

Packaging of the Future: when the card gains intelligence

For decades, packaging was viewed primarily as a practical solution to a basic need: to protect, transport, and present a product. In the case of food, this function has become even more demanding, as packaging must ensure safety, preserve quality, withstand complex supply chains, and address environmental concerns. Today, however, the industry is facing a more profound transformation. Packaging is no longer just the wrapping that accompanies the product; it is also becoming a platform for information, traceability, interaction, and trust.



A hybrid barcode applied to smart packaging, combining a public component compatible with conventional scanners and an encrypted private component for secure access to information.

It is in this context that the “Packaging of the Future: Greener, Digital, and Inclusive” Agenda has emerged, as part of the Recovery and Resilience Plan (RRP) and the Agendas for Business Innovation. The project brings together companies, research centers, and entities from the scientific and technological community to address a strategic challenge: developing packaging solutions that are more sustainable, smarter, and better aligned with a circular and digital economy. Among the Agenda’s various subprojects, PPS10 stands out—“New cardboard packages with unique properties for food contact and e-commerce”—focused on new cardboard packaging with distinctive properties for food contact and e-commerce.

The ambition is clear: to create cardboard packaging capable of providing better protection, better information, and more efficient circulation throughout the value chain. This means combining expertise in materials, design, industrial production, logistics, sensors, coding, printed electronics, and software. It also means applying technological innovation to very concrete problems: for example, determining whether a product has been exposed to inappropriate temperatures. How can we ensure that certain information is accessed only by authorized entities? How can we make packaging more useful for producers, distributors, authorities, retailers, and consumers? How can we add intelligence without compromising cost, sustainability, and scalability?

One of the key contributions in this field comes from the Institute of Systems and Robotics (ISR), a Center of Excellence at the University of Coimbra and a scientific partner with expertise in electronics, sensing, communication, intelligent systems, and microelectronics. As part of PPS10, the ISR has been working on low-cost solutions that enable packaging to become an active interface between the physical product and the digital world. This transformation involves three key areas: secure packaging coding, the integration of sensing devices with NFC (Near Field Communication), and the creation of ultra-thin, stretchable, and recyclable electronic circuits for smart packaging. The first line of work focuses on coding technologies. Barcodes, QR codes, RFID, and NFC are already part of modern logistics, but smart packaging requires more than just identification. It requires authentication, access control, information security, and the ability to interact at different points in the supply chain. In the case of the project developed, the solution involves a hybrid barcode based on a QR code containing a public message and a private, encrypted component. The public portion remains compatible with traditional scanners and the existing distribution chain. The private component allows for the storage of protected information, accessible only by authorized users, including the keys necessary to unlock the sensors on the packaging.

This approach is particularly relevant because there is not always a connection to a database or a remote system when information needs to be accessed. At certain stages of distribution, during transport, in warehouses, or in inspection contexts, connectivity may be limited. By incorporating mechanisms for secure offline unlocking, the packaging becomes more autonomous and resilient. The solution allows different user profiles to have different levels of access: end consumer, producer, retailer, carrier, or competent authority. The packaging thus functions as a physical object with its own digital identity, but also with built-in privacy and security rules.

To make this vision operational, a library was developed for generating and decoding codes with public and private messages. The public message may refer to general information about the project or the product, while the private region of the code includes specific sequences intended for the secure unlocking of data. The existence of this library is an important step because it brings research closer to future industrial integration: instead of a purely conceptual solution, a tool is now emerging capable of generating unique, adaptable codes that can potentially be integrated into printing, labeling, and product management processes.



Sequence of interactions with the smart packaging: unauthorized access attempt, code scanning by an authorized user, and unlocking of the information after authentication.

The second line of work focuses on sensor technology. Smart packaging must be able to record what happens to the product. In the food industry, this capability can be critical. Temperature, humidity, mechanical shock/vibration, exposure to light, or

incidents of improper handling are factors that can affect the quality, safety, and shelf life of products. Sensorization allows for the collection of objective data on these events, creating a tracking history for the packaging. This history does not replace existing control systems, but adds a layer of evidence: the packaging can now bear witness to part of the product's history.

Development began with a test version on a breadboard, using temperature and humidity sensors, accelerometers, NFC tags, and microcontrollers. This phase allowed the team to test components, evaluate power consumption, identify limitations, and select the most appropriate architecture. From there, the team moved on to designing a custom electronic board, or PCB, with the goal of miniaturizing the device and fitting the necessary components into a small space. The project's evolution shows the transition from an initial, larger assembly to progressively more compact versions (half the size of a credit card), already geared toward future integration into packaging.

The sensor system includes temperature and humidity sensors, an accelerometer, and an ambient light sensor. The temperature and humidity sensor allows for the monitoring of relevant environmental conditions, distinguishing between periods within normal ranges and alert situations. The accelerometer allows for the detection of events such as the package being upside down for longer than a specified period—potentially useful data for products requiring specific orientation—as well as excessive mechanical shock or vibration. The light sensor allows for the identification of excessive light exposure, which is relevant for light-sensitive products. Data collection is designed efficiently: not everything needs to be recorded at the same frequency, and critical events warrant different treatment from routine data.

