Digitization Technologies to Ensure Production Conformity

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ABSTRACT

Ensuring production conformity is a growing challenge in the automotive industry. The reasons for this are the increasing number of vehicle variants combined with increasing regulatory requirements in import markets.
Instances of non-compliance with production standards, also referred to as 'Conformity of Production' (CoP), may lead to significant penalties. Today, a partially random and manual assurance process is used in production.
Previous research has shown that automation offers promising potential for improving the CoP process.
The goal is to identify and evaluate an appropriate automation solution for the overall CoP process. The focus of this contribution is on the digitization of the selection process for part IDs and other homologation-relevant labels.
The approach is to apply state-of-the-art evaluation logic to the automated identification of part IDs and homologation-relevant markings in the context of the assurance process in order to identify these markings with the greatest potential for improvement in the automated identification process.
The method with the best prospects of success will undergo initial piloting.

KEYWORDS

Conformity of Production, homologation, automotive, production, manual assurance, assurance process

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1. Introduction

In the automotive industry, marking regulations and requirements are essential to ensure the safety, quality and conformity of vehicles and their parts. These regulations are defined by national and international authorities and structures [1].

Ensuring production conformity in this industry is becoming an ever greater challenge due to the increasing variety of vehicles and the growing demands of import markets.

Each country has its own legal requirements that must be met in the context of "Conformity of Production" (CoP). In Europe, for example, compliance with the "European Regulation 2018/858" is mandatory [2–4].

The CoP refers to ensure compliance with homologated type approval requirements during vehicle production.This process requires the regular assurance that the products manufactured in the series process have the same characteristics and specifications as the vehicle and its parts used for type approval. To ensure this, various assurance measures are performed, including the part identification test.

The part identification test is a procedure within the CoP in which the parts installed in the vehicle are checked to see if they have the same specifications as those in the type of approval documents submitted to the authorities.

At the BMW Group, part identification testing is currently carried out by means of a manual spot check using a paper checklist on the vehicle. The data of the parts on the vehicle is compared with the CoP data to ensure that the parts used comply with the specified standards and thus production conformity is guaranteed. The part identification test is a crucial step in ensuring the quality and safety of vehicles, as well as in promptly identifying potential deviations in the production plant.

Previous work has shown [5] that the part identification number (part ID) did not always meet the legal requirements or was partially illegible, which led to non-conformity in the CoP process. The part identification number is a unique identifier that is assigned to a specific part and is used to uniquely identify it within a system or process [6].

Due to the current manual part identification checks, only a limited number of part IDs or homologation relevant markings are checked, which can potentially lead to incorrect markings going undetected.

Automotive recalls are an industry-wide issue that affects all automakers as they are required to ensure the safety and quality of their products in accordance with regulatory requirements. In the U.S., 331 million vehicles were recalled between 2011 and 2020 due to safety defects and non-compliance. The recall numbers for 2020 and the first half of 2021 do not show a positive trend, but a further worsening [7]. Further statistics on recalls over a time period of two years can be found in Sturm [5].

The numbers show an upward trend, which is due to the increasing amounts of variants as well as the increasing conformity requirements [5].

The results of previous work [5] show that the corrective measures taken so far in the CoP process are not sufficient to achieve a "zero defect strategy" regarding homologation defects. Against this background, measures for automating the assurance process during production are to be investigated.
In essence, there are several technologies for the automated assurance of part IDs or homologation-relevant markings with which the part identification test of the CoP process can be carried out automatically.
A comprehensive investigation into the automated assurance of the CoP process and into which technologies are appropriate for this purpose has not yet been carried out at the current state of the art and is therefore the aim of this contribution.

For this contribution, the following research questions can be derived:
- Which requirements must be met by the technology for part identification within the CoP process?
- Which technologies are appropriate for CoP to automate the part identification process?
- How is the identified technology appropriate for practical application in a real scenario?

2. State of the Art

The analysis of the state of the art is crucial to discuss the current knowledge on "Digitalization Technologies for Ensuring Production Conformity."

This contribution focuses on automating part identification in the CoP process. Section 2.1 describes potentially applicable technologies according to the current state of the art. Here, methods of quality monitoring are examined as they can enable automated part identification and have not yet been applied in the CoP process according to the state of the art.

Sections 2.2 and 2.3 address the state of the art regarding optoelectronic and transmitter-receiver systems. Furthermore, Section 2.4 describes the application of digital quality control in industry, and finally, Section 2.5 conducts comparative studies on digital technologies.

2.1 Digital Object Capture Technologies

Bauer [8] divided the digital capture of objects, such as part IDs or homologation-relevant markings, into three main categories: optoelectronic systems, transmitter-receiver systems, and real-time location systems. These categories were based on different approaches for object recognition.

