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Assessing the engineering design costs to meet environmental regulations: the case of packaging

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ABSTRACT: This novel contributions reveal how environmental regulations drive engineering design costs, focusing on the emblematic case of packaging. Using a regulatory database and simulation-based modeling, we evaluate functional expansion as a key driver of cost escalation, identifying its volume effect (rising costs from added environmental functions) and scope effect (increased interdependencies among ecosystem actors). The findings offer a simulated cost envelope to support engineering design teams in their forecasts, but also underscore the hurdles of sustainably managing these regulatory-driven costs in the packaging product system, by benchmarking cost trajectories against sustainability metrics, such as carbon pricing.

KEYWORDS: design costing, sustainability, evaluation, regulation, packaging

1. Introduction

For the environmental transition, product regulations have been a strong driver of progress. Nonetheless, meeting these regulatory demands often requires considerable additional effort from engineering teams. Gilain et al. (2019) emphasize that this effort can become substantial, especially when functional expansion leads to nonlinear effects. Amplification mechanisms, known in engineering design as change propagation (Clarkson et al., 2004), show how even minor regulatory changes in coupled systems can result in exponential design costs. While there is consensus on accelerating the environmental transition and accepting the associated costs, the challenge lies in managing these costs effectively within complex systems. This places a responsibility on engineering teams to anticipate and limit cost increases.

In this paper, we adapt a well-established cost model to packaging, which is a very relevant sector. Lindh et al. (2006) highlight that packaging plays a central role in sustainability, linking waste management and resource efficiency with broader environmental targets. Recent EU regulations promoting circular economy principles for packaging, outlined by Zhu et al. (2022), contribute to innovation in materials, modularity and end-of-life solutions such as reusability or biodegradability. This makes packaging an ideal focus for analyzing cost escalation driven by environmental regulatory requirements.

For this case study, more specifically, a French and EU regulatory database encompassing broad functional requirements—from product characteristics, processes, and life-cycle considerations to market uses—is leveraged. It also defines the scope of application to answer these three objectives:

1) **What is the extent of environmental functional expansion in packaging?**
2) **What is the associated estimated cost envelope and how does it compare to carbon pricing?**
3) **How can functional couplings be identified, evaluated and how do they influence the associated cost trajectories within this cost envelope?**

2. State of the art

This section discusses how engineering design addresses the rising costs of environmental transition in packaging design, a sector with significant sustainability concerns. Indeed, packaging is a major source of pollution, with large amounts of plastic waste remaining unrecycled while production continues to increase (Eurostat, 2023). The migration of toxic chemicals and microplastics disrupts carbon cycles and threatens biodiversity (Galloway et al., 2017). Moreover, packaging also reflects societal shifts in consumption, as well as evolving cultural and technological trends (Lindh et al., 2006). In line with this, recent reviews (e.g., Zhu et al., 2022; Kaestner et al., 2023) pinpoint various manufacturing applications that tackle environmental challenges through engineering design.

2.1. Review of the key drivers for design cost increases

Firstly, the literature indicates that, in our objective of estimating the costs associated with complying with environmental regulations, two key cost-increasing factors emerge: change propagation (Clarkson et al., 2004) and functional expansion (El Qaoumi et al., 2017). When combined, these factors can trigger an unmanageable cost explosion (Gilain et al., 2019). Anticipating these key drivers is crucial.

2.1.1. Analysis of change propagation and functional expansion

This is why, for the first factor, numerous studies have focused on evaluating propagation effects (Eckert et al., 2004; Giffin et al., 2009), while others have examined the ability to absorb changes and how to analyze influencing parameters to mitigate their impact (Brahma & Wynn, 2022). The objective is to manage system complexity to ensure resilience and adaptability over time (de Weck et al., 2011).

Regarding the second factor, research has shown that innovation increasingly depends on the expansion of new functionalities within the same product (Le Masson et al., 2019). In other words, additional functions are integrated once consumers adopt the existing ones. This sequential evolution has been observed in consumer goods over decades and contributes to their growing complexity.

The interplay between these two drivers has been explored by Gilain (2021), who built upon the Change Propagation Cost Analysis (CPCA) model developed by Rebentisch et al. (2017) to identify high-cost pathways in modular systems and mitigate cascading impacts. By incorporating metrics of functional expansion into a decoupling matrix structure designed to control costs, this work laid the foundation for the development of our cost simulation algorithm.

