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Towards a Total Packaging System: Integrating Material Performance, Safety, and Circular Sustainability

ABSTRACT

The discipline of packaging development has historically evolved not as a unified science, but as a fragmented collection of independent sub-disciplines. Academic and industry packaging development frameworks mimic this fragmentation where packaging design, material science, logistics, and end-of-life recovery are treated as isolated domains rather than a single, integrated system .Recent changes where sustainability requirements through more system thinking approach (life cycle analysis) and different economic instruments like plastic taxes, extended producer responsibility fees and new directives regarding toxicology requirements require a paradigm shift. Driven by escalating climate pressures, stringent European Union regulatory mandates, and the imperative of the circular economy, packaging is no longer evaluated merely as a single-use vessel. Instead, we must conceptualize it as a Total Packaging System (TPS). While similar to Total Quality concepts (reduce waste, continuous improvement, data driven) this review outlines a new comprehensive framework which goes beyond as tries to go outside just the rigid fragmented techno sphere domain. This new framework harmonizes structural material performance (permeability, mechanical integrity) with advanced chemical safety standards—specifically the complex convergence of REACH, Food Contact Material (FCM) regulations, and the newly active Packaging and Packaging Waste Regulation (PPWR, Regulation (EU) 2025/40) together with sustainability requirements done through new material development approaches like Sustainable and Safe by Design (SSbD) tools, life cycle analysis (LCA) and multifactorial optimization.

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KEY WORDS

Packaging development, material performance, sustainability, system thinking

1. The roots of fragmentation in packaging development: a systems-thinking introduction

The discipline of packaging development has historically evolved not as a unified science, but as a fragmented collection of independent sub-disciplines. While modern scholarship advocates for integrated paradigms like "Sustainable Packaging Logistics" (SPL) (García-Arca, Garrido & Prado-Prado, 2017) or "Packaging Logistics" (Hellström, 2007; García-Arca, Comesaña-Benavides & Prado-Prado, 2021), both industrial practice and academic literature remain stubbornly siloed. Traditionally, packaging development frameworks are bifurcated into three distinct, non-communicating functional spheres: the commercial/marketing function (graphics, haptics, and brand building), the logistics/manufacturing function (containment, protection, and automation), and the environmental/end-of-life function (circularity, collection, and degradation) (Bramklev, 2009b; de Koeijer, de Lange & Wever, 2017). At a fundamental level, the separation of packaging frameworks is an artifact of Cartesian reductionism—the belief that

a complex system can be understood by breaking it down into its individual parts and optimizing each one. Both in academia and industry this manifests as:

Disciplinary Silos: Universities and research institutions train professionals in highly specialized, non-communicating verticals. A structural engineer is trained to optimize for mechanical strength; a graphic designer for visual brand cues; a chemical engineer for barrier properties; and a waste-management specialist for sorting throughput.

Sequential "Over-the-Wall" Development: Because of this training, frameworks traditionally follow a linear, sequential pipeline. Marketing designs the concept and "throws it over the wall" to engineering; engineering sources the materials and throws it to manufacturing; manufacturing struggles to run it on existing machinery and throws it to logistics. By the time the package is produced, it is too late to retroactively design it for systemic circularity or optimal shipping cubage.