The first two approaches were primarily focused on the identification of objects. I n contrast, the focus of the third category was on real-time localization of objects, which focused on acquiring location and identification data.

Both optoelectronic systems and transmitter-receiver systems enabled an exchange of information through the transmission of signals and the identification of features with regard to the part ID identification and comparison with the CoP data.

Since this contribution focused on the part identification process, the emphasis was on optoelectronic systems and transmitter-receiver systems. Real-time location systems were not considered in this contribution [8].

2.2 Optoelectronic Systems

Böhmer [9] explained that optoelectronic systems were used to identify objects based on their contours or markings such as colors, reflective marks, fonts, symbols, or bar codes. This was done using optoelectronic reading devices such as laser scanners or cameras, which captured information by illuminating the object with an external light source and receiving the reflected light [10].

Hesse and Schnell [10] report that barcodes are the most widely used concept for marking and tracking objects in logistics. There are different types of barcodes, including 1D, 2D, 3D, and 4D barcodes.

Kern [11] describes an optoelectronic system for character recognition by optical character reading. The efficiency of this technology is highly dependent on the quality of the input documents. In an Optical Character Recognition (OCR) system, an optical scanner first digitises analog documents, identifies text areas, and extracts individual characters. These characters then undergo normalization and noise reduction. OCR thus enables the extraction of inscriptions on parts or images in electronic form for further processing and analysis [11]. extended the functionality of OCR by extracting data from unstructured documents. By incorporating AI technologies, ICR systems improved the recognition of input data, as described in Shidaganti [12].

2.3 Electromagnetic Transceiver Systems

Bauer [8] explains that the exchange of information in electromagnetic transmitter-receiver systems is based on the transmission of signals. The transmitter generates signals that are transmitted by electromagnetic waves. These signals are picked up by antennas on the corresponding objects and transmitted to the receiver.

The receiver then interprets the received signals to reconstruct the transmitted information. Examples for this are Radio Frequency Identification (RFID) [11, 13] and Near Field Communication (NFC) [12, 14].

2.4 Application of Digital Quality Control in Industry

The trade magazine InVision reports about a production conformity assurance process by means of a hand scanner. The content of the label is captured in real time by a hand scanner, and the position of the label is determined. If both characteristics are correct, the device triggers a vibration [15]. The trade magazine InVision reported about a production conformity assurance by means of a hand scanner. The content of the label was captured in real time by a hand scanner, and the position of the label was determined. If both characteristics were correct, the device triggered a vibration [15].

The Volkswagen Group is one of the world's leading automotive companies and uses various technologies for part marking to ensure the quality and traceability of vehicle parts. These include optoelectronic systems (e.g., bar codes), transmitter-receiver systems (e.g., RFID - Radio-frequency identification), and real-time location systems (e.g., GPS - Global Positioning System).The literature reviewed did not describe the use of any technology to ensure CoP identification [16].

The BMW Group's Munich plant relies increasingly on AI for quality monitoring in vehicle production, complementing Smart Data Analytics (SDA) [17] and state-of-the-art measurement technology [18]. Smart Data Analytics is used to analyze large amounts of data using AI and advanced analysis techniques to extract relevant information.

In terms of modern measurement technology, BMW has developed an in-house assurance platform called AIQX (Artificial Intelligence Quality Next) [19] to automate quality processes in production using sensor technology and AI. The platform ensures the quality and completeness of various parts during the assembly process. It is based on intelligent camera systems and sensors along the production line that capture data in real time and analyze it using algorithms and AI.

In the press shop, AI is used to monitor material and process parameters in real time when processing sheet metal panels. This increased transparency and facilitates quality control [20].

BMW and other Original Equipment Manufacturers (OEMs) used RFID technology in their supply chain to track and manage products and parts [21].

In the automotive and food industries, in retail and logistics, barcode and QR code tags were used to ensure product traceability and quality assurance [22–24].

The analysis of the current state of the art shows that a variety of different technologies were already in use in the quality area, but not in the CoP process.

2.5 Comparative Studies of Digital Technologies

In addition, the state of the art has shown that comparisons have already been made between optoelectronic and transmitter-receiver systems [8]. The comparison studies aim to identify the advantages and disadvantages as well as the different application possibilities of these technologies.

The focus of the studies in this contribution is on the automatic identification of the part IDs or the homologation-relevant markings and the subsequent comparison with the homologation data.

Várallyai [23] explains the advantages and disadvantages of the technologies, including their different application possibilities, using the example of an internal changeover from a barcode identification system to a QR code system. In doing so, he gives an overview of different barcode and QR code standards, their printing methods and the way they are read. As a result, it is shown that QR codes are more versatile.