However, this model has never been applied to packaging before, so it is essential to previously confirm that packaging functions as a complex system capable of triggering systemic change propagation effects and that the law of functional expansion is applicable to this product category.

2.1.2. Integration of new environmental functions in packaging design

When examining the packaging design literature, the addition of new functionalities presents significant challenges. Traditionally, packaging has been designed to fulfill key roles such as protection, containment, communication, and convenience (Lydekaityte & Tambo, 2020). Over time, shifts in consumption patterns and market evolution have already introduced several new functionalities within packaging design. Thus, packaging evolves increasingly toward a complex system with possible change propagation effects. Moreover, increasing sustainability pressures have driven even more adaptations to meet societal and regulatory expectations. Once non-functional, environmental requirements have become central in product-system design over time. Consumer demand for eco-friendly options and technological advancements further shape this transition (Granato et al., 2022; Lydekaityte & Tambo, 2020). Regulations influence product design (Mahmoudi & Rasti-Barzoki, 2018). The Packaging and Packaging Waste Regulation (PPWR, 2024) introduces new environmental functions such as reducing virgin material use and fostering secondary raw material markets (Niero, 2023). Other regulations promote material innovation and pollution control (Wang et al., 2022).

While everything suggests that there is functional expansion in packaging with an environmental driver, this remains to be scientifically demonstrated. More importantly, the gap lies in evaluating the intensity of this expansion and simulating the design cost envelope in which engineering teams operate. Rather than a market-based economic analysis on sustainability or a verification that strategies are effectively implemented by companies, this study focuses on evaluating the engineering design efforts required to meet these environmental functional requirements.

2.2. The role of functional couplings in environmental transition

Secondly, the next step is to assess where, within the cost envelope, the packaging engineering teams are likely to shift from costly to more efficient trajectories. Literature on functional couplings in axiomatic design (Suh, 2001, 2005) offers valuable insights for this purpose.

2.2.1. Decoupling for managing systems complexity

Reducing cost trajectories requires revisiting research on managing complex systems. Studies have identified functional couplings as a major source of system complexity (Suh, 2005). Suh's second axiom (2001) explains how decoupling functional requirements and diagonalizing design matrices can reduce interdependencies, providing an alternative to more traditional trade-offs. However, some functional couplings resist decoupling, leading to '*functional lock-ins*' (Dong, 2017), where interdependencies persist despite mitigation efforts. This suggests their influence on systems and the higher design efforts required to unlock them.

Indeed, given the critical role of couplings in driving costs, our study must assess whether packaging systems are particularly coupled. In parallel, we need to investigate the nature of environmental functional couplings to propose a method for evaluating their intensity within packaging.

2.2.2. Nature of environmental functional couplings in packaging

For environmental transition, methodologies such as Modular Design, Design for Environment (DfE), and Design for Sustainability (DfS) provide tools to integrate new environmental functions. They shift the focus from product-level to system-level design, promoting sustainable consumption, circularity, and policy changes (Ceschin and Gaziulusoy, 2016; McAloone and Pigosso, 2017).

However, functional decoupling is not examined as a key factor in the environmental transition. For example, reducing packaging weight may conflict with maintaining product durability, particularly in glass packaging, where lighter designs increase the risk of breakage. Similarly, reuse systems benefit from standardized designs but conflict with branding needs for unique packaging. The complexity of determining functional couplings across different shapes and materials challenges automation. Thus, it highlights another research gap in assessing environmental functional couplings.

Another perspective on couplings is that environmental functions involve systemic transformations, not just technological ones (Niero, 2023), requiring alignment among stakeholders and active consumer engagement. For instance, reusable packaging systems demand design adjustments, shifts in behavior, and new supply chain processes. An ecosystem perspective, centered on value propositions rather than firms, offers a strategic framework for addressing functional couplings in packaging design. Research on platform ecosystems (Gawer & Henderson, 2007) suggests that shared functions among actors create both opportunities, and more importantly, unprecedented complexities. This provides valuable insights for developing our methodology, highlighting the role of coordination in managing decoupled functions. In other words, it offers a way to identify couplings by examining how the different actors within the packaging ecosystem contribute to the same functional requirements.

