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Low-cost extension of information transparency throughout the product life-cycle via optical identification and quality indication

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Abstract

Growing needs for data transparency are experienced in production networks, calling for individual product traceability and accurate information on actual state, quality or history of the individual product. Special challenges arise when “low-tech” network members, retailers or customers are likewise to be served during the product life-cycle, or in case low unit prices or tight profit margins require highly cost-efficient solutions. In line with the latter, the paper examines the integration of optical identifiers with optically perceptible quality indicators as an alternative to sensor-equipped RFID, including new designs not yet covered by implemented solutions. Following a separate survey of the two combined technological domains, possibilities of synthesis are examined from the point of view of optical codes, as their (semi)automatic acquisition and subsequent processing presents the key value added to most present-day indicator-only labels. As different targeted application ranges, e.g., supply chain members of different size, may require different pre-implementation surveys, the paper includes a collection of acceptance aspects for all of the identified user groups.

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Keywords: RFID; optical identifier; optical indicator; product life-cycle; low-cost

1. Introduction

Production networks have spread and evolved much in recent decades, as did services become more important that stretch beyond strictly production-related stages of the product life-cycle (e.g., guarantees and customer care, or product feedback for future design upgrades). These trends all require improved transparency on one hand, and may imply more data “travelling with the product” on the other hand. As services and operations stretch across further life-cycle stages, it becomes more and more likely that the individual product will meet network members, retailers or users who represent a “low-tech” group and have very limited possibilities at hand to access and interpret data attached to the product. In parallel with this trend, improved transparency and provision of product data gradually begins to penetrate product ranges that are characterised by lower per-unit value or low profit margin. The latter raises the need for low-cost technologies that can carry data unique to the individual product—often in relation to its individual state—remain suitable for inclusion in data sharing, but also being interpretable with low-tech equipment or no reading devices at all. While various problems of this kind exist, the paper focuses on data supplied with perishable goods in particular, with an emphasis on the low-end problems of small retailers and consumers.

Providing item-level information about de-facto quality or integrity of sensitive or perishable products is now being offered commercially, often as part of intelligent packaging solutions. Labels equipped with sensors or indicators play a substantial role in these, as they provide the required degree of observability on the level of individual items or packaging units [3, 4] (remarkably, this trend runs hand-in-hand with a redesign of material handling practices [5] and supply chain structures [6, 7]). This is especially present in areas where demands for efficient and safe operation of supply chains are becoming more and more pressing, as in the food sector [8]. It

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can be observed that this process, as it frequently occurs in adopting new technologies, is mostly initiated by large members of the supply chain who take a pioneering role but also shape the mainstream of application demands in accordance with their own typical needs, i.e., solutions that efficiently support large-throughput operation but may require the high initial investment and technical expertise only a major player can afford. In this context, RFID is generally regarded as the most promising technology providing the required transparency and efficiency of reliable and automated use with minimal labour costs [9]—also this technology started out as an expensive adventure of isolated pioneering solutions, gradually spreading from supervision of durable assets [10] to scenarios with massive material throughput. RFID tags can easily be coupled with sensors [11, 12, 13] that provide information about actual ambient conditions or material status, opening up a new vista of accurate traceability. The adoption threshold for RFID is decreasing and affordable reading devices are becoming available even to consumers (e.g., near-field communication or NFC phones), with associated traceability practices now beginning to penetrate the small-business domain, too [10, 14]. Still, the cost and further aspects of RFID (e.g., not even partial information being accessible without a reader) suggest that optically readable labels are likely to persevere for a longer time in certain areas. This is especially true for "low-end" application or cases extremely sensitive to overhead costs. These previous findings are the key motivation for this paper proposing the integration of optically readable binary code and optically perceptible indicators displaying the freshness or estimated remaining shelf life of individual items.

