FORMALIZATION OF FABRIC RECYCLING METHODS DEPENDING ON RAW MATERIAL COMPOSITION FOR INTELLIGENT DECISION SUPPORT SYSTEMS.

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In the current conditions of transition to a circular economy, the textile industry is one of the most problematic in terms of waste generation, material reuse and reduction of anthropogenic load on the environment [1]. A significant proportion of textile products after the end of their life cycle end up in mixed waste streams, which complicates the reuse of fibers, reduces the quality of secondary raw materials and increases the cost of sorting [2]. A recent publication based on materials from your scientific school emphasized that in the EU alone, more than 5 million tons of textile waste are generated annually [3], and the lack of effective sorting mechanisms directly limits the possibilities of high-quality recycling [4].

The relevance of the topic is enhanced by the fact that traditional determination of fabric composition during sorting [4] is often performed manually or requires the use of expensive laboratory equipment, in particular spectroscopic systems. A review of current research shows that automated sorting of textile waste increasingly combines machine learning, deep learning, computer vision, and spectral analysis methods, but key unresolved issues include mixed fiber recognition, the lack of open representative datasets, and the need for hybrid decision-making models [5].

Of particular interest is the use of computer vision and convolutional neural networks in image-based fabric classification tasks. Such approaches are attractive due to their relatively low implementation cost, scalability, and the ability to be integrated into applied digital decision support systems [6, 7]. Research in the field of machine vision for textile sorting demonstrates that modern models are capable of achieving high accuracy even in challenging conditions, when objects have deformations, overlaps, or similar visual characteristics. For example, in work on automated classification of used clothing for recycling, the proposed approach increased accuracy to a level of over 90%, close to human, on a sample of about 27 thousand samples.

The aim of the work is to formalize the methods of processing fabrics depending on the raw material composition for further use in intelligent decision support systems. To achieve this goal, it is advisable to: identify informative features by which it is possible to establish the belonging of the material to a certain raw material class; form a formalized representation of processing options; build a rule or set of rules for choosing the recommended method of handling the material; determine the place of the computer vision module in the general architecture of the decision support system; and also assess the practical suitability of such an approach based on experimental results of fabric classification.

Within the framework of the study, the decision-making process regarding the further handling of a textile product is presented in the form of a formalized sequence of interconnected stages, which includes the analysis of input data, identification of the raw material composition of the material, assessment of the reliability of the classification conclusion, determination of a rational method of processing or reuse, and formation of an explained recommendation for the decision support system [8]. Unlike approaches that are limited to image classification, the central point here is the formalized connection between the identified composition of the material and the recommended scenario for its further processing.

Let the textile object be described by a vector of observations $X = \{I, M, S\}$, where I – fabric image, M – product metadata available, S – signs of the physical condition of the material, in particular the degree of wear, the presence of contamination, damage or deformation. Then the classification module forms an assessment of belonging to the class of raw material composition $C \in \{natural, synthetic, blended, uncertain\}$. In the current experimental setup, the basic recognition is based on two classes – «natural» and «synthetic», which corresponds to the available training sample. At the same time, for the decision support system it is advisable to immediately establish the classes "blended" and «uncertain», since in real waste streams mixed fabrics and uncertain cases are typical. Let $P(C|X)$ – posterior probability distribution generated by the computer vision model. Then the initial decision about the material class can be determined by the rule $C^* = argmax\ P(C|X)$. However, for industrial or semi-industrial use, this is not enough. If the maximum probability is lower than the threshold value τ, the system should not automatically issue a final recommendation, but should transfer the sample to additional verification mode: *if* $max\ P(C|X) < \tau$ *then expert/manual inspection*. This rule reduces the risk of misdirecting material into the wrong recycling channel.

The next level of formalization is related to the choice of how to handle the material. Let the set of possible solutions be R = {*reuse*, *mechanical recycling*, *chemical recycling*, *downcycling*, *energy recovery*, *manual inspection*}. Then the decision support function can be given as $R^* = g(C^*, q, d, u)$, where q – sample quality assessment, d – degree of damage, u – classifier confidence level.

For natural materials in satisfactory condition, it is advisable to prioritize reuse or mechanical processing, since such fabrics are able to retain useful properties after sorting and shredding. For synthetic materials, mechanical processing of polymer raw materials is more relevant, and in some cases, chemical processing, especially when it comes to restoring polyester or similar fibers. If the material has significant contamination or low quality, but its composition is determined with confidence, the system can recommend «downcycling» – conversion into lower-value, but functionally suitable products, such as insulation or filling materials. For doubtful or mixed cases, «manual inspection» is the priority.

Thus, the proposed formalization transfers the task from the plane of conventional classification to the plane of multi-step intelligent selection. In practical terms, this means that the system should not only recognize the type of fabric, but also reasonably suggest the most appropriate scenario for its further use. This approach better meets the needs of real sorting of textile waste than models that are limited only to the output of the class name.

To test this approach, the results of experimental classification of fabrics by images, given in the downloaded material, can be used. In it, the «FabricsDataset» set containing 3108 images divided into classes of natural and synthetic materials was used for the study; the sample was distributed in the ratio of 80% / 20% to the training and validation parts. A CNN model was used for the task, including convolution, subsampling, global averaging and Dropout regularization blocks. 97.59% accuracy was obtained on the training sample and 97.58% on the validation sample; the loss function values were 0.075 and 0.081, respectively. In addition to classification, the software implementation provides for the formation of a block of recommendations for further handling of the material.

These results are important for two reasons. First, they confirm that visual features of fabrics can be sufficiently informative for reliable binary distinction of raw material classes without the use of complex laboratory infrastructure. Second, they create a practical basis for the transition from the task of «classifying images» to the task of «forming a recommendation for processing» [9]. This is precisely the methodological content of an intelligent decision support system: the classification module acts as a source of formalized features, and the recommendation module is a means of transforming these features into an applied solution [10]. The prospects of this direction are also confirmed by the latest results of deep tissue analysis. In a related work in 2025 on an open dataset of 3107 microimages of fabrics, the ViT and ConvNeXt models achieved an accuracy of 0.9984 and an F1-score of 0.9984, which indicates the great potential of modern computer vision architectures for automated sorting of textile materials. At the same time, the authors directly point out the complex cases associated with striped and ribbed patterns, and also emphasize the need for further data diversification and multi-scale analysis.

Given this, it is advisable to direct the further development of the proposed formalization in several directions. The first is the expansion of the set of classes to mixed compositions with a partial assessment of the dominant component. The second is the integration of additional sources of information, such as text marks, labels, spectral data or manual expert confirmation for borderline cases. The third is the implementation of explainability of decisions, when the system, along with the recommendation, indicates which visual features most influenced the classification and why this particular channel of further processing was chosen [11, 12]. The fourth is the construction of an economic selection criterion, under which, among several permissible processing scenarios, the system will choose the one that provides the highest environmental and production feasibility.

The practical significance of the proposed approach lies in the fact that it can be used in digital services for light industry enterprises, sorting lines, eco-centers, textile waste collection points, as well as in educational or consumer mobile applications. For industrial users, the system can serve as a pre-sorting tool, for environmental initiatives - a means of supporting responsible consumption, and for researchers - a platform for accumulating and analyzing new data on the behavior of textile materials in secondary raw material flows.

Thus, the formalization of fabric processing methods depending on the raw material composition is a reasonable basis for building intelligent decision-making support systems in the field of textile recycling. The proposed approach combines a visual fabric recognition module with a rule-based or hybrid mechanism for selecting the recommended method of further handling of the material. Unlike conventional classification systems, such a model is focused not only on identifying.

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