BUCHAREST ACADEMY OF ECONOMIC STUDIES

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Doctoral thesis summary:

Artificial intelligence in support of the circular economy: research and applications for reducing food waste

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KEYWORDS: circular economy, artificial intelligence, food waste, visual identification, ripeness distribution

SUMMARY

Technological progress has led to the emergence of increasingly sophisticated and efficient solutions to contemporary challenges. One of these addresses the management of limited natural resources, an issue that has driven the adoption of new economic models based on principles of reuse and recycling. In this context, the agri-food sector, as one of the largest consumers of resources, is directly confronted with the problem of food waste, which has become a major priority within initiatives aimed at transforming the economic model.

This thesis defines and describes the processes of developing and testing an intelligent web platform designed for the automatic visual assessment of perishable foods, with the goal of contributing to food loss reduction and improved economic efficiency. The platform is distinguished by several original elements, most notably the manual implementation (both on CPU and GPU) of image preprocessing logic to reduce response times, the integration of an advanced temporal tracking mechanism that includes a ten-dimensional Kalman filter complemented by complex filtering methods, as well as the computation of ripeness distribution through algorithms based on the color spectrum combined with the Sobel filter to identify regions with irregular texture.

The identified limitations, such as the absence of a segmentation model for improved accuracy or the lack of assisted continuous learning mechanisms, represent starting points for future research. These directions could contribute to extending the platform's capabilities and integrating it into a broader digital ecosystem dedicated to agri-food sustainability and resource waste reduction.

The doctoral thesis is organized into five chapters. The first two chapters are dedicated to the conceptual framework and the current state of research, including the definition of the economic context, the identification of the main issues, and the presentation of existing international solutions (particularly in Europe and the United States). This section also analyzes the influence of artificial intelligence on the circular economy and emphasizes its contribution to the development of digital solutions aimed at increasing process efficiency and mitigating the negative effects of the linear economic model.

The following three chapters focus on the applied dimension of the research, highlighting the practical utility of the study, the development of original solutions, and the formulation of conclusions that validate the consistency and relevance of the scientific endeavor.

The first chapter, entitled *Current economic context. The need for the circular economy transition*, outlines the characteristics of today's linear economic context and the importance of transitioning to circular models.

The first part contrasts the linear and circular models. It defines the limitations of the linear model (dependence on finite resources, vulnerability to supply chain shocks, and price volatility) and explains how the paradigm shift towards a circular economy creates opportunities across different sectors of activity. Furthermore, in order to link with the issue addressed by the platform developed within this thesis, the section dedicated to food waste demonstrates why the agri-food sector is a priority for the implementation of circular policies. Synthesized data indicate significant losses along the value chain and different distribution patterns across its segments (households, retail, HoReCa, production). Finally, the major benefits of the circular model are presented: reducing pressure on resources, lowering emissions and pollution, increasing energy efficiency through more reliable products, the creation of green jobs and the stimulation of innovation, as well as reducing dependence on imported raw materials.

The second part synthesizes the European strategic framework (the European Green Deal and the Circular Economy Action Plan), the energy transition (including through REPowerEU), sustainable mobility, and agriculture (from farm to fork). Industrial alliances are also mentioned (focusing on batteries, raw materials, hydrogen, and plastics). In addition, initiatives from the United States are included, implemented through the Environmental Protection Agency (EPA): regulations and programs for water, air, and energy, fiscal incentives for energy efficiency, as well as emission reduction partnerships.

The second chapter, entitled *Digitalization and the circular economy*, analyzes the main ways in which digital solutions can support the implementation of circular economic models. This section provides an overview of the key technologies that can accelerate the transition to a new economic model: the Internet of Things (sensor networks and connected devices that collect data on condition, usage, and environment), Cloud Computing (IaaS, PaaS, SaaS for storage, processing, and application delivery), Big Data Analytics (leveraging the volume, velocity, variety, and veracity of data to extract value), Artificial Intelligence (models that automate pattern detection, prediction, and optimization), Blockchain (distributed ledgers providing immutability and traceability), and online platforms (coordination, marketplaces, collaboration). Physical transformation technologies are also highlighted, such as 3D printing, which support modularity, repairability, and on-demand production.

To demonstrate the positive impact of these technologies, the chapter also presents the main advantages of digitalizing the circular economy, including the implementation of traceability, the

monitoring of components for maintenance and repair purposes, and cost reduction (transactional and consumption-related).

Finally, the technology employed in this thesis (AI) is described in detail, with emphasis on its role in driving circular transformation: accelerating waste sorting, optimizing maintenance, assisting in material design, improving supply chains, and personalizing interactions with the end user (through applications such as chatbots).

The chapter concludes that digital transformation acts as a catalyst for the circular economy: it reduces uncertainty, lowers transaction frictions, and aligns incentives among actors. The result is a more transparent, resilient, and efficient system capable of decoupling economic growth from resource consumption. This foundation sets the stage for the following chapters of the thesis, in which AI and Computer Vision are practically applied to reducing food waste.

Chapter 3, entitled *Computer Vision and food waste*, provides the transition to the conceptual framework underpinning the scientific approach: it introduces the concepts of Computer Vision (CV), explains why CV is suitable for the objective of reducing food waste, and compares existing market solutions in order to highlight the innovation brought by the platform proposed in this thesis.

The first part presents CV as a technology through which information is extracted from images and videos, and tasks are automated—from recognition (OCR, object detection, face identification, pose estimation) to motion analysis (egomotion, tracking, optical flow). This framework justifies the subsequent design choices: detection, temporal tracking, and the visual analysis of product condition are precisely the functions required to mitigate significant losses across the food supply chain. Furthermore, the literature review confirms the technical feasibility (pre-trained networks, YOLO and its variants for detection, freshness classifiers), while also highlighting limitations such as dependence on precise datasets and controlled lighting conditions, as well as high hardware costs for advanced imaging.