While some examples of the above synthesis have already been commercially implemented, like CoolVu [15], the complete range of possibilities is far from exploited. The goal of this paper is i) to show that optical alternatives to sensor-equipped RFID are a feasible bridging solution, and ii) to present a map of possibilities with corresponding requirements and limits. It is not purpose of this article to judge which of the technically possible solutions would be preferable in a given application scenario, rather, it is meant to present a catalogue of possible integration principles and implementations along with their key characteristics, so that making a specific choice for a targeted user community is facilitated.

To this end, we first present preliminaries of available optically readable codes (technically suitable to convey digital information as unique identifiers and auxiliary data) and optically perceptible indicators (capable of displaying measured or estimated freshness of perishable items). Hereafter, as the main contribution of the paper, a framework of integration possibilities is presented, with applicability and expected acceptance in selected user groups receiving special attention.

2. Identification with optical symbologies

Commonly used optical identifiers are, in essence, images consisting of regular fields of different colour that can be reliably recognized and mapped onto an interpreted message by a reading device (see Palmer [16], or LaMoreaux [17]). The concept of optically perceptible patterns conveying information was proposed as early as the 1950s by [18], however, practicable implementation of the concept had to wait for 2–3 decades until adequate equipment became available for acquiring and processing the information carried by optical labels. Widespread use, especially of bar codes, began in the 1980s, and since then, the most common type of bar code, EAN13, became a symbol of commerce. Nowadays, the vast majority of optical codes uses two distinct colours only (i.e., reflecting vs. non-reflecting), even though multicolour codes did occur in history [19] and are currently in occasional use with devices (typically camera-equipped phones) that can compensate their low image resolution with good multicolour sensing capabilities, as described by Zhou and Rong [20]. In the paper, we assume a general preference for pure black-and-white codes, however, classification principles of the presented solutions do apply likewise to colour codes as well.

Optically readable codes offer the advantage of automatic data acquisition, i.e., the process of entering data into a computer system is performed automatically, even if some human assistance of positioning or motion may be required for the scanning procedure. This considerably reduces the probability of human error and the need for (skilled) human labour—often, to the degree that identifier acquisition would not be worthwhile at all without such automation. In most cases, the optical codes themselves contain a mere identifier, classifying them as a type of automatic identification (AutoID). The degree of identifier uniqueness (e.g., item-by-item, batch-by-batch, article-byarticle) depends on the nature of the given application: EAN13, for example, only makes a distinction between articles, however, perishable goods exposed to different conditions or belonging to different production batches are likely to require a finer granularity of unique distinction. Optical codes, as many other AutoID technologies, may offer the option of carrying additional data as well—these could be key data of the item, or instructions regarding the interpretation of readings. Nowadays, a wide variety of standards is available for optical codes: various symbologies (i.e., specifications for expressing information as optical patterns of a given kind) allow different levels of unique distinction, different amounts of data stored, different levels of correcting reading errors, etc. As a complete review would transcend the limits of this paper by several orders of magnitude, we only list the most important characteristics of optical codes that must be assessed when implementation and application decisions are made.

- Shape of optical code: 1D or 2D? In the most simple case, optical codes consist of bars of varying thickness or length aligned in a one-dimensional row—these are referred to as 1D code, and can be read in a single scan by any linear reader (wand moved by hand, oscillating scanner moving point of sensing automatically, or line sensor acquiring the code in a single pass). Stacked codes are basically several 1D codes printed above each other—in this case, a linear reader needs multiple passes, while a full two-dimensional imager (essentially a camera) can acquire the entire code in a single pass. Any other form (such as the most widespread

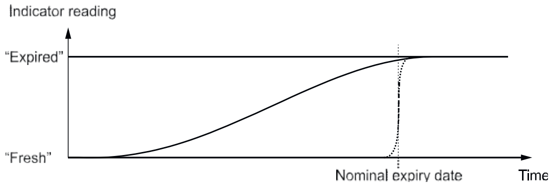

Fig. 1: Progressive (continuous line) vs. end-point type (dotted) indicator response

