Intellectual System of the Life Cycle of Packaging Materials Characteristic Analysis

Tamara Chistyakova, Aleksandr Razygraev, and Christian Kohlert

Abstract The article considers an intelligent system for analyzing the life cycle characteristics of packaging materials, which allows, at given requirements for packaging materials, to evaluate the complex of properties of packaging materials, to calculate specific and generalized criteria for evaluating packaging materials, and to provide the user with the opportunity to choose the most suitable packaging material based on the results. The life cycle of packaging includes the following main stages: production of raw materials for packaging, production of packaging, recycling, and disposal of packaging. Each stage of the packaging life cycle includes its own set of qualitative and quantitative characteristics. The developed system is open, flexible, and built using modern client-server technologies, including a library of customizable criteria, a database of rules for selecting packages, databases of life cycle stages, packages, packaging materials, and characteristics of packaging materials. The system has an ergonomic interface and includes modules for entering package selection requirements, a module for evaluating package life cycle characteristics, a module for calculating package selection criteria, a module for changing expert data, a module for displaying comparison results in the form of various graphs and nomograms. The system is tested on the example of comparative analysis of the process of manufacturing packages, which may include: polyvinylchloride, polypropylene, polystyrene, low-pressure polyethylene, high-pressure polyethylene, polyethylene terephthalate, glass, paper, cardboard, white tin, aluminum. The developed intelligent system can be used for a comprehensive assessment of the life cycle of the production of packaging materials taking into account environmental safety, consumer, and economic characteristics.

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1 Introduction

Packaging plays an important role in promoting the product to the market, so preliminary studies of various packaging parameters, including environmental ones, will avoid errors and help manufacturers position their products correctly [1–3].

The history of packaging began with the use of natural materials, and then fabric, ceramics, glass, wood, tin, paper, cardboard, plastic appeared. Packages of different combinations of packaging material have now been widely used to benefit from the individual characteristics of each material [2, 3].

The life cycle of packaging includes the following main stages: production of raw materials for packaging, production of packaging, recycling (transition to the production stage), and disposal of packaging.

Figure 1 shows an example of the life cycle of packaging materials using polyvinylchloride (PVC) as an example. Each stage of the packaging life cycle is comparable to its own set of indicators, which can change over time due to social trends and scientific and technological progress. For example, the following characteristics [4–8] can be considered at the stage of packaging production:

- environmental characteristics of packaging materials, which take into account aspects of the use of natural resources in production, namely the parameters: the amount of energy consumed, the amount of air required for production, the amount of water required for production, the amount of waste produced, the amount of water consumed, the amount of oil consumed.
- consumer characteristics of packaging materials imply the physical properties of packaging materials important to the customer: water permeability, vapor

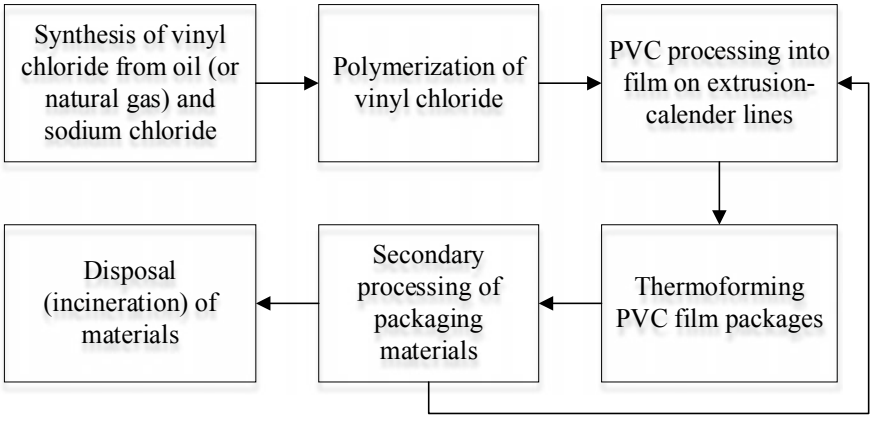

Fig. 1 Packaging product life cycle (PVC example)

permeability, density, heat resistance, elasticity, the maximum temperature of use, minimum temperature of use, surface tension, energy for the manufacturing process, forming depth, printing capability, antistatic, photosensitivity, stiffness, tensile strength, impact resistance.

- economic characteristics of packaging materials imply economic effect from the production of packaging material and include parameters: raw material cost, packaging production costs, income from packaging production.