These manifestations are deeply rooted in three structural dimensions: cognitive and social human traits, economic path-dependencies, and institutional reductionism. At the individual and social scale, human evolutionary biology actively works against the integration required for systems thinking. Systems thinking requires an engineer or designer to hold a massive array of interconnected variables in their mind simultaneously—balancing chemical barrier requirements, structural compressive strength, high-speed machine tolerances, shipping cubage, consumer ergonomics, and localized municipal recycling capabilities. However, human cognition is bound by Working Memory Capacity (Miller, 1956). According to Cognitive Load Theory, when an individual is tasked with managing highly complex, open-ended systems, their intrinsic cognitive load (the inherent difficulty of the task) and extraneous load (the mental effort of processing poorly structured data) quickly overwhelm their limited working memory capacity (Sweller, Ayres & Kalyuga, 2011). To prevent cognitive overload, human designers revert to bounded rationality (Simon, 1957). Another cognitive challenge pointed out by several anthropologists but synthetized by Bateson (1972) where the Western civilization is dominated by: linear causality, reductionism and control-oriented thinking while natural system work by feedback loops, circular causality and self-organization. Donella Meadows (2008) repeatedly argued that many policy failures occur because humans intuitively think linearly while complex systems behave cyclically. To ease the cognitive load people split the complex system into simpler, isolated sub-problems— here focusing on packaging example: optimizing the packaging's weight first, then its aesthetics, then its recyclability. This reductionist approach reduces the immediate cognitive load on the designer but completely fractures the integrity of the broader product-packaging-logistics system. As packaging development moves from a single designer to an organizational level, a different cognitive constraint emerges: social scaling limits. Anthropological and organizational research demonstrates that humans have a natural cognitive limit—historically termed Dunbar's Number—constraining the size of a cohesive, trusting social network to roughly 150 individuals (Dunbar, 1993; Clegg, 2022). Beyond this boundary of ~150 people, human groups naturally fragment into subgroups to reduce the social and cognitive transaction costs of maintaining relationships. In large corporations, these subgroups manifest as highly protective functional silos (e.g., procurement, marketing, supply chain). As Clegg (2022) highlights, these silos construct distinct, insular "thought worlds" and proprietary lexicons. A procurement professional's "thought world" is governed by cost-per-unit, whereas an environmental specialist's world is governed by carbon-equivalent metrics. Because of human social-scaling limits, cross-functional collaboration over 150-person boundaries breaks down, and communication is replaced by sequential, formal "over-the-wall" handoffs. The organizational fragmentation created by human cognitive limitations is further cemented by corporate cost-accounting structures and macro-economic models. Within corporate settings, financial performance is tracked through localized, department-specific Key Performance Indicators (KPIs). Procurement is evaluated on raw material purchase costs; plant managers are evaluated on packaging line speeds; logistics managers are evaluated on transport cubage and pallet utilization (Hellström, 2007). Standard financial frameworks struggle to quantify cross-functional trade-offs. For example, procurement may hit their localized KPI by sourcing a cheaper, thinner corrugated box, but this decision risks systemic failure if the box buckles under humidity, causing product damage during transport and costing the logistics department far more than the procurement savings (García-Arca & Prado-Prado, 2008). Traditional management accounting systems fail to attribute downstream logistics or waste costs back to early-stage design decisions, reinforcing siloed optimization. For decades, global markets allowed companies to treat the end-of-life disposal of packaging as an economic externality. Because the financial burden of managing, landfilling, or recycling packaging waste fell on municipal tax bases or the natural environment rather than the brand owners, corporate development frameworks had zero economic incentive to include circularity variables in their initial designs. Only with the modern rise of legislated Extended Producer Responsibility (EPR) and circular-economy mandates (such as the EU's Packaging and Packaging Waste Regulation) are these external costs beginning to be internalized, forcing a painful, retrospective pivot toward systemic design (de Koeijer, de Lange & Wever, 2017). A recent comprehensive overlook of the miscommunication problems due to these factors and how directly influences the packaging can be found in an online book Unpacked (Rogerson, 2025) and claims that

the answer lies in communication—or more precisely, the misalignment in the packaging development process is the failure to communicate clearly, accurately, and persuasively between different siloed in stakeholder group.

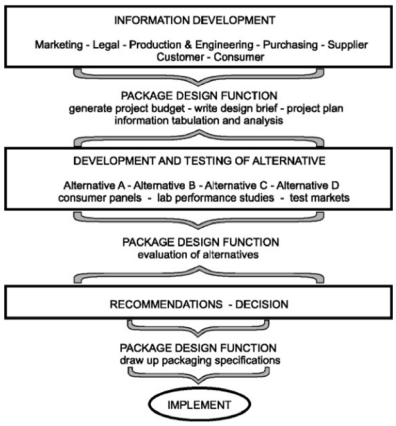
2. Overview of existing packaging development models

In the early stages of formalized packaging science, models focused strictly on the immediate physical relationship between the package, the product, and its environment. Developed by Hugh Lockhart at Michigan State University (Lockhart, 1997), this framework established packaging as a formal "Socio-Scientific Discipline." It organized design criteria into a static 3x3 grid mapping the three core functions of packaging (Protection, Utility, Communication) against the three primary environments it encounters:

- The Physical Environment: Mitigating shock, vibration, drops, and compression
- The Ambient (Biospheric) Environment: Controlling moisture, oxygen, UV light, and temperature.
- The Human (Social) Environment: Ensuring ease of opening, portion control, tamper-evidence, and branding.