2.3. Research questions

Based on the gaps previously mentioned in the literature review, our three research questions are:

***RQ1*: What is the extent of environmental functional expansion in packaging?**
***RQ2*: What is the associated estimated cost envelope and how does it compare to carbon pricing?**
***RQ3*: How can functional couplings be identified, evaluated, and how do they influence the associated cost trajectories within this cost envelope?**

3. Methodology

This study follows an empirical research approach combining inductive exploration to identify emerging patterns in regulatory data and a deductive framework implementing theoretical models.

3.1. Data analysis of functional expansion in packaging

This section outlines our methodology for analyzing packaging regulations to assess functional expansion. We clarify our proxies, data selection, and coding process.

3.1.1. Regulations as proxies for functional requirements

From an engineering design perspective, any norm imposes product requirements and can be considered a function (Eisenbart & Gericke, 2020). However, not all functions are norms. By using norms to construct our database, we establish a lower-bound estimate of functions, acknowledging that our analysis likely underestimates functional expansion. Additionally, since regulations prioritize safety and environmental objectives, branding and communication functions may be underrepresented. While this may introduce bias, the binding nature of regulations significantly influences product development, mitigating its impact. As a result, our regulatory dataset is both unique and essential for evaluating functional expansion of packaging.

3.1.2. Identification and selection of key regulatory texts

The selection of regulatory texts follows three criteria:

1) Binding nature,
2) Comprehensive legislative coverage,
3) Relevance to stakeholders, validated through expert interviews.

A total of 276 articles from five key legal sources, covering 20 years of regulatory changes (2004-2024), are analyzed. This sample provides a representative overview of packaging regulations in France:

- French decrees and orders: *Code de l'environnement* (62 articles), *Code de la santé publique* (98 articles), and *Code la consommation* (18 articles).
- French law: *Loi AGEC n°2020-105* (52 articles), addressing waste reduction, circular economy.
- European regulation: *Packaging & Packaging Waste Regulation* (PPWR) (46 articles).

3.1.3. Building a structured dataset with dual coding to capture the functional expansion

Each legislative article is meticulously coded using a dual functional-thematic process:

1) First stage: Two independent coders extract every functional requirement from the regulatory texts, splitting long articles into meaningful subgroups where necessary.
2) Second stage: Collaborative discussions reconcile discrepancies between the coders' interpretations, refining the first-order codes into second-order codes.
3) Validation: Second-order codes are validated by external packaging legal experts. This step ensures the themes align with practical engineering requirements.
4) Aggregation: Higher-level dimensions are derived by grouping second-order codes. They are validated against the packaging literature (Lydekaityte & Tambo, 2020). Moreover, our coding supports expanding this functional structure to integrate the environment as a fifth pillar for packaging (Fig. 1), mirroring the growing importance of sustainability in regulation.

