cognitive overload, diminished reliability, reduced sustainability, and suppressed productivity – that remain invisible to current regulatory frameworks.

This raises a fundamental policy question:

How can regulatory systems promote architectural quality, ensuring that technological progress translates into real utility without stifling innovation?

This chapter outlines how regulators can integrate ArchCap into policymaking and why such an approach complements existing digital, environmental, and consumer-protection regimes.

1. The Core Problem: Regulators Measure Components, Not Architectures

Modern regulatory frameworks across the automotive, electronics, energy, and digital sectors are overwhelmingly *component-based*. They evaluate:

- the *presence* of technologies (e.g., ABS, ESC, sensors),
- specific performance thresholds of isolated subsystems, and
- minimum safety or emissions criteria.
- However, they do *not* evaluate:
- internal system coherence,
- architectural consistency,
- cognitive load for end-users, or

- maintainability and long-term resilience.

A central empirical example is *UN R13-H*, which requires the presence of ABS but does not assess the architectural logic of the braking system itself (UNECE R13-H, 2022).

Institutional frameworks shape economic incentives but frequently lag behind the technological and architectural evolution of systems (North, 1990).

Consequences of Component-Based Regulation
Such frameworks unintentionally encourage:

- the accumulation of technological layers without architectural integration,
- reduced maintainability and rising repair costs,
- increased cognitive load and user frustration,
- fragile or unpredictable system behaviour, and
- *inflation of features* ("feature inflation") rather than structural optimisation.

Thus, regulatory systems inadvertently promote *architectural entropy*, undermining the real utility of technological innovation.

2. The Need for Architecture-Sensitive Regulation

For technological knowledge (ATech) to generate real utility, regulations must evaluate *how systems are organised*, not only *what* they contain.

This requires the introduction of three categories of architectural indicators.

(1) Cognitive Load Limits (CLS-Control Framework)

Regulators can establish maximum acceptable cognitive loads for essential functions, similar to the logic used in aviation human-factors guidelines (Federal Aviation Administration [FAA], 2016).

Possible requirements:

- critical functions must be accessible without multi-level screen navigation;
- system behaviour must be predictable under stress;
- interfaces must maintain internal consistency across versions and updates;
- real-time operations (driving, HVAC, lighting, safety systems) must be operable *without visual distraction*.

This approach protects users by reducing avoidable cognitive burdens and increasing safety.

(2) Maintainability and Repairability Assessment (RE Index)

Current "Right to Repair" initiatives are an important starting point, but they often focus on parts availability rather than *architectural logic*.

A comprehensive RE Index should consider:

- accessibility of core components without disassembling unrelated modules;
- ability to repair rather than replace subsystems;
- transparency of interfaces and system diagrams;
- availability of standardised parts and connectors.

Architectural maintainability systematically reduces TCO and increases system longevity – without requiring subsidies or price controls.

(3) Architectural Coherence Score (ACI)

Architectural coherence can be integrated into:

- safety standards,
- reliability certifications (e.g., ISO 26262),
- digital product passports, and
- sustainability frameworks.

Criteria may include:

- clarity and logic of subsystem interactions;
- consistency in command hierarchies;
- fault tolerance and graceful degradation;
- absence of internal contradictions between modules.

Empirical evidence shows that higher ACI correlates with reduced failures and longer system life cycles (Baldwin & Clark, 2000).

3. Policy Argument: Architectural Simplicity Increases Societal Welfare

Architectural Capital is not a restrictive requirement; it is a macroeconomic strategy that increases welfare.

High ArchCap generates:

- *lower TCO for households* (Eurostat, 2024);
- *less electronic waste* and longer product cycles (OECD, 2020);
- *higher safety* through reduced cognitive demands (FAA, 2016);
- *greater productivity* by eliminating unnecessary friction;
- *stronger positive spillovers* in line with endogenous growth theory (Romer, 1990).

Thus:

ArchCap is a public good, not merely a private design preference. Its benefits accrue not only for individual consumers, but also for the economy, infrastructure, and the environment.

4. ArchCap as a Policy Tool for Innovation

Unlike component-based regulation, ArchCap can serve as a *strategic filter* for evaluating:

- innovation projects,
- public R&D funding proposals,
- automotive and electronics subsidies,
- digital infrastructure investments, and
- long-term industrial planning.

Public authorities can use ArchCap to:

(1) Prioritise high-quality, high-coherence designs, maximising societal returns on R&D.

(2) Identify projects where technological accumulation does not increase real utility, preventing technological inflation and structural waste.

(3) Detect architectural dependencies and long-term systemic risks, protecting consumers from lock-in, escalating maintenance, and premature obsolescence.

5. The European Perspective: Why the EU Is Well Positioned for ArchCap Policy

The European Union already leads in:

- eco-design,
- repairability regulation,
- circular economy frameworks,
- consumer standards, and
- digital rights and platform governance.

However, EU regulation is still dominated by *component-checklist logic*, which creates:

- hidden complexity,
- higher TCO,
- lower maintainability,
- rapid obsolescence, and
- rising cognitive load.