It shifted packaging design away from purely trial-and-error physical testing toward a systematic, multi-variable engineering matrix (Bix et al., 2009). But it also has some downsides: the Lockhart matrix was entirely static. It treated these vectors as isolated grid cells, offering no mathematical models to resolve functional trade-offs (e.g., maximizing barrier protection vs. maintaining ease of opening) and entirely omitted lifecycle, carbon footprint, or chemical safety metrics. Saghir (2002) expanded packaging theory by introducing the concept of Packaging Logistics, emphasizing the alignment of packaging decisions with supply chain operational efficiency. His framework operated with the tri-level structure of primary (consumer), secondary (transport/groupage), and tertiary (pallet/unit load) packaging systems. He also integrated functional tradeoffs by balancing conflicting requirements between marketing (appeal, volume, branding) and logistics (cube utilization, stack ability, handling efficiency). And all this is synchronized through the supply chain where one can evaluate how packaging parameters directly impact fill rates, transport costs, material handling, and inventory management across the entire network (Saghir, 2004).

The next phase tried to more integrate product and packaging development models in the period between 2007 and 2009 by the works of Bramklev (2009a), who advocated for concurrent engineering, where product design and packaging design occur simultaneously rather than sequentially. Traditional approaches design the product first and package it later, often leading to sub-optimal shipping volumes or fragile product designs. IPPD treats product and packaging as a co-dependent, unified system. It also Incorporates requirements from raw material selection, manufacturing constraints, retail displays, and end-of-life recovery into the early conceptual phases of product development (Bramklev, 2009b). A similar approach was promoted also by (Bix et al., 2009) who, building on Lockhart Matrix and concurrent engineering, proposed that truly optimal designs consider all viewpoints, a combination of PCD (Product Centric Design) and UCD (User Centric Design) processes. During the entire process the design team must attempt to balance requirements of the three environments (physical, ecospheric, and human) and the three functions (protection, utility, and communication) described earlier from varying stakeholder perspectives. Their system is also a linear six step approach with the steps: Planning, Concept Design, System Design, Specification, Refinement and Production. In a similar fashion to classic packaging textbooks (Larkin & Burcham, 2022) you can find also a linear based model focusing on the technical operations and flows of information (Figure 1).



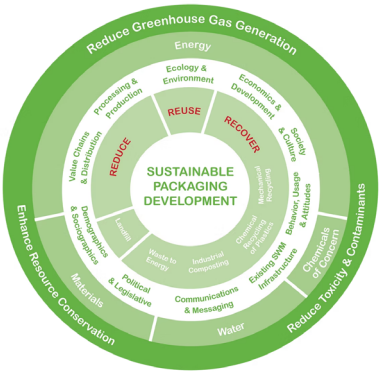
» **Figure 1:** *General package design process (Larkin & Burcham, 2022)*

This model goes into specifications and data needed to support every stage of the packaging design process (including some of the legislation, technical and other data) but does not draws conclusion about the interconnection of different design decisions, but uses more of a to do list lacking overall comprehension of systems outside the focused packaging process. These approaches do not contain more detailed environmental and toxicological methods, which are addressed in the next models. In response to growing environmental awareness, design frameworks evolved to prioritize resource efficiency, waste reduction, and end-of-life (EoL) recoverability. The Sustainable Packaging Coalition (SPC) moved the industry away from vague "eco-friendly" buzzwords by introducing the SMART design methodol-

ogy (Pålsson, Finnsgård & Wänström, 2011).: S | Systems Approach: Designing with the entire distribution and recovery infrastructure in mind. M | Material Health: Restricting toxic additives and prioritizing safe chemical inputs. A | Accessibility: Ensuring packaging remains functional and safe for all consumers. R | Reduction & Elimination: Minimizing excess headspace, wall thickness, and unnecessary components. T | Life-Cycle Thinking: Using Life Cycle Assessments (LCA) to guide material selection. Grounding sustainable design in the Circular Economy, the Ellen MacArthur Foundation (2021) (introduced the "Eliminate, Innovate, circulate" framework, separating packaging flows into two distinct thermodynamic loops (the "Butterfly Diagram"):

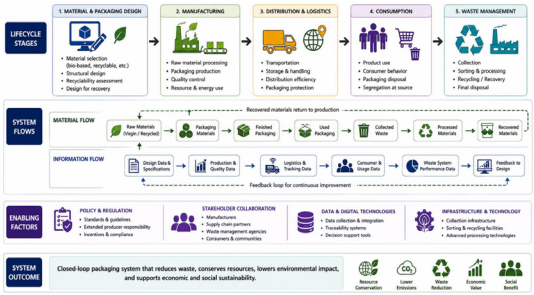
- The Technical Cycle: Keeping synthetic materials (like polymers and metals) in high-value, closed-loop mechanical or chemical recycling systems, avoiding downcycling.
- The Biological Cycle: Utilizing non-toxic, bio-based materials that can safely return to the earth via biodegradation or composting without leaving hazardous residues.