Kulshreshtha, Kamboj and Singh [24] conducted a comparison study of data matrix and QR code on images and increased the level of blurriness for each measurement step. The investigations were related to the decoding robustness of both codes under varying noise levels. The results of the experiments show that the data matrix code is more robust to noise than the QR code and has better decoding performance at the same noise level.

Sivakami [25] conducts a comparison of RFID, barcode and QR code technologies in terms of durability, cost, information capacity and reading range. Each of these technologies basically has advantages and disadvantages, which must be weighed depending on the application. An example of a barcode advantage over RFID is the lower cost. RFID can transmit through objects, allowing multiple tagged objects to be read simultaneously. The reading range of barcodes and QR codes is from a few centimeters to several meters, while RFID can reach several meters. RFID tags are reusable and, unlike barcodes and QR codes, can be modified an unlimited number of times. This is only an excerpt, further advantages and disadvantages can be found in the work of Sivakami [25].

Arendarenko [26] investigated the use of RFID and 2D barcodes and makes several comparisons. RFID showed clear advantages in terms of reading range, storage capacity, reading speed, line of sight independence, and reusability. On the other hand, 2D barcodes are less expensive, less susceptible to electromagnetic interference, and have established standards. The results indicate that both technologies can be used depending on the requirements and conditions of an application.

Brother International GmbH [27] offers a comprehensive overview of the advantages and disadvantages of different barcode, RFID and QR code technologies. The selection of the optimal tracking system depends strongly on the specific application. RFID technology is particularly suitable for identifying groups of goods, tracking high-value products in real time, and dealing with challenging environmental conditions. For simpler and less sophisticated solutions, optical codes such as QR codes and barcodes are appropriate.

In summary, the versatility of QR codes compared to barcodes, the higher decoding robustness of data matrix compared to QR codes and the individual strengths of RFID, barcodes and QR codes depending on the application are to be emphasized. In addition, the higher costs and environmental impacts of RFID technology must be considered, especially when dealing with high volumes of production parts.

The analyzed state of the art does not include a comparison of all these technologies with each other, nor does it reference the CoP process. Therefore, the objective of this contribution is to mitigate this knowledge deficiency.

3. Methodology

Firstly, the methodological approach to selecting a suitable technology is described in Section 3.1 and the structure of the associated sections in this contribution is laid out in Section 3.2.

3.1 Selection of the Methodological Approach

Schuh and Klappert [28] divided the selection of methods into three areas: technology foresight, development planning, and exploitation. These areas represent the phases that a company's technologies go through in order to identify and introduce technologies. Early recognition of new technology focuses on defining the requirement profile and evaluating the various technologies in order to systematically identify an appropriate technology for the CoP process.

Technology recognition is therefore the first important step in automating the CoP process and is therefore the focus of this contribution. This process involves the methodical identification, analysis, and piloting of new and emerging technologies in order to understand their potential for future applications [29].

First, it is necessary to clearly define the criteria for selection based on the requirements from the perspective of the use cases of the technologies and the boundary conditions of the most appropriate technology with a focus on the CoP process. The criteria are divided into technical, economic, social and environmental aspects.

When evaluating technologies for the CoP process, several steps are crucial. The first step is data collection and analysis. This involves gathering the relevant data and information needed to assess the technology. The recognition is done through data analysis and expert interviews. After the necessary information has been gathered, the application of the appropriate methods for the evaluation follows. According to Schuh and Klappert [28], proven methods for early recognition of new technology are argumentation and value benefit analysis [30, 32, 33].

The methods of early recognition of new technology prove to be useful in selecting the optimal approach, comparing technologies, and thus making well-founded decisions. Defining the requirement profile by defining evaluation criteria marks the beginning of early recognition of new technology and is explained in Section 4.

3.2 Structure of the Methodology

In order to provide a clear overview of the structure, Figure 1 illustrates the methodological structure of this contribution.