Communication with the device is via NFC, a technology widely present in smartphones, low in energy consumption, and suitable for proximity interactions. This choice avoids complex and costly solutions for all scenarios. Instead of packaging permanently connected to the internet, the project explores a more balanced approach: the packaging records data, which can be read by proximity, when necessary, via a mobile app. This option combines simplicity, security, and economic viability—essential factors when considering a solution that can move beyond the laboratory and reach real production and distribution chains.

Data is stored on a dynamic NFC tag with non-volatile memory, which means that the information is retained even when the device is not powered. The memory is organized into password-protected areas, allowing for the separation of configuration data, temperature and humidity measurements, motion events, and light events. This architecture reflects a key concern: a smart package must be informative but not vulnerable. Sensitive information must be protected, and access to data must adhere to authorization levels. The link between secure encryption and sensor technology thus becomes one of the most innovative elements of the project.

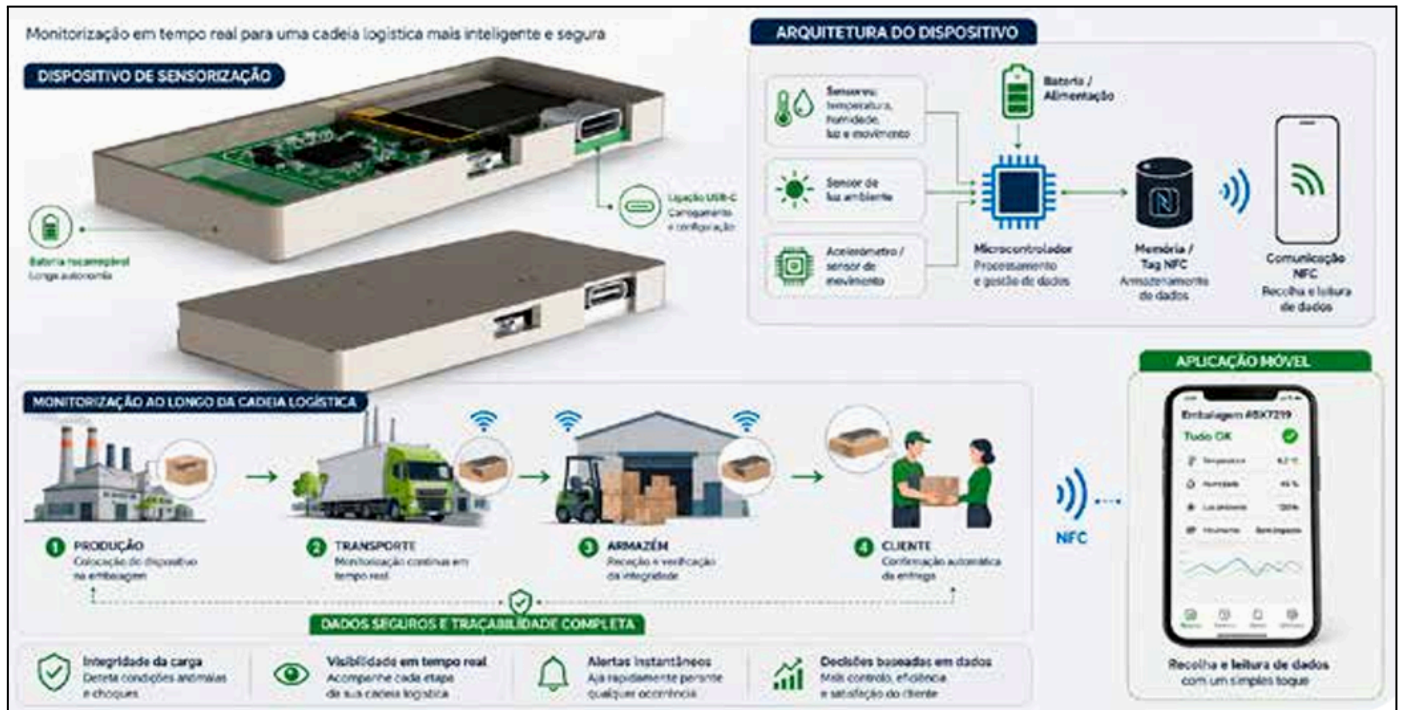
The third line of work developed by ISR introduces a complementary dimension: sustainable printed electronics. The team created ultra-thin, stretchable, and recyclable electronic circuits for applications in smart packaging. These circuits are printed on ultra-thin plastic films using digital printing techniques, employing proprietary composites developed at the Institute of Systems and Robotics (ISR) at the University of Coimbra. Their reduced thickness and flexibility allow for integration into packaging surfaces without significantly altering their shape, weight, or use.