In developed industrial countries, the ratio of economic and consumer characteristics is constant, that is, packaging with better consumer properties is expensive and vice versa. The principle of rational use of natural resources (environmental characteristics) in the selection of packaging materials has become more and more important since about 2015. Developing countries often overestimate the economic aspect of packages, saving on quality in favor of value without taking into account environmental characteristics [9].

Product Life Cycle Analysis (LCA) [10] is often used to assess natural resource management. This analysis is used to assess the environmental impact of a product associated with all its life cycle stages. At the same time, a life cycle assessment (taking into account the environmental aspect of the impact on the environment of an individual product) and a comparative life cycle assessment (is a comparison of several products with holistic consideration of environmental, consumer, and economic characteristics) are distinguished.

The methodology for life cycle analysis is established in international standards ISO 14040-ISO 1404 [11, 12]. The interpretation of the results of the product life cycle assessment should lead to subsequent improvement of the product, for example, due to the improvement of production technology [13, 14]. Implementation of product improvement solutions often results in product marketing benefits [15].

In view of the above, the task of developing an intelligent system for analyzing the life cycle characteristics of packaging materials has become relevant enabling the assessment of properties and calculation of specific and generalized criteria for the evaluation of packaging materials, according to the specified composition of the compared packaging materials, according to the comparison criteria determined by the product rules in accordance with the specified stage of the life cycle and the scope of application of the packaging, and enable the user to compare the life cycle and select the most appropriate package based on the results.

2 Description of the Developed Intelligent System

Figure 2 shows the architecture of the developed intelligent system for analyzing the life cycle characteristics of packaging materials.

The developed architecture consists of their three main modules [8]:

- the administrator interface (knowledge engineer) is introduced to implement the function of replenishing the rule database and the database with expert data, such

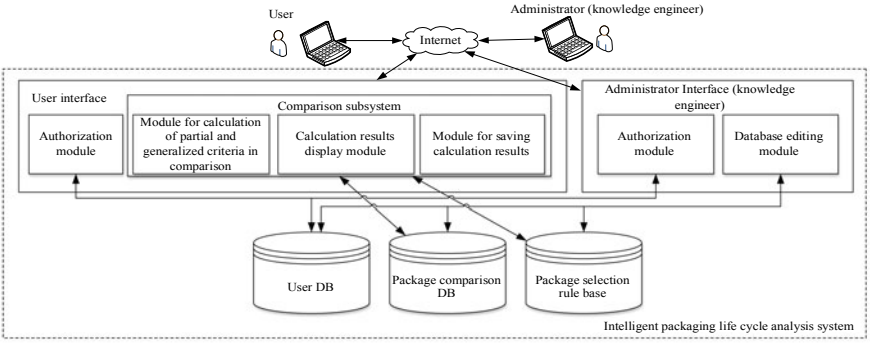

Fig. 2 Packaging materials intelligent life cycle analysis architecture

as: specific values of the characteristics of packaging materials, the number of characteristics used in comparing packaging materials for a given area of application of packaging and a given stage of the life cycle, the values of the weight coefficients of the characteristics (used in calculating the comparison criterion using the method of linear convolution of criteria), and other reference books. This expert data cannot be changed by the user, and some of this data is hidden from the user, for example, specific values of the characteristics of packaging materials. For this purpose, an authorization module is introduced into the interfaces;

- the user interface includes a subsystem for comparing packaging materials, which includes: a module for calculating partial and generalized comparison criteria, a module for displaying the result in the form of tables and nomograms, and a module for storing calculation results;
- information subsystem includes: data describing package comparison modules (scope of comparison packages, name of comparison module, names of compared packages, composition and weight values of packages); data necessary for the calculation of criteria for evaluation of characteristics of packaging materials (specific values of characteristics of packaging materials, weight coefficients used in the calculation of a generalized criterion); rules for the selection of packages determining the composition and weight coefficients of the comparison criteria depending on the application of the compared packages and the stage of the life cycle of the packages; system user data.