The SPRING Sustainability Roadmap and the sustainable packaging development wheel (Figure 2.) formulated by the Sustainable Packaging Research, Information, and Networking Group (SPRING emphasizes a holistic decision-making framework focused on three overarching goals: reducing greenhouse gas generation, enhancing resource conservation, and eliminating toxicity/contaminants. It replaces the traditional "Reduce, Reuse, Recycle" triad with four core strategies—Energy & Water Conservation, Material Optimization, Elimination of Substances of Concern, and Recovery as the "New Third R" (including industrial composting and chemical recovery where traditional recycling falls short) (Lilienfeld, 2021). It is inspired (most probably by the famous Donut Economics) diagram developed by Kate Raworth (2012).



» **Figure 2:** *SPRING sustainable packaging development wheel (2021 SPRING and Robert M. Lillienfield)*

One more recent model was introduced by Ali (2026) in a form of a system-level framework that connects packaging design with waste management processes across the full lifecycle. The method combines system modeling, lifecycle mapping, and performance evaluation to capture interactions among design, production, distribution, consumption, and disposal stages. It also introduces several new System Performance Evaluation Metrics (mainly focusing on the end-of-life stages (recovery, recycling and Environmental Index Metrics). The framework is presented in Figure 3. While encompassing new parameters and metrics, it omits some established tools like LCA (life cycle analysis) and ISO defined impact categories on the environment and also does not establish dynamic interconnection between system elements but rather offers an extended and more detailed linear packaging development model.



» **Figure 3:** *System-Level Packaging Lifecycle Framework (Ali, 2026)*

3. Recent methodological developments and regulatory requirements

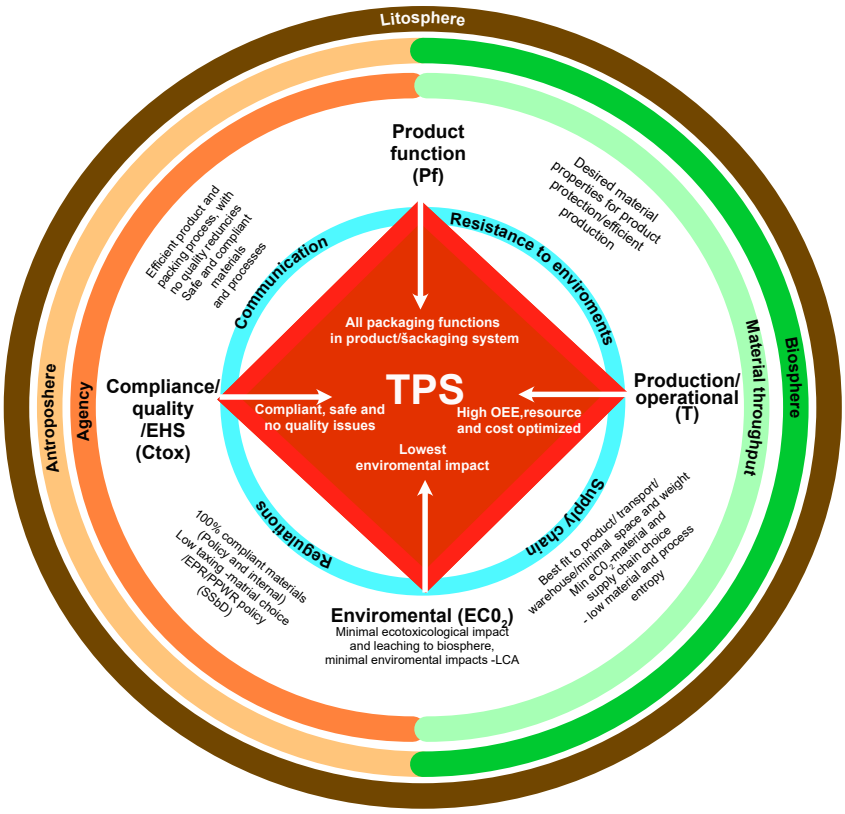
European packaging policy has traditionally been guided by Directive 94/62/EC on Packaging and Packaging Waste (European Parliament and Council, 1994), which established essential requirements for packaging recovery, recycling, and waste minimization. Although the Directive played a pivotal role in harmonizing packaging legislation across the European Union, its emphasis remained largely focused on waste management after packaging had already entered the market. Over time, rising packaging volumes, increasing environmental concerns, and the strategic objectives of the European Green Deall highlighted the need for a more comprehensive framework. This transition is particularly visible in the European Union, where legislation increasingly addresses the entire life cycle of packaging rather than focusing solely on waste management. The Packaging and Packaging Waste Regulation (PPWR) , Extended Producer Responsibility (EPR) schemes, and restrictions on synthetic polymer microparticles are among the most influential legislative drivers shaping packaging development and innovation today (European Parliament and Council, 2025; European Commission, 2025).