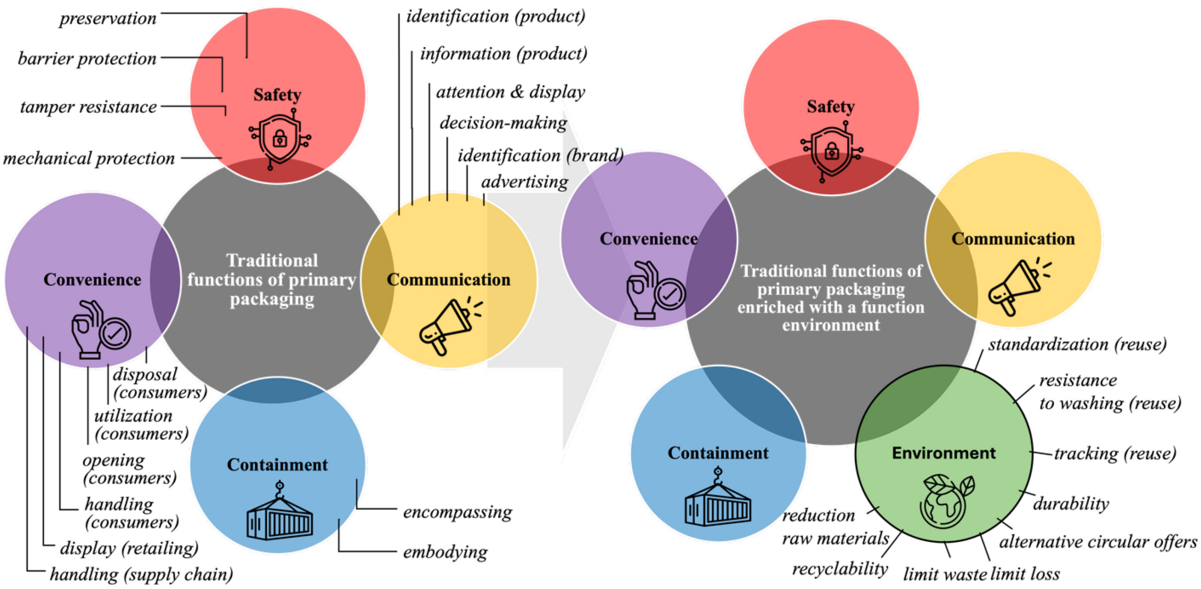

Figure 1. From a 4 to 5 pillars functional structure integrating environment

Figure 2 (left) presents the coding framework derived from our coding process, highlighting the higher dimensions from the functional analysis of our regulatory database (coding reference A). In addition, a parallel dual coding process identifies the packaging ecosystem actors (depicted in Fig. 2), responsible for implementing these functions. This coding reference B is also presented in Figure 2 (left) and used for RQ3 to explore specific functional couplings between actors, explicitly mentioned in the legal texts.

Coding reference A	5 pillars functional structure
1	Safety
2	Convenience
3	Containment
4	Communication
5	Environment
0	Not directly related to packaging (but to its contents)

Coding reference B	Types of ecosystem actors
1	Raw material extractor
2	Raw material processor, Manufacturer and Decorator of packaging
3	B2B Product Carrier
4	Manufacturer of the content/ product inside of the packaging
5	Mass Retailer
6	User (consumer or business)
7	Collector, Sorter
8	Reuse stakeholder
9	Recycling stakeholder
10	Waste treatment stakeholder
11	Regulatory stakeholders (EU Commission or others)

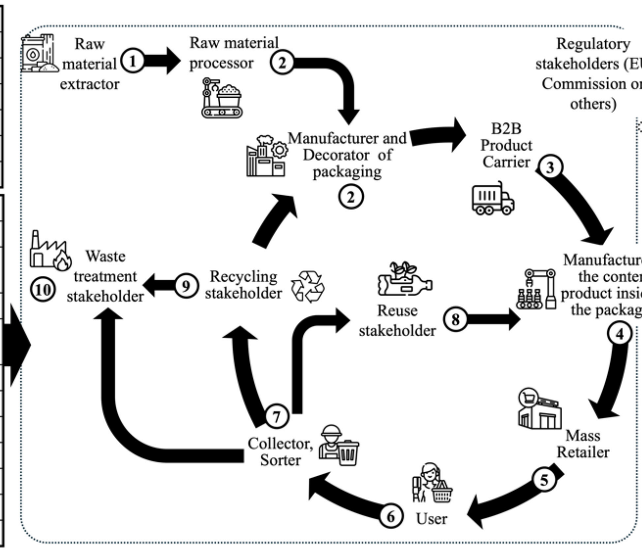

Figure 2. Left: Coding references; Right: Packaging ecosystem actors

3.2. Cost analysis using established engineering design models

The second methodology section outlines the theoretical framework and methodology behind our own custom algorithm, which constructs a cost envelope for functional expansion in a packaging ecosystem. It also clarifies the rationale for comparing these results to environmental transition benchmarks.

3.2.1. Algorithm to measure cost escalation in the context of functional expansion

This study builds on established models of functional expansion and cost propagation developed by El Qaoumi et al. (2017), Rebentisch et al. (2017), and Gilain (2021). Refer to these papers for conceptual details on the models. The foundations of the methodology are modularization capability through Design Structure Matrices (DSM) and scenario-based visualization with Change Propagation Analysis (CPA).

- ***Cost simulation using DSM***: To model costs associated with functional expansion, we employ the DSM approach. It captures system architecture in an $N \times N$ matrix (*density*), where rows and columns represent system elements (e.g., functional requirements or design parameters), and off-diagonal cells denote interdependencies.
  1) Baseline cost calculation: Gilain (2021) extends Rebentisch's model to assess the cost of functional expansion in complex systems. The baseline formula is $\boldsymbol{C_1=0.2*C_0}$, where C_1 represents the cost after functional expansion and C_0 denotes initial costs.
  2) Extended cost calculation: In our model, coordination costs are divided into internal (within a single actor's design space) and external (interfaces between different actors). The formula becomes $\boldsymbol{C_1= \alpha_0*C_0+\alpha_1*C_0}$ where α_0 and α_1 are internal and external coordination costs.
- ***Change propagation simulation***: Using an adaptation of the DSM model, we incorporate parameters for k-order propagation likelihood matrices $CL(k)$, which quantify the extent of functional changes propagating through the system. Low k-values correspond to well-controlled propagation and lower cost escalation.