The second part compares the main market solutions that integrate CV and points out the major challenges: very high costs, the need for specialized equipment, lack of scalability, and the inability to be integrated at the level of medium and small institutions or households.

Thus, this chapter establishes the technical rationale for Chapter 4 and demonstrates both the need and the novelty of the solution: an accessible, web-based system that operates in real time, with temporal tracking and ripeness estimation at the level of individual food items.

Chapter 4, *Web platform for intelligent visual analysis of perishable foods*, describes the proposed solution developed within this research: a web-based platform dedicated to the visual analysis of perishable food. The platform aims to directly address the limitations previously

identified in the literature: the lack of real-time processing, the difficulty of dynamic object tracking, and the need for a solution that does not rely on costly or complex infrastructures.

The overall objective of the application is the intelligent visual analysis of food, achieved through the integration of a pipeline that includes image preprocessing, detection, classification, temporal tracking, and scoring. These stages enable both the identification of objects and the estimation of their ripeness, subsequently providing consumption recommendations according to context.

The architecture is modular, separating the image capture and processing components from the user interaction logic. The graphical interface is designed to be modern, intuitive, and accessible, occupying the entire browser space and optimized to operate even on devices with limited resources. To this end, the application offers two operational modes: CPU (central processing unit) and GPU (graphics processing unit), with the user able to switch between them depending on context and available resources.

The general workflow of the application consists of capturing video streams through the webcam, applying preprocessing procedures to normalize the input data, and transmitting them to a server where an advanced visual detection model (YOLOv8) is executed. The results are filtered and stabilized temporally, with each object tracked over time by a specialized agent that employs a ten-dimensional Kalman filter. Based on the detected and tracked objects, samples are selected to allow the analysis of ripeness distribution. The distribution is estimated according to dominant hues, chromatic variation, and the presence of irregular visual textures, with the results transformed into recommendations.

A central element of the platform is the temporal tracking agent, designed to ensure coherence and stability in detections. Each object is managed as a time-monitored entity, assigned a unique identifier, and subject to decisions regarding retention or elimination based on temporal consistency. It also implements a class allocation mechanism based on stability, preventing abrupt category changes caused by temporary detection errors.

Ripeness distribution estimation represents a critical stage, relying on the analysis of chromatic samples selected from within each detected object. These are filtered to exclude areas that are too dark, overexposed, or part of the background. The final distribution accounts for the proportion of dominant hues, their variation, and texture indicators (such as the Sobel coefficient), enabling classification into stages such as Unripe, Early Ripe, Ripe, Overripe, and Rotten. Based on these results, the recommendation engine provides suggestions regarding consumption, sorting, or the subsequent destination of foods, considering the context chosen by the user (storage, retail, kitchen, or farm).

The integrated optimizations allow the application to operate in real time. These include GPU-accelerated preprocessing, the management of intermediate frames to avoid processing bottlenecks, and interpolation through predictions when full processing cannot be performed. Through these mechanisms, the platform achieves the performance threshold required for practical use, maintaining over 30 frames per second even on systems with limited resources.

Solution validation was conducted through experiments performed on both CPU and GPU, under different conditions of resolution, object count, and scene dynamics. The results demonstrated the robustness of the platform: the system remains stable, exceeds the 30 FPS threshold, and maintains detection accuracy even when nearly half of the frames are interpolated through the Kalman filter. This ability to compensate for missing direct detections confirms the usefulness of the proposed approach in real-world scenarios.

The practical relevance of the platform extends across multiple domains: retail (for rapid identification of spoiled products and stock management), warehouses and collection centers, farms and orchards (harvesting and distribution decisions), consumer applications, the HoReCa industry, as well as food markets and educational contexts.

Finally, Chapter 5, entitled *Conclusions*, presents the original contributions of the research, highlights the platform's limitations, and outlines future development directions. It also includes the articles, conferences, and scientific presentations carried out during the doctoral stage.

The thesis brings original contributions through the identification of AI technologies applied in support of the circular economy and the comparative analysis of existing platforms, as well as through the development of a hybrid web–backend platform with in-browser preprocessing and asynchronous inference (YOLOv8m/n).

At the algorithmic level, the thesis proposes the use of a 10D Kalman filter, detection filtering and fusion, class stabilization, filtering based on proximity, motion, and stability, direct interaction with the GPU through shaders, as well as interpolation methods and distribution calculation based on color hues combined with the Sobel filter.

The identified limitations concern the restricted coverage area (not all perishable foods are considered), the requirement of a controlled environment (uniform lighting, absence of shadows and reflections), the need to extend the Kalman filter to handle acceleration cases, and the lack of segmentation for improving the accuracy of ripeness distribution calculation.

Based on the results obtained and the identified limitations, future research directions aim at consolidating and expanding the platform through a series of technical and methodological improvements. A first objective is the integration of Explainable AI mechanisms, by generating attention maps (heatmaps) that provide users with transparency and understanding of how the

system makes decisions. In addition, three-dimensional or volumetric estimation of fruits and vegetables from video sequences would enable a more accurate assessment of size and maturity. To increase accuracy, the introduction of segmentation is proposed, allowing for precise sample selection beyond the limitations of the current elliptical mask. In parallel, optimizing ripeness calculations on the CPU would contribute to more efficient resource usage, further facilitating implementation on devices with limited hardware capabilities.