The regulation covers the entire packaging life cycle, from design and manufacture through use, collection, recycling and disposal and has several key implications for the packaging design: material selection and design, recycled content ratios and reusing quotas. One of the most significant and not yet fully comprehended emerging regulatory developments affecting packaging graphics and printing is also the Commission Regulation (EU) 2023/2055 concerning intentionally added microplastics. The regulation restricts synthetic polymer microparticles smaller than 5 mm that are insoluble and non-biodegradable, aiming to reduce environmental releases of microplastics (European Commission, 2023; ECHA, 2025). Many modern printing inks and varnishes contain polymer dispersions, polyethylene waxes, synthetic resin additives and functional coatings. Some of these materials may fall within the regulatory definition of synthetic polymer microparticles (EuPIA, 2025). Although printing inks and varnishes used in industrial applications are currently exempt from the direct sales prohibition because they are used in controlled industrial environments, the legislation introduces important obligations regarding material identification and documentation requirements together with the reporting of emissions and end of life management (European Commission, 2023; EuPIA, 2025). To support all these additional requirements also new tools are needed. For a modern packaging system, Safe and Sustainable by Design (SSbD) and Life Cycle Assessment (LCA) are complementary tools that help companies move from simple regulatory compliance toward optimized circular packaging design. Developed by the European Commission's Joint Research Centre (JRC) to align the Green Deal with chemical safety, the SSbD framework is a transformative methodology for designing packaging materials from the molecular level up. SSbD mandates that packaging materials be pre-screened for chemical safety (toxicology, migration) concurrently with Environmental Life Cycle Assessments (LCA) from the earliest Technology Readiness Levels (TRLs) (European Commission, 2022).

4. Total (unified) packaging system

In this section a newly developed packaging framework is presented. Previous iterations were presented in (Karlovits, 2025). The aim of this framework and the newest iteration is to break the fragmentation of the current mental development process by applying a systemic approach and unifying the multiple aspects a packaging or a packaging product system must encompass. Also, it tries in a visually easy model to represent the connection between underlying natural and energy systems beyond current economic models which funnel the previous models into the fragmented linear approaches.

The framework is visually presented in Figure 4.



» **Figure 4:** *The Total Packaging System framework*

In the model and framework, we start with the outer ring which is governed by the three laws of thermodynamics and the innate geosphere (solid, inanimate parts of the world). Inside that we make a blended circle with two distinctive spheres the anthroposphere and biosphere, or some others called it the techno sphere but it is an artificial extension where without energy depletion from the biosphere the techno sphere cannot exist on its own. One the left side is the half ring of the anthroposphere with an additional subring of agency which delegates power from the anthroposphere. Which institutions, legal entities, persons, states, unions wield power to shape the legislation and market side of the packaging development process. On the right side the half ring of the biosphere is extended to material throughput which is directly connecting the influences of humans with the biosphere in form or extraction, transformation and output phase (the breakdown when earth is absorbing back the materials). In the middle is a diamond shape which easily shows the four main pillars of a packaging material: material properties /resistance to different environments, performance during packaging production and supply chain operations, sustainability and compliance and safety (for anthroposphere and biosphere – humans and all biological life on the geosphere. The angles are interconnected through several human induced material throughput pathways. The effects and influences of these interactions are measurable with a few high-level key process indicators, and supported by several tools and methodologies like SSbD and LCA.

Product functions (Pf) are the inherent material properties engineered or natural properties of packaging materials in terms of resistance to different environments. These functions include the physical biological environmental (biosphere) in terms of resistance to heat, moisture, UV light and human environments (production lines on terms of friction, shocks, drops) or human intervention (opening up the protective packaging). These are sometimes known as the protection/containment properties where oxygen, moisture barriers provide the right protection from the biosphere for a prolonged shelf life for food packaging or rust prevention on machine parts for example.

Production/operational (T) performance can be defined on high level of overall equipment effectiveness (OEE), scrap/reject rate, throughput/output rate, first pass yield (FPY)/rejection rate where the packaging machinery or packaging line does not stop with downtime due to poorly designed or materials with non-adequate properties. These properties can be connected with tensile strength, stiffness, coefficient of friction, a wide category of material properties ensuring smooth machine runnability. Also, the ability to shape it, pool it and transport in a manner with the most optimized space, weight ratios during which the entropy of the transport and materials process is low is the key for low impact supply chains.