The model is implemented in MATLAB to simulate functional expansion in a packaging ecosystem, where actors coordinate to modify the functional architecture. It iteratively expands the DSM, adding new functions and capturing dependencies. Coordination costs are computed at each iteration. For a more detailed process, refer to Cogez (2024), a dedicated thesis on prospective modeling.

Details on the application of the model:

- This simulation integrates the magnitude of the packaging functional expansion (evaluated using the coded regulatory data) and its impacts on cost modeling. Data integration is based on the number of functions added per time step (year).
- More than 1,000 simulations were run for each hypothesis (k,*density*), where *density*={0.1;0.2}, representing the number of architectural interfaces for an $N \times N$ matrix, and k=1,2,3 *and* 4, representing the k-order propagation path.
- We chose to limit the maximum k-order to k=4 based on the Change Propagation Analysis literature, as packaging is unlikely to be a large complex system causing extensive propagation.
- Different parameter sets for α_0 and α_1(which represent multi-actor collaboration costs) were tested. Costs increase with both α_0 and α_1; however, the impact on cost curves is less significant than that of the k-order. We chose intermediate values from our tests: α_0=0.15 and α_1=0.25.

3.2.2. Comparison with environmental transition benchmarks

In the absence of a standardized regulatory target for packaging design, the research adopts carbon quota prices under the EU Emission Trading System (ETS) as a proxy for environmental performance benchmarks. Carbon quotas measure marginal pollution abatement costs, providing a tangible reference for evaluating environmental transition costs. Using past trends and future projections modeled through the POLES framework (Mantulet et al., 2024), we construct an expected marginal abatement cost curve to compare functional expansion costs in packaging design. Since environmental functions drive expansion, this proxy assesses whether design-related costs align with sustainability benchmarks or present excessive challenges. For more details on limitations, refer to Cogez (2024).

4. Results

The results address the RQs using the described methods. ***RQ1*** applies data analysis of packaging regulations to show the extent of functional expansion. ***RQ2*** uses a cost simulation algorithm. ***RQ3*** refines cost envelope projections with functional couplings insights from regulatory data analysis.

4.1. Evidence of functional expansion in the packaging sector

By analyzing the regulatory dataset, we investigate the evolution of packaging functions over 20 years by tracking annual norm additions. ***The data confirm functional expansion*** (***RQ1***), with active norms increasing from 100 in 2005 to over 200 in 2024 (Fig. 3), covering all five pillars of the packaging

