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Accelerated life testing for packaging decisions in the edible oils distribution

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ABSTRACT

Food packaging is subjected to environmental stresses during its life cycle. Thermal stresses, which are highly recurrent in long-ray shipments, influence and compromise the expected performance of the package, as well as the quality of the product. This paper illustrates three significant applications of accelerated life testing analysis (ALTA) to food packaging for edible oils, demonstrating the effectiveness of such an approach to aid decision-making in the design of robust packaging solutions. The first and second case studies adopt constant-stress loading and Arrhenius prediction modeling, while the third adopts cyclical stresses and cumulated-damage prediction modeling rarely discussed in the literature. The conducted predictive and comparative analyses demonstrate the effectiveness of ALTA in the novel application of food packaging prototyping and provide guidelines for packaging improvements in response to the experienced transport conditions.

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1. Introduction

The main four functions of food packaging are containment, protection, convenience and communication (Robertson, 2006). In particular, the first function addresses the obvious and basic need to contain food products during transportation, i.e., the logistical tasks throughout the food supply chain. Protection means preserving the product from the environmental stresses caused by several agents, e.g., water, gases, dust, shocks, vibrations, and light. Containment and protection are interconnected and strongly affected by the integrity of the package. The package integrity should be ensured throughout the product life cycle until the final consumption to reduce food losses and the associated environmental impacts.

This paper focuses on the containment and protection functions of different packaging solutions for edible oils and assesses their response to the physical and ambient environments experienced during international shipments. These are characterized by unpredictable temperatures, which are indeed the main cause of package failures and of resulting product damages (Paternostera et al., 2017; Wang et al., 2015).

The how the packaging performs in the presence of stresses of different natures (e.g., temperature and vibration) relies on the ability to quickly prototype new solutions for food handling, storage and distribution (Berardinelli, Donati, Giunchi, Guarnieri, & Ragni, 2005; Brockgreitens & Abbas, 2015). Better understanding how the package faces with real-world conditions speeds up the design phase and minimizes the time-to-market of new products, reduces the probability of failures, damages and associated costs frequently affecting the storage and shipping operations, reduces the shelf-life erosion of food, increases the reliability of storage and delivery services, and, lastly, increases the reputation of the product's brand in existing and new markets.

The aim of this paper is to predict the reliability performance of a packaging solution in terms of "*package integrity*", instead of assessing its ability to preserve the shelf-life of the observed vegetable oils. Since the caps significantly affect the integrity of the bottled oils, this paper addresses a comparative analysis of the effectiveness of different enclosures.

This paper presents and illustrates a set of three case studies on reliability prediction and performance evaluation of edible oils packaging to support their robust design, by the application of accelerated life test analyses (ALTA) applied in electronic and mechanical fields, but rarely in food packaging design (Dunnoa, Cookseya, Gerardb, Thomasa, & Whitesidea, 2016).

The remainder of this paper is organized as follows. Section 2 presents a brief literature review on edible oil supply chain, criticalities in transportation and ALTA. Section 3 presents the basic models adopted for ALTA. Section 4 presents the problem formulation, the basic assumptions and the standard models

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adopted for the conduction of the selected case studies. Sections 5–6 present three case studies on edible oil supply chains. Case study 1 and case study 2 present two different applications of the constant stress accelerated models. Case study 3 illustrates the results obtained by the application of a cyclic cumulated model for the prediction of the packaging system performance. Section 8 presents the study's conclusions and further research.

2. Literature review

Piergiovanni and Limbo (2009) present a comprehensive survey on packaging and shelf life of vegetable oils. In particular, they discuss how packaging decisions impact on the metrics of failure and on the deteriorative reactions that influence the shelf-life.

Accorsi, Versari, and Manzini, 2015 illustrate a typical supply chain of edible oils. Whereas the consolidation of olives and the transport from the olive-mills are made in bulk, the processed oil is bottled and then distributed to the customers (e.g., the retailer and the importer) palletized in containers using multi-modal solutions (Accorsi, Bortolini, et al. 2014; Accorsi, Manzini, & Ferrari, 2014). Especially in long-ray shipments, the transport phase affects the bottles with temperature stresses, humidity variation, shocks and vibrations.

Among these, the conservation temperature significantly affects the oil quality (Maggio et al., 2011; Piergiovanni & Limbo 2009; Valli et al., 2013). Low temperatures (below 4 °C) negatively alter some micro-components (phenolic compounds) of olive oil due to the crystallization of triacylglycerol (Bendini et al., 2007), while high temperatures (above 30 °C) may incur rancid defects and volume expansion that results in oil leakage.