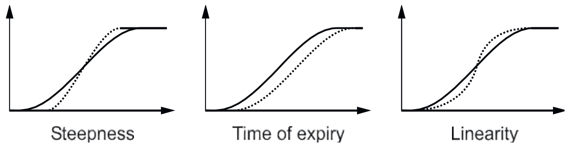

Fig. 2: Various possibilities of indicator response parameterization

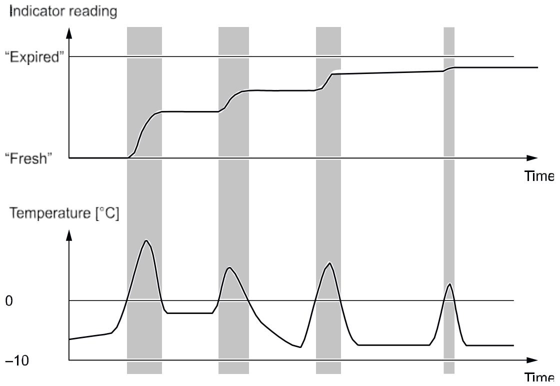

Fig. 3: Partial history example—indicator progresses during periods of thermal abuse only (background marked grey)

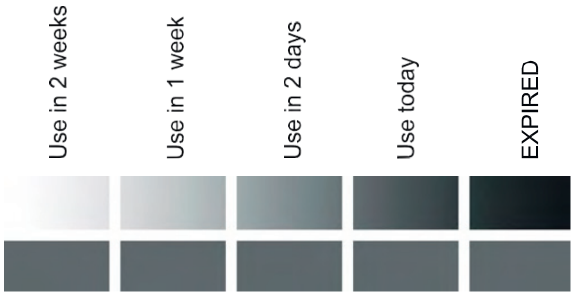

Fig. 4: Example of calibration stripe assisting intuitive human interpretation

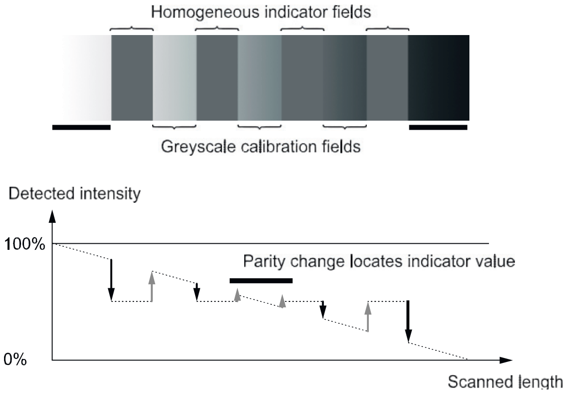

Fig. 5: Interlacing indicator and calibration fields can easily be detected by a machine, however, their human interpretation does require some training

QR or Quick Response code) exploits the possibilities of fully two-dimensional patterns, and are referred to as true 2D codes— these require a 2D imager with sufficient resolution. Prices of different reader types vary largely, and in case first cost of suitable equipment is an issue, one should carefully select the type of symbology to remain compatible with equipment already present or available at reasonable cost.

- Wavelengths/colours of reading. Most optical readers can sense either a narrow band in the range of visible light or near infrared; sometimes, reading is assisted by an active light source of appropriate wavelength. The mainstream of optical codes relies on purely binary intensity information (light or dark), and most of the highly specialised readers are not able to sense more than light below/above a given threshold. Symbologies using colour or greyscale values do, however, exist and have gained some acceptance for use with camera-equipped smart phones that can easily sense multi-band light values "in between", but are inferior to specialised readers regarding image resolution.
- Content and its limitations: numbering restrictions, amount of data, error correction. Certain symbologies are only used in connection with specific numbering schemes, and in most of these cases, IDs or ID ranges are issued by central authorities to grant global uniqueness. Another limitation of content is the amount of data a given symbology can accommodate—in many cases, limits are finite. Possibilities of encryption and fault-tolerant encoding (allowing detection or correction of reading errors at the cost of redundancy) are also offered by numerous symbologies.