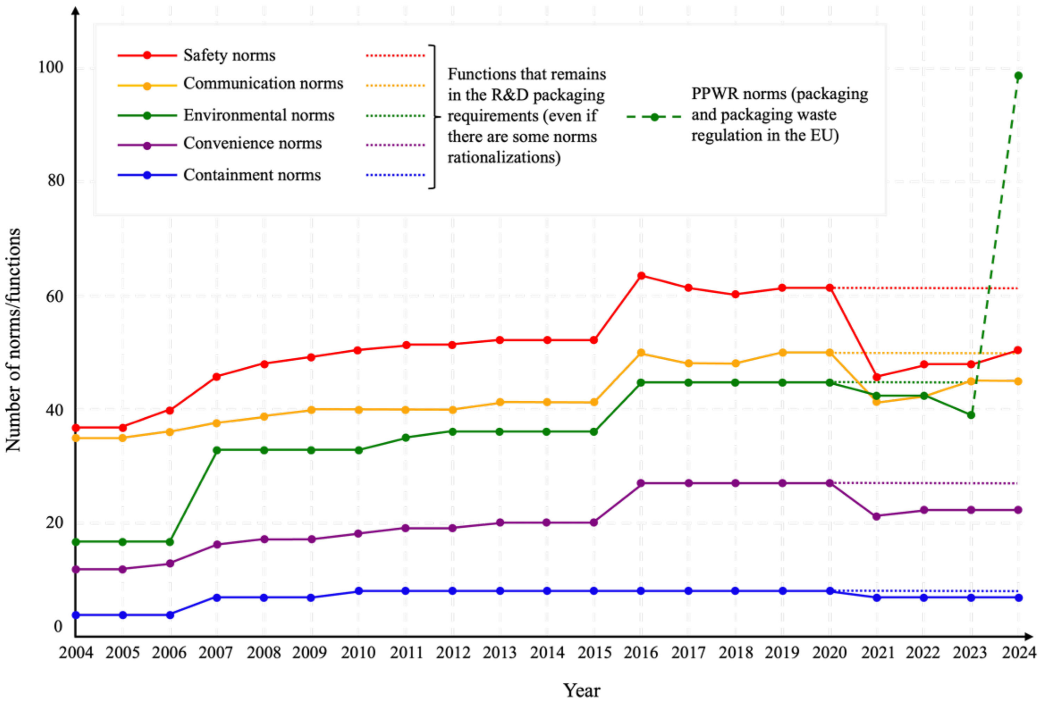

Figure 3. Packaging functional expansion curves based on regulatory dataset

functional structure. A decline between 2020 and 2023 stems from local decrees replacing norms, EU harmonization, and anticipation of the PPWR. Although discrepancies may arise from the partial inclusion of French legislative texts, this decline is an artifact of our coding method. From an industrial perspective, functional requirements remain stable, as older norms continue to apply until new ones take effect. Our tool captures legislative shifts and normative changes, with overall trends being the primary focus. The dotted lines on all curves in Fig. 3 illustrate a continuation of functional demands from an industrial perspective. ***Furthermore, the analysis of functional expansion identifies environmental norms as a key driver. The Environment pillar has risen from third to first place in normalization rank.*** Between 2005 and 2020, environmental functions grew by 139%, outpacing convenience (115%), containment (100%), safety (61%), and communication (35%). These surges align with key milestones such as the 2003 French Environmental Code, 2007 norms, the Paris Agreement (2015), and regulatory simplifications like AGEC (2020) and Climate and Resilience (2021). Recent increases are driven by European initiatives, notably the PPWR. The Environment pillar exhibits a distinct functional growth pattern with a sharp rise in 2024, raising concerns about the sustainability of such rates. In Fig. 3, longer green dashes should be interpreted cautiously, as they may reflect a coding artifact linked to the PPWR.

4.2. Estimated cost-envelope and carbon pricing threshold

4.2.1. Cost effects of functional expansion

Cost simulations based on regulatory data (Fig. 4) highlight the cost impact of environmental functional expansion in packaging, posing increasing challenges for engineering design teams. Using k-order values ($k = 1$ to $k = 4$), simulations introduce step-like cost increases ranging from 5% to 70% per cycle. At higher k-orders, the cost gap widens significantly as added functions amplify propagation effects. Data are scaled using min-max normalization (0-10), reflecting years without new norms and deliberately excluding norm removal in the simulation, and are tested under various parameter variations. While short-term increases seem manageable, cumulative function additions and change propagation create mounting challenges, particularly for higher propagation orders ($k = 4$). To refine our understanding of how environmental functional expansion affects costs, Fig. 5 assumes lower-bound projections, adding one function per year (without regulatory data induction) with a fitted curve for simplification and readibility purposes. Starting at €0 in 2015 and almost reaching €250 by 2038 for $k = 4$, the envelope likely underestimates actual costs. Despite these conservative assumptions, Fig. 5 still demonstrates exponential cost increases, particularly for $k = 3$ and $k = 4$, emphasizing the escalating burden on design teams and the urgency for proactive cost management.

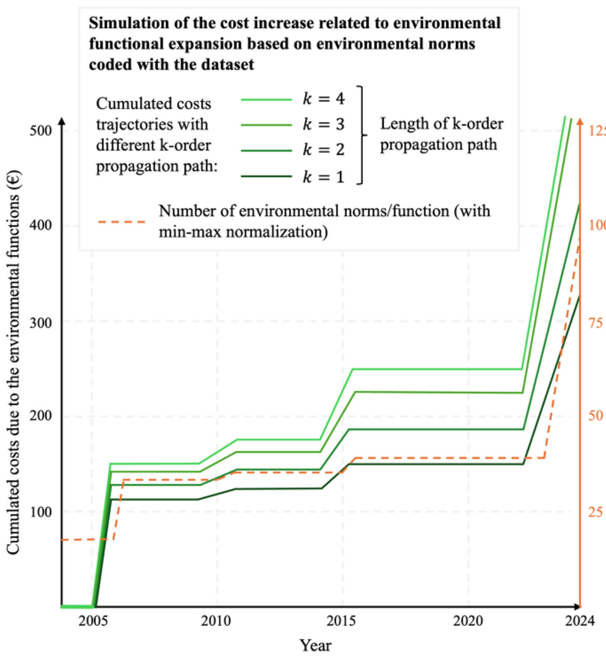

Figure 4. Simulated cost envelope *(based on environmental norms in the regulation dataset)*