Literature on the food supply chain is increasingly focused on logistical operations and issues highlighting the crucial role of storage and transport in preserving the safety and quality of food products at the consumer site (Biji, Ravishankar, Mohan, & Srinivasa Gopal, 2015; Chen, Ying, Zhen, & Chen, 2013; Hansen et al., 2015; Padmashree, Khan, Semwal, Govindaraj, & Sharma, 2009; Valli et al., 2013). Ayyad et al. (2017) and Manzini et al. (2014) debated the extant literature regarding the assessment via simulation of the quality and safety of edible oils after international shipments.

Accelerated life testing (ALT) is the process of testing an item, i.e., a product, with *overstressed* conditions, compared to *nominal* conditions, to shorten its life-cycle because of fast degradation (Dodson 2006; Nelson, 1990 Nelson, 1990). The prediction process is made under overstressed conditions and indirectly estimates the failure process at nominal conditions.

The stress loading is an accelerated test that can be applied in various modalities according to renowned profiles (Nelson, 1990): (1) *constant* stress; (2) *step* stress if the item is subjected to the following stresses; (3) *progressive* stress, when subjected to increasingly higher stresses; (4) *cyclic* stress, when items repeatedly undergo a cycling stress loading; (5) *random* stress, when items undergo randomly changing levels of stress.

The profiles from (2) to (4) are known as "cumulative stress exposures" because of the varying stress in service or in the stressed test. Thus, the so-called accelerated model considers the cumulative effect of exposure and is known as the "cumulative model". The typical context of the application of the varying stress and cumulative exposure are the steel fatigue analyses (Castiglioni & Pucinotti, 2009).

In *cyclic* stress, the frequency and length of a cycle influence the items life and are thereby involved in the prediction model.

The extant literature widely applies accelerated testing models, e.g., Arrhenius equation, and multivariate degradation kinetics to predict the shelf-life and the quality of food products by considering sensorial, physical and chemical attributes (Piergiovanni & Limbo, 2010). García-García, López-López, and Garrido-Fernández, 2008 used ALTA to estimate the shelf life of ripe olives, Ganje et al. (2016) of tomato paste, and Derossi, Mastrandrea, Amodio, De Chiara, and Colelli, 2016 worked on fresh-cut lettuce. These models can provide an accurate description of the degradation phenomena occurring during the storage activities. Further investigations are then expected on the effect of transport activities on packaging performances and associated food degradation. Given the long duration of the international shipments (up to 30–40 days), and in general of the transport activities, the packaging prototyping and testing phases that involve the logistics stresses could be long and cost-intensive. Thus, the ALT analysis represents a valuable and cost-effective approach to address this issue.

The literature does not yet present significant contributions on the application of ALTA to aid the design of packaging solutions able to respond to critical logistics tasks (e.g., storage, handling, international shipment). Manzini and Accorsi (2013) presented a single contribution; they define a conceptual framework for food supply chain assessment based on the simultaneous control of quality, safety, sustainability and logistic efficiency, focusing on the critical role of packaging for successful international shipment. In addition, they present a case study that addresses the distribution of edible oils from Italy to Taiwan, and apply an ALT analysis for the lifetime prediction of two different plastic enclosures. This was to exemplify ALTA to study the packaging in the presence of constant thermal stresses.

This paper extends this study and illustrates how alternative models can predict the performance of primary packages for edible oils. A selection of case studies on the international distribution of bottled edible oils demonstrates how to use the extant prediction models to aid packaging design and their effectiveness with real-world transport stresses.

One of the most original contributions of this paper lies on the application of the so-called "*cumulated damage models*" (known as "time varying ALT"), rarely discussed in the literature, especially in the field of packaging prototyping.

3. Accelerated life test models

This section addresses the basic statistical and reliability models adopted for the conduction of the accelerated life test analyses. A further and more detailed illustration of such models is presented by several contributions, e.g., Dodson and Schwab (2006), Manzini et al. (2010), Pascual, Meeker, and Escobar, 2006, and Phillips (2003).

The Arrhenius model for modeling reliability as the function of loading (applied stress V) is based on the following equation for the scale parameter η assuming a Weibull life distribution:

$$\begin{cases} \eta(V) = \dfrac{1}{kV^n} \\ R(t, V) = e^{-\left[\dfrac{t}{\eta(V)}\right]^{\beta}} \end{cases} \quad (1)$$

where $R(t)$ is the Weibull reliability function, and β is the shape parameter of the statistical distribution. k and n are model parameters. This is the inverse power function of the stress adopted in presence of a constant level of stress.

The Cumulative Damage model applied to the life-stress prediction of a product is illustrated by Mettas and Vassiliou (2002). They assumed Weibull as life distribution and the Arrhenius as life-stress relationship. The parameters of the reliability model are estimated adopting the maximum likelihood (the estimation method). They also present the algorithm

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