Setting the task of evaluation of characteristics of packaging materials: for specified input variables (package life cycle stage A, package application area B, comparison module name S, number of packages in comparison module n, number of packaging materials in comparison module m, array of package names U, array of weight values of packaging materials in package P) and selected using a rule database and a database of variables (an array of packing material K characteristic names; quantity of characteristics of packaging materials s; array of specific values of characteristics of packaging materials Y, array of names of packaging materials M; array of weight coefficients of characteristics W) to form output variables (array of absolute values of

characteristics of packages G; an array of relative values of the environmental characteristics of the Grel packages; an array of aggregated packing indicators by group I) in the form of tables, graphs and nomograms, according to which the user will carry out a comparative life cycle assessment and choose the most suitable packaging.

The algorithm for evaluating the characteristics of packaging materials consists of the following procedures:

- calculation of values of characteristics of packaging materials for compared packages;
- bringing all characteristics to a single scale by calculating the relative values of the characteristics of packaging materials;
- calculation of criteria for evaluation of characteristics of packaging material by linear convolution method [16–18].

The intelligent system database contains specific values for the characteristics of packaging materials and must be recalculated for packages according to their recipe. If the specific values in the database are given in absolute units (for example, for the environmental and economic characteristics of the packaging production stage), then the recalculation is carried out according to the formula:

$$G_{ki} = \sum_{j=1}^{m} \left(Y_{kj} \times P_{ij}\right), \tag{1}$$

where G_{ki}–the array of package characteristic values taking into account package recipe, $k = 1..s$, $i = 1..n$; Y_{kj}–the array of specific values of packing materials characteristics, $k = 1..s$, $j = 1..m$; P_{ij}–the array of weight values of packaging materials in package, $i = 1..n$, $j = 1..m$; n–number of packages in comparison module; m–the number of packaging materials in comparison module; s–the quantity of packing material characteristics.

If the specific values in the database are given in relative units (for example, for consumer characteristics of the packaging production stage, all parameters in points from 0 to 2 relative to polyvinylchloride, in which all values are 1), then the recalculation is carried out according to the formula with averaging:

$$G_{ki} = \sum_{j=1}^{m} \left(Y_{kj} \times P_{ij}\right) / \sum_{j=1}^{m} P_{ij}. \tag{2}$$

Calculation of relative values of package characteristics is performed by the formula:

$$G_{ki}^{rel} = G_{ki} / \sum_{i=1}^{n} G_{ki}, \tag{3}$$

where G_{ki}^{rel}–the array of relative values of package characteristics, $k = 1..s$, $i = 1..n$.

Calculation of the criterion for evaluating the characteristics of packaging material and calculation of linear convolution generalized by the method is made according to the Formula:

$$I_i = \sum_{k=1}^{s} \left(G_{ki}^{rel} \times W_k\right) / \sum_{i=1}^{n} \sum_{k=1}^{s} \left(G_{ki}^{rel} \times W_k\right), \tag{4}$$

where I_i–vector of generalized packing indicators, $i = 1...n$; W_k–vector of weight coefficients of environmental characteristics, $k = 1...s$.

The package selection rule base is represented by product rules allowing, according to the given name of the package life cycle stage A and the packaging application area B, to form a plurality of characteristics of the packaging materials K and their weights W used in the comparison of packages. Table 1 shows an example of a production rule for comparing food PET packages at the stage of packaging production.

The process of interaction of the user with the developed intelligent system in order to carry out the analysis of characteristics of packaging material includes the following steps:

- creation of a module for comparison of characteristics of packaging materials: generation of a name of the comparison module with the indication of the scope of application of compared packages and stage of the life cycle of packages, the formation of an array of package names, generation of weight values of packaging materials in the package, preservation of the comparison module and its settings;
- calculation of characteristics of packaging materials: calculation of characteristics, the formation of tabular results, generation of nomograms, preservation of results;
- comparison and selection of packages.

An intelligent system for analyzing the life cycle characteristics of packaging materials has been developed using modern client-server technologies. The client part is developed using HTML, CSS, JS, Axios, Vue.js, and Vuetify.js. The server part is designed using NodeJS. The development of the relational database was carried out in the database management system MySQL.

Table 1 Sample product rule

If	So
A = « PRODUCTION OF PACKAGES» AND B = « FOOD PET PACKAGING»	(K_1 = « AMOUNT OF ENERGY CONSUMED» , W_1 = « 0.2») AND (K_2 = « AMOUNT OF CARBON MONOXIDE EMISSION IN PRODUCTION » , W_2 = « 0.3 » AND (K_3 = « AMOUNT OF OIL CONSUMED» , W_3 = «0.4 »)

3 Intelligent System Test Case

Table 2 shows an example of input data for comparing three pharmaceutical packages at the stage of packaging production. Open-source data was used to test the database with specific characteristics of packaging materials [19].