3. Optical indicators

Optical indicators signalise selected properties of the given product by changing one or more specific, optically perceptible, properties (mostly colour/intensity or shape/size of the indicator field). Detected characteristics may be either i) integrity, e.g., indicator showing package breach [21], ii) quality, i.e., detection of a marker as pH level, concentration of decomposition products, metabolites, etc. as shown by Nopwinyuwong et al. [22], or iii) time/time-temperature, or, in general, any relevant ambient condition that allows indirect

Table 1. Compatibility of readers with implementation cases. Note that possible conflicts between reader and symbology type should be checked separately.

	Case 1	Case 2	Case 3
B&W wand	Yes	Yes (with assistance)	No
B&W scanner	Yes	Yes (with assistance)	No
B&W imager	Yes	No	No
Greyscale camera	Yes	Yes	Yes
Human inspection	Yes	Yes	Yes

estimation of product quality or remaining shelf-life, leaning on a chemical or physical process running in parallel with actual deterioration but not directly taking place within the product [23]. While the nature of the detection is an important factor in selecting the best indicator for an application case, its perceptible behaviour is by far the most relevant characteristic when combination possibilities with optical identifiers are assessed. Therefore, these visible aspects will receive here most of the attention:

- Wavelength of indication. Each optical indicator works in one or several wavelength intervals where it exhibits detectable changes with the required reliability. When combined use with optical identifiers is planned, one must take into account that this reliable interval has to lie within the detection range of readers envisaged for use (visible wavelengths if human readability is an issue).
- Perceptible properties. Optical indicators can change their shape/size (e.g., in the form of a progress bar) or their colour/intensity (while usually retaining the original size of the detectable field), depending on the nature of processes they rely on. Many of the shape/size-changing indicators keep crisp borders during their life span, making them also suitable for readers that are not constructed to detect intermediate intensity levels (or are edge-triggered). Colour/intensity-changing in-dicators, on the other hand, are likely to be captured more reliably by readers with greyscale sensing capabilities.
- Indicator response type. Different indicators can react differently in time (or gradual exposure to aging conditions). End-of-life types react abruptly after a certain exposure (thus being well-suited for automatic capture by purely black-and-white readers), and manufacturers can set the triggering point by adequate composition of the indicator. Progressive indicators, on the other hand, change gradually over a longer exposure range (see also Figure 1)—if the changing property is colour or intensity of an indicator field, readers with greyscale capabilities may be needed to fully capture the indicated status. The characteristics of progressive indicators (response steepness, expiry point, linearity) can be tailored to the needs of the specific application, as shown in Figure 2. Some indicators are laid out to record partial history (e.g., expiry advances during periods of thermal abuse only, as in Figure 3), or begin to progress after a triggering event (e.g., thawing). While this is a relevant consideration for deployment with a given product, it bears little impact on human or machine-readability.

Machine-readability of optical indicators is influenced by further factors that can easily remain unnoticed if human readability is observed alone— some of these are not even limited to the indicator itself.

- Specular properties of the indicator carrier/envelope. A glossy or grainy surface can easily interfere with proper reading, both with or without an assisting light source working in the reader. The industry has developed a variety of robust solutions for optical identifiers; these can be taken as a good starting point when designing machine-readable indicators.
- Lighting conditions and calibration. Automated capturing can be extremely sensitive to uneven or changing ambient light. In some cases (typically pure black-and-white readings), the intensity of a built-in light source solves the problem reliably, in other cases, some form of calibration is needed for delivering reliable greyscale values. In the latter case, calibration fields may be placed beside the indicator (Figure 4), or may be directly integrated with it (Figure 5). Calibration fields can also assist human reading and interpretation, nevertheless, not all solutions are intuitive enough for such “untrained” observers as customers or occasional users.