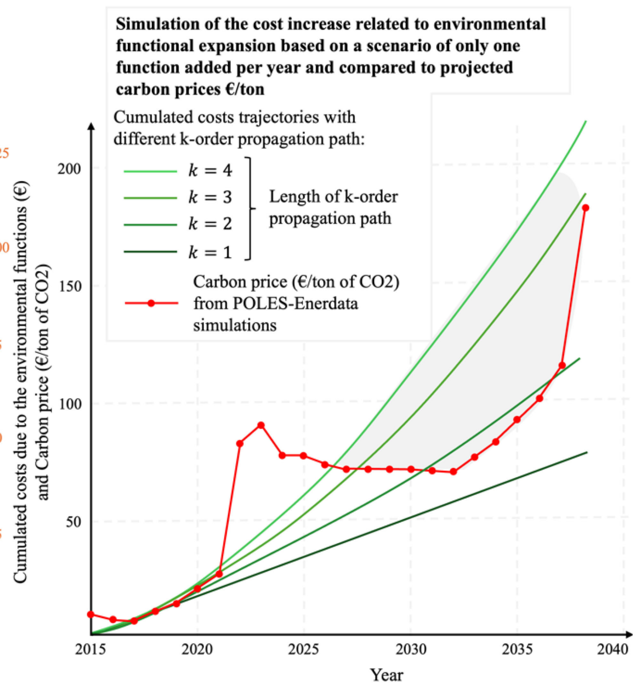

Figure 5. Simulated costs envelope *(1 function per year)* compared to carbon price per ton

4.2.2. Comparison with carbon quota pricing

For forecasts beyond 2024, we compare the simulated cost envelope under lower-bound assumptions (Fig. 5) to an external market cost that approximates the effort required for environmental transition: the carbon price under ETS. Leveraging the POLES-Enerdata scenario (Mantulet et al., 2024), we generate a trajectory, shown in red in Fig. 5. For our study, however, a key threshold is when the simulated functional expansion costs under lower-bound assumptions exceed the carbon price. In Fig. 5, this threshold appears in the grey zone, which dominates after 2027 in most k-order simulations, except for $k = 1$, which represents a packaging system with a lower change propagation rate. ***This comparison confirms that while initial cost increases may have seemed manageable, they become unsustainable when compared to market-based transition benchmarks like the carbon price*** (***RQ2***). Even for $k = 3$ and $k = 4$, our simulation shows that these costs were already untenable between 2017 to 2021. Only the $k = 1$ curve remains viable under lower-bound assumptions. For much of the cost envelope, costs surpass the market standard, creating a significant design barrier.

Minimizing system propagation is crucial for addressing future functional expansion challenges. Further analysis leverages functional couplings to refine likely trajectories within the cost envelope and propose mitigation strategies for these propagations.

4.3. Impact of functional couplings and ecosystem effects

4.3.1. Couplings across ecosystem actors

Research has demonstrated that functional expansion highly contributes to system complexity and interdependencies (Gilain et al., 2019). We have analyzed whether this also applies to environmental functions in packaging, and to enhance our cost trajectory analysis, our study now examines functional couplings in complex technical systems (Suh, 2001, 2005).

Instead of experimentally testing decoupling strategies experimentally, we assess the existing levels of coupling across packaging ecosystem actors. For instance, recyclability and closed-loop processes often span multiple subsystems and actors, complicating management. That is why, we have analyzed the regulatory dataset to identify stakeholders affected by each norm during the coding phase, as they are explicitly mentioned in the regulatory texts. The results show that environmental norms tend to impact more stakeholders per norm compared to other functional pillars of packaging (Fig. 6).