The third corner or pillar is sustainability or environmental functions where the elements taken from the biosphere to make the packaging (and of course the product itself) use a minimal amount of energy and does now impact the biosphere long term and enables regenerating the biosphere source. Based on the sustainability roadmap by Lilienfeld/Spring (2021) these can be defined as minimizing the environmental impacts of sourcing raw materials and converting them into packaging. Further minimizing the environmental impact of both package and product disposal, including unanticipated release into both land and marine environments. Minimize the production of greenhouse gases and the potential to exacerbate AGW (anthropogenic global warming). This applies to both the package and the product(s) it contains. All this with efficient transport and logistics and designing use scenarios which minimize the influence of this stage (single use or reusable). On a high level this can be calculated through eCO_2 kg of GWP of the chosen raw materials and transportation and use phase environmental impacts, with scalable end of life options (recycling, composting).

Moving towards the next step for safety is the minimization of contaminants and toxicity associated with the production, use, and disposal of packaging. Here one important notice is the second law of thermodynamics - specifically entropy generation ($\Delta S > 0$) during mechanical re-processing with entropic constraints exposes the physics-based boundaries of circular economy models, proving that "closed-loop" mechanical recycling cannot operate perpetually without continuous virgin material inputs and high energy expenditures. Thermal-mechanical shear during re-extrusion breaks covalent bonds in polymer backbones. This irreversible chain scission reduces average molecular weight, severely compromising tensile strength, impact resistance, and barrier properties. Separating complex, multi-material waste streams (such as multi-layer PE/EVOH film structures) back into pure polymer phases requires work Reprocessing cycles continuously concentrate Non-Intentionally Added Substances (NIAS), legacy additives (e.g., phthalates, heavy metal catalysts), and volatile degradation products. This causes recycled packaging to routinely exceed regulatory toxicity limits (C_{tox}) under REACH and EU PPWR. Decontaminating, washing, and re-polymerizing highly entropy-dense waste streams consumes massive quantities of useful energy (exergy). When the energy input needed to purify post-consumer, resin exceeds the energy required to synthesize pristine virgin polymer, recycling transitions from an environmental savings mechanism into a net-positive thermodynamic burden. Connecting with the previous parts it means to preserve minimum operational line speeds (OEE) and prevent packaging failures on high-speed filling lines, reprocesses must continuously blend degraded recycled content with pristine virgin polymer.

The forth corner is safety/health and compliance which are mix of physical, chemical properties which influence the anthroposphere and biosphere through complying with national and international laws defining these chemicals and their present limits where chemicals of concern must be minimized, removed, isolated or immobilized within a package and its contents. These limits and laws are defined through agencies like governments, international bodies or different organizations with social power. For example, the physical safety is that during the handling of the packaged units also no harm is done to the users or operators which includes the scope of the Operational Health and Safety Aspects (EU-OSHA, 2021) of the packaging product system. Here pallet unit deformation (collapsed rate) together with the Ergonomics & Manual Handling Risks (Directive 90/269/EEC) (European Council, 1990) can monitor handle/grip failure rate. The chemical and toxicology compliance through definition of micro leakages and chemical safety limits are defined as for example: the concentrations of Substances of Very High Concern (SVHC) on the ECHA REACH Candidate List. The target threshold is strictly < 0.1% weight by weight (w/w), Heavy Metal Cap Compliance: which tracks concentration of Lead (Pb), Cadmium (Cd), Mercury (Hg), and Hexavalent Chromium (Cr). PPWR Article 5 mandates this KPI must be below 100 mg/kg (100 ppm). Additionally, PFAS content (ppb/ppm) can be included to monitor the presence of restricted per- and polyfluoroalkyl substances, which is critical for food-contact packaging. Standard limits dictate < 25 ppb for individual non-polymeric PFAS and < 50 ppm for Total Fluorine, where a high level KPI can be the Hazard Classification Score Which Evaluates the number of materials classified under CLP Regulation hazard categories (e.g., carcinogenicity, mutagenicity, or aquatic toxicity), with an SSbD target of zero high-tier hazards. All this data can part of the EU Digital Product Passports (DPP) under the "Agency/Anthroposphere" sub-ring which is a critical regulatory vector for data transparency and is digital container for products, components, and materials, which will store relevant information to support products' sustainability, promote their circularity and strengthen and facilitate legal compliance. Currently it is aimed to be introduced for batteries, but in future this format could be a viable data structure for all types of products, including packaging.

By taking account into all these necessary data we can reduce the uncertainty to decrease the hidden impacts of our packaging or packaging/product system choices.