In one of the examples demonstrated, these circuits were used to monitor the temperature of a package throughout the supply chain. When temperature conditions are no longer maintained during transport, an LED is activated and remains permanently lit, serving as a simple and reliable visual indicator of a break in the cold chain. This solution has a clear advantage: it allows any stakeholder, even without specialized equipment, to immediately recognize that a significant anomaly has occurred. The technology transforms an invisible event, such as improper thermal exposure, into a direct physical signal.

Sustainability is one of the main advantages of this approach. Both the constituent materials and the conductive inks can be recycled and reused in the manufacture of new circuits, contributing to a circular economy model in the printed electronics sector. In addition, the ISR team has developed battery-free versions of these devices, in the form of smart labels or patches, capable of monitoring critical packaging parameters such as temperature and orientation during transport. These solutions reduce costs, minimize environmental impact, and simplify integration into existing logistics systems, paving the way for a new generation of smart packaging that is safer, more efficient, and more sustainable.

The innovation here lies not merely in placing sensors or codes on packaging. It lies in conceiving the integrated system as a whole: packaging, code, sensor, memory, application, printed electronics, access levels, and value chain. A solution of this type is only relevant if it simultaneously meets technical, economic, and environmental requirements. The project must therefore balance miniaturization, energy autonomy, component cost, robustness, readability, compatibility with industrial processes, and

material sustainability. This combination is demanding, but it is also what makes the Packaging of the Future Agenda particularly strategic for the sector.



Sensor system for smart packaging, with NFC monitoring throughout the supply chain.

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From an economic standpoint, the applications are clear. In e-commerce, where packages travel through dispersed and often difficult-to-control logistics networks, the ability to record relevant events can help resolve disputes, improve processes, and build trust among sellers, logistics operators, and consumers. In the food sector, monitoring environmental conditions can add value to sensitive products, helping to reduce losses and waste. In distribution, enhanced traceability can improve quality management. For consumers, packaging can offer greater transparency regarding the product's journey. For authorities, it can facilitate verification and inspection processes.

But the potential impact goes beyond efficiency. The Packaging of the Future Agenda seeks to address a cultural and regulatory shift: 21st-century packaging must be more responsible. It is not enough to simply protect the product; we must reduce environmental impact, facilitate reuse or recycling, improve information, combat waste, and integrate principles of circularity. The **+Ecological +Digital +Inclusive** dimension precisely reflects this vision. Digital technology is not merely a technological embellishment, but a tool to make packaging more efficient, safe, and transparent. Sustainability is not just a matter of materials, but also of information and management throughout the life cycle.

The role of the Institute of Systems and Robotics in developing innovative solutions at the international level is particularly significant because it demonstrates how scientific research can be applied to specific industrial challenges. Integrating electronics, NFC communication, sensors, secure codes, software, and printed circuits into a cardboard package requires multidisciplinary expertise. It is not a matter of developing an isolated device, but of creating knowledge applicable to real products, subject to constraints of cost, production, and use. It is precisely in this space between the laboratory and industry

that projects supported by the PRR can generate value: bringing companies and science closer together, creating prototypes, testing solutions, and paving the way for new products and services.



Recyclable printed circuits for continuous temperature monitoring of packages throughout the entire supply chain

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PPS10, developed in collaboration with several co-promoters, also highlights the importance of collaborative work. The packaging of the future will not emerge from a single company, a laboratory, or a digital application. It will emerge from the convergence between packaging manufacturers, user companies, research centers, materials specialists, design teams, programmers, and project managers. Each partner adds a piece to the system. The expected result is packaging better prepared for the challenges of food, logistics, and e-commerce.

Naturally, there are challenges to overcome. The integration of electronics into packaging must be carefully considered so as not to create new environmental problems. Unit cost is decisive for large-scale adoption. The robustness of the devices must be proven under real-world conditions. Data protection must be ensured from the design stage. And the user experience must be simple: a technology will only be adopted if it adds value without creating excessive complexity. Even so, the advances already achieved show that it is possible to build a cardboard package that combines physical properties, digital identity, monitoring capabilities, and sustainable electronic solutions.

Ultimately, the Packaging of the Future project shows that innovation in the packaging sector is not limited to changing formats or materials. It involves rethinking the role of packaging in a more demanding economy, where consumers, businesses, and

regulators demand more information, greater sustainability, and greater trust. A cardboard box can remain a cardboard box, but it can also become a digital touchpoint, a quality record, a traceability tool, and an active element of product protection.

By integrating the expertise of the Institute of Systems and Robotics with the strategic framework of the Recovery and Resilience Plan, the Packaging of the Future Agenda positions Portugal at the center of a decisive debate for European industry: how to produce better, waste less, and use technology to add value to the most common everyday products. The answer, in this case, begins with a seemingly simple object: packaging. But packaging capable of communicating, recording, protecting, and informing. Packaging that points toward the future.



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