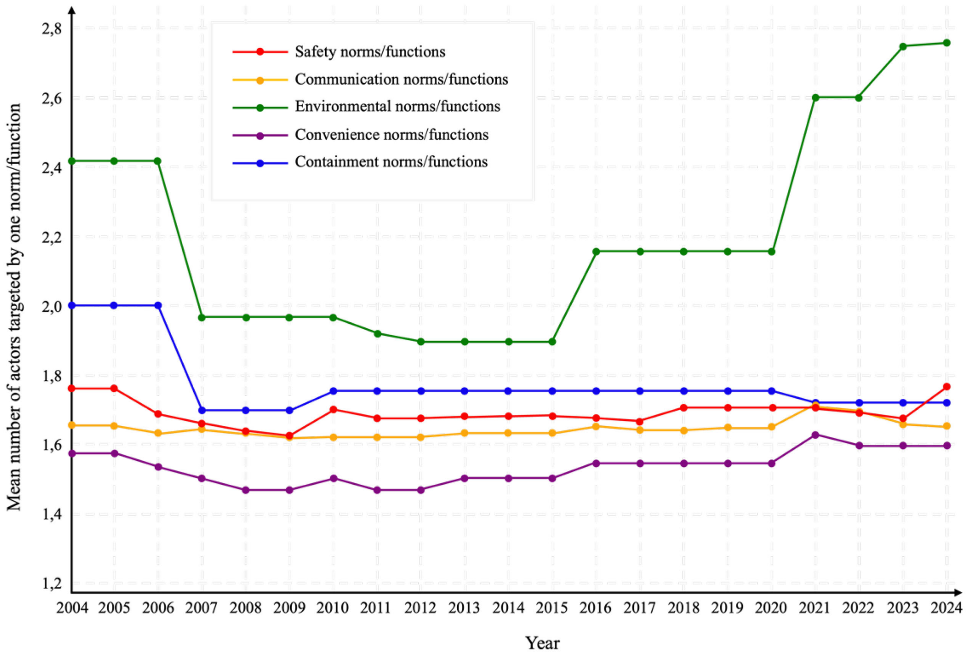

Figure 6. Average number of packaging actors targeted by one function per functional pillar

The green curve for environmental functions rises sharply after 2020 with the AGEC law. This confirms the systemic impact of environmental functions and the need for external coordination across multiple actors. For example, reducing packaging weight involves manufacturers, distributors, and recyclers, introducing system-wide challenges beyond traditional supplier-client relationships. Extended Producer

Responsibility (EPR) requirements and waste traceability demand collaboration across previously unrelated actors, disrupting established processes. Environmental functions consistently affect more actors, averaging 2.75 in 2024 compared to 1.5 to 1.75 for other pillars. ***This broader scope increases complexity and correlates to the higher segment of the cost envelope*** (***RQ3***). ***In Figs. 4 and 5, refined cost trajectories should then be closer to*** $k = 3$ ***and*** $k = 4$.

4.3.2. Discussion of coordination challenges and cost redistribution

Shifting from the $k = 4$ cost trajectory to $k = 1$ requires rethinking traditional engineering design approaches and initiating discussions about ecosystem-based engineering design for packaging. This research underscores the importance of fair cost redistribution strategies, collective efforts to enhance coordination mechanisms, and effective management of interdependencies. In modular product design —not limited to packaging—previous studies (Ülkü & Hsuan, 2018; Wang & Shulin, 2022) similarly examine the financial impact of new functional requirements but through profit-driven or price-based models. However, coordination within the packaging ecosystem extends beyond the supply chain, involving regulatory bodies, waste management stakeholders, recyclers or compliance organizations such as Extended Producer Responsibility (EPR) organizations. Thus, further efforts should explore the role of new intermediaries within the packaging ecosystem to tackle systemic challenges associated with environmental function, supporting more effective integration and decoupling strategies.

5. Conclusion

This study outlines two primary effects of functional expansion in the packaging sector, measured under lower bound norm assumptions, on engineering design costs:

1) The volume effect, driven by rising costs due to added functions, especially environmental ones.
2) The scope effect, stemming from greater environmental interdependencies among actors.

These findings emphasize the urgent need for strategies to manage regulatory-driven costs. While decoupling strategies remain challenging, our methodology leverages engineering design cost models to analyze an induced cost envelope and explore actionable ecosystem mitigation pathways. This contribution serves as an initial step toward addressing the Grand Challenge of environmental transition by identifying key cost-related issues and initiating discussions on effectively managing costs at the ecosystem scale, while fostering sustainable innovation.

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