4. Combination of AutoID with indicators

The idea of combining optically readable AutoID with indicators is not entirely new, and some pioneering implementations have already found practical application. The direct goal of such a combination is to enable the (semi-)automatic acquisition, forwarding and interpretation of perceived indicator status in the context of the given individual item. This, in turn, can reduce spoilage-related losses, enable more efficient stock keeping, picking and pricing policies, or allow expiry-related safety measures to be more in keeping with the actual status of stock. Aside from machine-readability, intuitive human interpretation has to be supported as well in a number of cases (notably in retail and after-sales handling of goods), therefore, the latter aspect will also receive attention in the following presentation of integration approaches.

The extension of optical AutoID by indicator fields can have direct, indirect, or no influence on reading/handling of optical code—this distinction serves as the starting point of the classification to follow.

Direct influence on acquired code (Case 1 in Table 1). In this case, the indicator field is integrated with the optical code so that it directly interferes with its readability or validity: the change of the indicator renders valid code invalid or invalid code valid. Altering of code content is also a theoretical possibility, however, expected implementation difficulties and reading uncertainties suggest the latter option to be of little practical importance in the next years to come.

As the indicator field and at least a part of the optical code share a common visible area of the label, practical implementation must provide for a suitable method of overlaying. Given today's commonly available solutions, this can be achieved by i) simple overprinting of optical code (usually black-and-white) and indicator ink (which may have to be transparent), or ii) placing a printed or cut mask over a background containing the indicator field. Implementation decisions require an in-depth knowledge of available materials, technologies and conditions of use—as these would certainly surpass the limits of this paper and could quickly change with technological progress, we do not present them here in further detail.

In the most simple case of this class, reading of a single ID is enabled or disabled, as it is the case, with some commercially offered indicator-equipped labels as CoolVu [15]. Should a single go/no-go decision not suffice, a set of several codes and indicator fields can be used with several discrete steps of validity. These can be, for example, easily mapped onto discount sale policies of perishable goods.

Validity of a code is of binary nature, and this method of indicator integration is well-suited for readers with black-and-white-only reading capabilities. Indicator changes are visible to the unaided eye, however, their interpretation may not be intuitive, especially in multi-step cases. Here, additional human-interpretable instructions may help, although it may still require considerable "break-in time" for the average consumer to become acquainted with the proper interpretation of the label.

Figure 6 illustrates a multi-step solution with instructions aiding human readability. When processing this label with an optical reader, several of the codes may be readable, of which the one corresponding to the longest remaining shelf life will be taken for valid.

Indirect influence on acquired code (Case 2 in Table 1). In this case, optical codes and indicator field are displayed side-by-side, with an optional calibration/colour matching stripe if the type of the indicator requires it. Practical implementation of such a layout circumvents overlay-related problems and leaves much freedom in choosing materials for optical label and indicator—they do not even have to share the same substrate.

Reading such a combination begins with acquiring and interpreting the indicator field (aided by the calibration/matching stripe), which triggers the action of reading one of the supplied optical codes. In other words, the status of the indicator tells the reader which of the codes must be read and taken for valid.

Fully automatic reading of this type of labels would require a true 2D camera with greyscale or colour sensing and resolution sufficient for reliably capturing the optical codes. Purely black-and-white legacy equipment can be used here at the cost of additional human intervention: the indicator would be inspected and interpreted by a human operator, and the reader would be manually positioned over the code area to be selected. Also, provisions for entirely human reading can be made, e.g., by displaying plain text standing for the interpretation of the code stripes (as shown in Figure 7).

No influence on acquired code (Case 3 in Table 1). As it is with the previous case, the indicator field does not interfere with the optical code—they are either displayed side-by-side, or the indicator field is fully integrated into the optical code occupying a dedicated "analogue" field. Again, tone calibration marks for the indicator may be required for reliable reading.