By adopting ArchCap:

- repairability directives would gain systemic depth;
- eco-design would expand beyond energy labels;
- digital product passports would encode architectural coherence;
- automotive regulation would address internal complexity rather than only

emissions and safety components.

ArchCap is therefore a natural extension of existing European regulatory strengths.

6. What ArchCap Is Not (Clarification requested by reviewers)

To avoid misinterpretation, it is essential to clarify several distinctions:

- *ArchCap is not a restriction on innovation.* It encourages *higher-quality* innovation.
- *ArchCap is not anti-technology.* It amplifies the benefits of technological knowledge (ATech).
- *ArchCap is not a substitute for technical regulation.* It functions as an analytical layer above it.
- *ArchCap is not a UX concept.* It includes UX as well mechanical design, maintainability, system logic, and TCO.

7. Key Regulatory Conclusions

1. Component-based regulation inevitably leads to architectural entropy.
2. Regulators should incorporate ArchCap indicators into safety, reliability, and sustainability frameworks.
3. ArchCap increases the societal return on technological investment.
4. ArchCap is an effective tool for policy-making, innovation governance, and industrial planning.
5. Architectural simplicity is an economic strategy – not a stylistic preference.

Conclusion

Technological progress in the early twenty-first century has produced a paradox: despite rapid increases in technological density (ATech), consumer utility, long-term satisfaction, and societal productivity have not risen proportionally.

This paper argues that the root cause of this divergence lies in a neglected structural variable – *Architectural Capital (ArchCap)* – which determines the extent to which technological knowledge is transformed into real value.

ArchCap captures the systemic quality of a product's internal organisation: its cognitive load (CLS), maintainability and sustainable (RE), total cost of ownership (TCO Ratio), and architectural coherence (ACI).

By operationalising ArchCap through these four components, the study shows that architectural quality is not an abstract design notion, but a measurable, policy-relevant determinant of welfare, productivity, and long-term growth.

A synthesis of theoretical and empirical findings

The analysis demonstrates that:

1. *Knowledge is necessary but not insufficient.* Technological features alone do not guarantee real utility. The structure that organises them is equally important.
2. *Architecture determines utility, cost, and sustainability.* High ArchCap systems consistently outperform low ArchCap systems, even when the latter contain more advanced technologies.
3. *Endogenous growth theory requires an architectural dimension.* ArchCap functions as a moderating variable that strengthens or weakens the translation of ATech into productivity, positive spillovers, and long-term welfare.
4. *Historical and contemporary evidence confirms the mechanism.* Products such as the Ford Model T, Volkswagen Beetle, FIAT/Lada 2101–2107, and early iPhones demonstrate that architectural clarity, low cognitive load, maintainability, and coherence can generate extraordinary real-world usefulness, longevity, and mass adoption.
5. *Architectural entropy erodes private, macroeconomic, and environmental value.* Rising complexity without systemic coherence increases TCO, accelerates capital depreciation, reduces productivity, and shortens product life cycles.

Regulatory and policy implications

A key conclusion of this study is that *component-based regulation systematically underestimates architectural quality*, unintentionally encouraging complexity, lock-in, and premature obsolescence.

Integrating ArchCap into regulatory frameworks – through cognitive-load standards, maintainability indices, and architectural coherence scores – can significantly increase the societal benefits of innovation.

ArchCap thus emerges as:

- a *public good* that enhances welfare, sustainability, and economic performance;
- a *policy tool* that allows governments to evaluate innovations and R&D strategies more effectively;
- a *framework for designing intentional architectural breakthroughs* rather than relying on historical accidents.

Path forward

This paper is part of a broader research programme dedicated to the architecture of complex systems and the economics of innovation. The goal is to synthesise the insights of past engineering and economic “geniuses” and adapt them into analytical tools suitable for the challenges of the Third Millennium.

Future research will focus on:

- developing quantitative ArchCap indices for specific industries;
- testing the framework with broader cross-industry datasets;
- designing regulatory prototypes for CLS, RE, ACI, and TCO evaluation;
- integrating ArchCap into models of industrial policy and technological transitions.

Final statement

In an era defined by accelerating technological complexity, *Architectural Capital* provides a crucial lens for understanding why innovation often fails to deliver its promised benefits – and how it can be redirected toward sustainable, equitable, and meaningful progress.

By placing architecture at the centere of economic and technological analysis, this framework offers a pathway toward turning technological knowledge into real utility for individuals, firms, and society as a whole.

Notes

Some of the concepts used in this paper are interpreted in a broader analytical context than their traditional economic meaning. This extension reflects the interdisciplinary nature of the study and aims to better capture systemic interactions between technology, architecture, and realised utility.

The article is conceived as a practical tool that decodes the engineering 'genius' embedded in historical masterpieces and systematises this knowledge through the concept of *Architectural Capital (ArchCap).*

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Conflicts of Interest

The author has no conflicts of interest to declare.

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