So, one important question will most probably come in the reflection of this proposed framework – how to integrate (current) economics in this one? Where is the cost of packaging in this framework? Is not that the most important parameter? What about the total cost ownership of the packaging (raw material cost, transportation, labor, etc…). Here it is again a question of the level of thinking. In microeconomics where packaging companies operate, they are bound by direct materials costs like expenses for raw materials (plastics, paper, glass, metals), inks, adhesives, and coatings, manufacturing and conversion costs like machinery depreciation, tooling, labor, line speeds, and throughput efficiency during assembly/filling. Further there are logistics & warehousing costs which are driven by packaging weight and volume (cube utilization), freight/shipping fees, pallet layout, and warehouse storage costs. Recently more and more end-of-Life & compliance costs are introduced through Extended Producer Responsibility (EPR) fees, recycling levies, waste handling fees, and regulatory compliance. And finally, the indirect & risk costs like product damage during transit, brand perception, consumer convenience, and shelf differentiation add to the total cost ownership of packaging. These are the so called microeconomic "household" accounting costs in which currently the society is organized and is bounding the survival or elimination of the economic entities. Here also we need to think in systems and take a step above to look at the foundations. Currently mainstream ("neoclassical") economic models treat the economy like a closed loop of money, entirely separate from nature. In these equations, energy is minimized to a minor footnote. Because energy costs only make up about 5% to 10% of total production expenses, the math assumes energy only drives 5% to 10% of economic growth (Ayres, 2001; Kümmel, Ayres & Lindenberger, 2010). The rest is credited to human cleverness and technological progress—a mathematical placeholder known as the "Solow Residual" (Stern, 2011). This viewpoint ignores a fundamental law of physics: the economy is not a perpetual motion machine. It is an open system that physically feeds on the biosphere. Every single product made requires material throughput—a continuous, one-way flow of energy and raw matter extracted from the earth, which is eventually spit back out as waste and pollution (Kümmel & Lindenberger, 2020). Whether we are burning fossil fuels (which are just ancient, deeply concentrated biomass) or utilizing active wood and crops, we are constantly draining the living biosphere to power our industries. Standard economics assumes that if energy runs out, we can simply "substitute" it with more human labor or high-tech machinery. In reality, machines and workers are just transformers of energy; they cannot do any work without a physical power source (Lindenberger & Kümmel, 2011). By treating energy as a minor financial expense rather than the lifeblood of physical work, standard models ignore the hard-environmental limits of consuming the planet's finite resources (Režný & Bureš, 2019). So, to integrate the real cost of the product packaging system a new type of economic system is needed which accounts for energy depletion and degradation from the biosphere to a much realistic scale. We can start with an extended total cost ownership type of formula where the environmental and health and safety factors are also accounted for:

$$\text{TPS} = \frac{T * P_f}{OE + \beta * E_{Co_2} + \gamma * C_{tox} + \delta * \Delta S} \quad (1)$$

Subject to $E_{CO2} \leq E_{max}$, $C_{tox} \leq C_{treshold}$, $\Delta S \leq \Delta S_{max}$

Where:

T: Net Production Throughput (good units passing First Pass Yield per hour or OEE).

P_f: Functional barrier (mechanical, oxygen, gas, etc…) and structural performance factor (0≤ Pf≤ 1).

OE: Direct Operational Expense (raw materials, processing energy, conversion, and logistics).

ECO_2: Lifecycle Greenhouse Gas Intensity (kg CO_2 eq) per functional packaging unit delivered).

C_{tox}: Chemical hazard index (migration risk, SVHC concentration, heavy metals).

ΔS: Entropic degradation score across circular reprocessing loops (chain scission, contamination).

B, δ, γ Conversion weight factors translating environmental carbon (EC02), chemical toxicity, and entropic degradation into system penalty values (e.g., carbon taxes, EPR penalties, internal shadow carbon pricing).

E_{max}: Maximum allowable lifecycle carbon footprint per unit under regulatory or corporate Science Based Targets.

This approach captures trade-offs across material transitions which are currently popular like the paperization or completely switching materials. For instance, swapping a polymer pouch for glass reduces entropic degradation (ΔS = 0) and chemical migration ($C_{tox} \approx 0$), but drastically increases transport E_{CO2} and OE for energy used/cost for remelting the glass. The expanded denominator penalizes this swap unless transport distances are near zero.