Here, the entire optical code is acquired during automatic reading, as it contains, in some form, instructions for the interpretation of the indicator field. These can be parameters of a continuous function applied to the raw greyscale values of the indicator, but it is more likely that a practical implementation would rely on a table instead, with a finite number of entries mapping to discrete "corner points". Depending on the nature of the application, these table entries may then either be used in an interpolation (e.g., to deliver continuous values for estimated remaining shelf-life), or handled in a "nearest neighbour" manner (e.g., if discounted prices of perishable products are laid out in discrete pricing classes).

This case has the potential of largest versatility, however, it does require up-to-date equipment for automatic reading, as both the processing of the optical code and interpretation of the indicator field must take place in the reading/processing equipment in the machine-evaluated case. Nevertheless, even this class of indicator-equipped labels can be made suitable for human inspection if indicator, colour matching fields and corresponding interpretation are arranged in an easy-to-comprehend way.

The example in Figure 8 shows such a layout. Here, indicator field and colour matching stripe are occupying a part of a sample QR-code. This specific arrangement exploits the redundancy of the QR-code (originally meant for error correction), so that the encoded instructions remain readable while a reader running extended QR reading software could easily locate the greyscale fields within the label, having already calibrated the location of key image positions during the QR interpretation phase. This example would certainly violate the original QR specifications but demonstrates that "piggybacking" existing solutions is a technically possible way of integrating optical code with indicator fields. As seen in the figure, this particular layout also supports human interpretation in an intuitive way.

5. Considerations of practical impact and acceptance

The above classification of proposed integration approaches showed a wide spectrum of possibilities lying within limits of what is currently technically feasible. Particular choices in implementation and standardisation, however, depend very much on the demands of the industry as well, therefore, it is important to carefully assess the expected acceptance of a given solution in the targeted application area. Comparable studies and considerations for RFID were

Fig. 6: Indicator integration by direct influence on readability—here, the readable code for the longest shelf-life is valid.

Fig. 8: Inclusion of indicator field without influence on code—here, instructions embedded in the code can define how indicator readings are to be interpreted.

Fig. 7: A non-overlapping indicator steering code interpretation. As in the previous case, an intuitive legend for human reading is integrated as well.

presented, among others, by Pramatari and Theotokis [24], and Kasiri and Sharda [25], while complex RFID solutions in the presence of several standards were examined by Thiesse et al. [26]. A complete methodology would certainly surpass the limits of this paper, however, we wish to outline the main aspects that are likely to have an impact on practical decisions.

- Characteristics of targeted products. While different product classes may have different relevant properties, two aspects are certain to receive attention: i) what level of detail is required for sufficient product status information (integrity, a single estimated expiry date, degree of gradual deterioration, discrete steps of freshness, etc.); ii) what handling conditions are to be expected for the product (mechanical stress, temperature and humidity range, exposure to radiation, disinfectants, etc.—affecting choice of both label carrier and indicator).
- User-side technological background. The technology-related conditions of users (mostly supply-chain members) expected to come in contact with indicator-equipped labels span a wide spectrum regarding current instrumentation and possibility/willingness of further development. The top of the spectrum are large-scale supply chain members who are interested in efficient, high-throughput operation—these are most inclined to utilise their extensive resources for investment in advanced technology (and acquisition of related expertise) already at an early stage of introducing new indicator-equipped labels. Their preference is clearly in favour of labels that can be read in a fully automated manner (and may even prefer RFID over optical labels). Retailers, especially medium-sized or small businesses, are typical for the intermediate range—they are likely to have some "legacy" equipment (e.g., pure black-and-white readers originally meant for simple bar codes) which they would prefer re-using to the largest possible extent. The attitude towards additional labour (manually assisted reading) is expected to be more tolerant in this user group, especially in the small-business range. The lower end of the spectrum is taken by consumers who can have the most diverse backgrounds and attitude towards new technologies [27, 28, 29]. Complete ignorance is not the worst case here—although generally rarely encountered, dynamically changing expiry information may even evoke mistrust in some consumers. If this occurs too often, retailers may wish to mask indicator information from the consumers by employing labels that are machine-readable only. More progressive consumers, on the other hand, may not only be conscious of the meaning of true freshness information but may also have their own reading devices—camera-equipped mobile phones, for example, frequently offer functionalities as reading certain optical codes, and even establishing connection with remote services associated with the acquired code. These devices are now well into mass production, and may evolve the character of a "disruptive technology", their price making them affordable reader substitute for small enterprises and their versatile and reliable operation quickly obsoleting other legacy equipment.
- Integration in an application context. Optical labels, like any other kind of AutoID, can unfold their full potential if they are deployed in a network that allows product information to be shared and channelled to improve safety and traceability, as shown by Kher et al. [2], support more efficient supply chain operation and offer additional services for customers and supply chain members. Taking a realistic approach, it should be expected that new label designs have to fit into an existing context of networks and services—this may determine certain key aspects as interoperability with existing numbering schemes and data models. Also, it should be observed that new development rarely starts with a clean sheet—often, it is far more feasible to roll out new functionalities by "piggybacking" existing solutions. Nevertheless, it should be observed that carrying on a technological legacy and using systems for purposes they were originally not meant for does present potential risks—it should, therefore, be carefully assessed when technological continuity can be preferred over a radically new solution.
- Legislation, responsibility. The food industry is one of the areas with the most rigorous requirements on safety, reliability and transparency— this is also reflected by the strict legislation measures of recent years. This has to be taken into account when the expected reliability of a label