Figure 3 shows an example of comparison results according to Table 2 as a graph of comparison by a group of environmental characteristics of packages. Figure 4 shows an example of comparison results according to Table 2 as a comparison of a generalized graph of the results of the evaluation of the characteristics of packaging materials in the stage of their production. By analyzing the results, the user will be able to choose the most environmentally friendly package (Package 3) or with the best consumer characteristics (Package 1) at the stage of packaging production.

Comprehensive testing of the software complex was carried out on the basis of the data provided by the international corporation Klöckner Pentaplast Europe GmbH & Co. KG characterized by multi-assorted production of packages. The system is tested on the data of the process of production of food and pharmaceutical packages, which may include: polyvinylchloride, polypropylene, polystyrene, low-pressure polyethylene, high-pressure polyethylene, polyethylene terephthalate, glass, paper, cardboard, white tin, aluminum.

Table 2 Composition of compared packages

Material	Package name		
	Package 1	Package 2	Package 3
Polyvinylchloride	5.72 г	0	0
Polypropylene	0	3.8 г	0
Aluminum	7.27 г	7.9 г	15.6 г

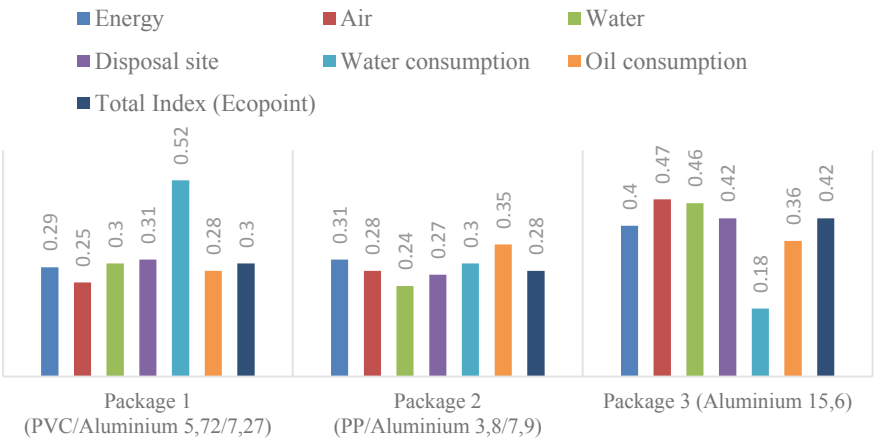

Fig. 3 Schedule of comparison of three pharmaceutical packages at the stage of production by a group of environmental characteristics of packages

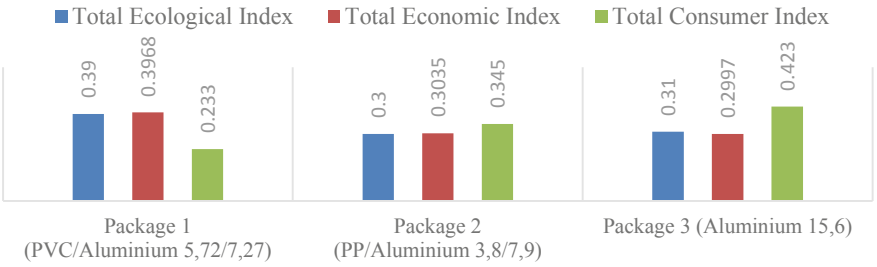

Fig. 4 Schedule of comparison of three pharmaceutical packages at the stage of production by generalized indicators

4 Conclusion

A flexible intelligent system has been developed, customizable to various comparison criteria, types of packaging materials, stages of the life cycle of packages, areas of application of packages, allowing for the specified requirements for packaging materials, to evaluate the characteristics of multi-component packages and provides the user with the opportunity to analyze and select a packaging material based on the results.

Testing of the intelligent system confirmed its operability to solve the problem of analyzing the life cycle characteristics of packaging materials. The developed intelligent system was introduced into experimental and industrial operation at the company for the production of polymer film materials Klöckner Pentaplast Europe GmbH & Co. KG [20].

The developed system can be used by packaging manufacturers to position products in dialogue with buyers, environmentalists, government services, and other stakeholders in a comprehensive assessment of the life cycle of packaging materials production taking into account environmental safety, consumer, and economic characteristics.

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