As an example we can take the case of currently popular paperization (switching polymer composites to paper composites) the TPS value would be:

$$\text{TPS}_{\text{paperization}} = \frac{\overbrace{(T\downarrow)}^{\text{Lower line speed}} * \overbrace{(P_f\downarrow)}^{\text{Weaker barrier}}}{\underbrace{OE\uparrow}_{\text{Higher basis mass}} + \beta * \underbrace{(E_{Co2}\uparrow)}_{\text{Pulp Energy and transport}} + \gamma * \underbrace{(C_{tox}\uparrow)}_{\text{PFAS/MOSH /adhesives}} + \delta * \underbrace{(\Delta S\uparrow)}_{\text{Composite entropic trap}}} \quad (2)$$

Here we would have several different angles to solve:

Mechanical & Throughput Penalties ($P_f \downarrow$, $T \downarrow$) Raw paper lacks intrinsic moisture, grease, and gas barrier properties. On high-speed converting and packaging lines, paper's lower tear resistance and stiffness lead to higher line downtime and reduced throughput (T). A lower P_f also increases product spoilage rates, creating indirect lifecycle carbon spikes.

Mass & Carbon Transport Burden ($E_{CO2} \uparrow$) To match the structural integrity of a thin polymer film, paper packaging requires significantly higher mass per functional unit (basis weight). This added weight drives up transportation emissions (E_{CO2}), while pulp production remains highly water- and energy-intensive compared to standard resin extrusion.

The Composite Entropic Trap ($\Delta S \uparrow$): To fix paper's barrier limitations, manufacturers laminate the fiber substrate with thin plastic coatings (e.g., PE or EVOH layers). This creates a multi-material composite structure that dramatically increases mixing entropy (ΔS_{mix}). The resulting hybrid material is difficult for standard paper mills to hydropulp, turning an ostensibly recyclable paper product into an unrecyclable entropic waste stream.

Chemical Hazard Migration ($C_{tox} \uparrow$): Paperization often introduces toxicological risks. Recycled paper pulps frequently carry mineral oil hydrocarbons (MOSH/MOAH) from inks, while grease-resistant paper variants historically relied on per- and polyfluoroalkyl substances (PFAS) or specialized functional adhesives, elevating the chemical hazard score (C_{tox}). Of course, this needs to be cross evaluated with the similar risk from polymeric recycling. The TPS-TOC model demonstrates that unless a paperization strategy uses mono-material, bio-based barrier coatings that preserve fiber pulping efficiency, it penalizes the system's net value denominator by trading lightweight polymer efficiency for heavy, chemically complex composite packaging.

So, to implement this approach first one has to identify the constraints and pinpointing whether system capacity is bottlenecked by line runnability (P_f), toxicity limits (C_{tox}) under PPWR/REACH), or thermodynamic degradation (ΔS). After that the next step is maximizing line output and shelf-life protection without exceeding toxicologic, environmental impact thresholds or triggering higher EPR penalty tiers. Through this approach all processes need to be subordinated from aligning upstream resin selection and downstream sorting strictly to support the identified constraint and excluding siloed in KPIs (like procurement lowest cost with no regards to other systems). Deploying Safe-and-Sustainable-by-Design (SSbD) innovations—such as bio-based mono-polymer coatings—to shift the physical performance and reducing toxicological, environmental and line production break impacts and at the end comes the mitigation of entropic inertia: re-evaluating system dynamics as shifts in PPWR compliance or material fatigue alter the primary constraint.

5. Conclusion

Modern packaging science is undergoing a fundamental paradigm shift. Driven by escalating climate pressures, stringent European Union regulatory mandates, and the imperative of the circular economy, packaging is no longer evaluated merely as a single-use vessel abstracted from the environment. Instead, we must conceptualize it as a Total (unified) Packaging System (TPS) where all subsystems where packaging and packaging /product are a part of the material world flow. While packaging is never an item itself but developed for a specific product, at its core, a packaging system must successfully execute several fundamental functions across physical, chemical, and human environments. These developments must surpass the fragmented siloed in and over the wall approach which perpetuates the status quo. By fully integrating all aspects with the available tools and key process indicators (and having consciousness about the interconnection of the decision to the biosphere) is a first step to start thinking and designing product packaging systems. The presented packaging development framework is a starting point on connecting all the dots to include and truly account for all upstream and downstream safety, toxicology and environmental impact with the most optimal choices available. They are either bound by material throughput of the production and transportation system or by agencies of governments which prescribe rules and policies. While the material performance, sustainability and safety have many newly developed tools and assessment frameworks like LCA, SSbD, which can be already today fully integrated the main challenge remains the current economic models which due to the downplayed energy cost and environmental costs (and its implication to biosphere and of course anthroposphere) are the main obstacles for full integration of these types of frameworks. The full accounting of all these downplayed factors would change the packaging and distribution of goods dramatically in some sectors demanding complete overhaul of the packaging concepts. While that is not likely in the near future due to the excess amount of energy needed to change the current systems and concepts, this proposal is a brick on paving the future road for a long journey many anthropogenic systems will need to go through to mitigate the climate risks we all are facing.

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