design is assessed. Also, indicator-equipped labels may serve as a token of responsibility—a supply chain member may refuse the reception of goods with bad indicator readings, and the previous supplier would have to assume responsibility for the implied losses. As such rejection can be triggered by a faulty indicator as well, it may be necessary to establish a sensible balance between the—usually conflicting—reliability and label unit price criteria.

- Costs. Unless strategic intervention is applied, pencils drawing the label designs are ultimately sharpened in the accounting department, i.e., solutions have to be fit for the financial requirements of production and use. Low per-unit price of goods or tight profit margins would require cheap, mass-produced labels, while a premium product line may call for high-quality labels that can deliver more detailed information. Also, label costs have influence on the size of packaging units the given type of label is applied to—individual items may be provided with low-cost labels, while larger packaging units as trays, boxes or pallets could be tagged with more advanced and more expensive ones. Also, it must be noted that several label types can be used simultaneously on various packaging units of the same product. This way, it is also possible to resolve conflicting preferences of different supply chain members: larger wholesalers, for example, may prefer a label type that allows fully automated, high-throughput material handling on the pallet level, while small retailers could still use their legacy hardware with a downward-compatible label type used on smaller boxes or individual items.

6. Conclusion

Leaning on previous findings predicting a moderately evolving acceptance of sensor-equipped RFID, the paper proposed the use of indicator-equipped optical AutoID labels, either as a temporary replacement, or as an affordable alternative for low-cost cases. Such cost-efficient—and possibly human-readable—solutions have the potential of extending traceability, transparency and individual product information to stages of the product life-cycle where the product is likely to come in contact with “low-tech” supply chain members (typically small retailers) or end consumers.

Some solutions are already being marketed, yet, possibilities are far from being fully exploited. Therefore, the paper contributed a systematic coverage of several technically feasible approaches for the integration of optically perceptible indicators with optical AutoID. As the requirements have shown, a variety of solutions beyond today’s practice can already be implemented with current equipment either as-is, or with minor extensions. Therefore, compatibility with today’s typical reader types also received attention in the classification, as did the possibilities of human interpretation of the inspected labels. Acceptance of indicator-equipped labels would also depend on the available IT background—nevertheless, parallel developments (e.g., camera-equipped mobile phones vs. NFC sets capable of reading RFID, as well as connectivity to different networks and services) do not yet point towards an exclusive or dominant technology.

While today’s technology allows several approaches to be taken, particular choices will largely be influenced by surfacing industrial and business demands—their most relevant aspects were also surveyed in the paper, also in order to provide a starting point when label solutions are considered for implementation.

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