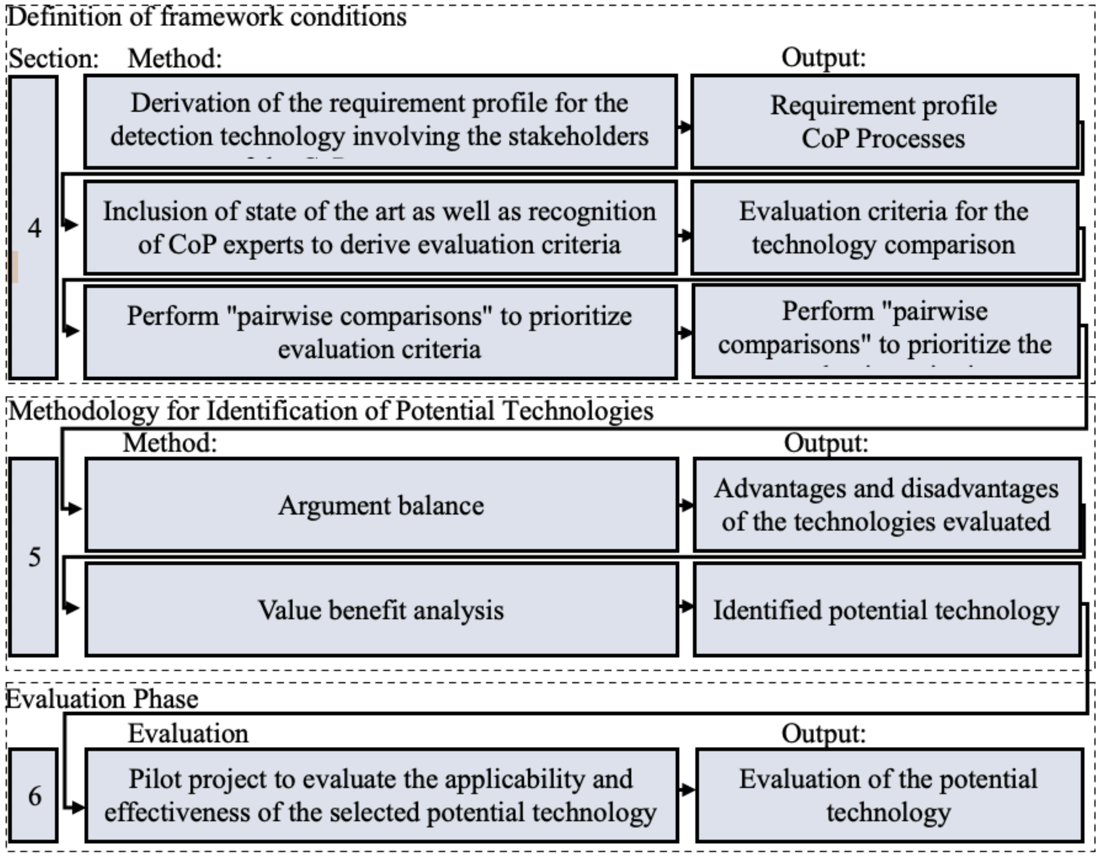


Figure 1: Methodology for technology recognition based on Schuh [30].

This contribution focuses on recognition of new technology (Figure 1). It aims to identify the best appropriate technology for the CoP process through a structured and systematic approach.

At the beginning, a requirement profile for the CoP technology with a focus on the CoP process is defined in cooperation with the stakeholders and the CoP experts of the BMW Group. Based on an analysis of the current state of the art and the previously defined requirement profile, the relevant evaluation criteria are identified together with the CoP experts of the BMW Group. The defined evaluation criteria are compared and evaluated by means of a pairwise comparison to obtain a prioritization.

In Section 5, the advantages and disadvantages of technologies in connection with the CoP process are analysed by means of an argumentation balance.

Finally, a value benefit analysis is performed to identify the potential technology.

Here, the previously defined criteria are weighted and evaluated in order to select the most suitable technology with a focus on the CoP process.

The term "potential technology" refers to the technology that has the greatest potential for process automation in the context of the CoP process [32].

In order to evaluate the practicability of the potential technology, a proof of concept (PoC) is performed in Section 6 [33].

4. Creation of the Requirement Profile and Prioritization of the Evaluation Criteria

In the context of Section 4, the requirement profile for the CoP technology is first established in Section 4.1. In Section 4.2, the current state of the art is analyzed with respect to potential technologies for the CoP process. Based on this analysis, essential evaluation criteria are derived, and the results are summarized in a matrix.

Based on the findings from the requirement profile and the current state of the art, relevant evaluation criteria are derived in Section 4.3. The evaluation and prioritization of the defined criteria is done by a pairwise comparison as described in the following Section 4.4. The creation of the requirement profile is described in Section 4.1.

4.1 Creation of the Requirement Profile by the Stakeholders

The first step in developing the requirement profile is to define the main objective. The next step is to identify the stakeholders who are affected by the automation of the CoP process and who have an influence on the technology. During a workshop with CoP experts, all relevant stakeholders were identified. The following Table 1 provides an overview of the main goal and the defined stakeholders.

Identification of the stakeholders:	**Factory/production facilities:** The transition from manual CoP processes to digitized technology affects the manufacturing process and production flows, which in turn affects the internal operations and employees at the plants.
	Homologation department: The homologation department plays a key role as a stakeholder, as it is responsible for ensuring compliance with homologation regulations. The introduction of a new technology can have an impact on the workflows and requirements of the homologation department.
	National authorities and technical services: National authorities and technical services play a decisive role as stakeholders, as they regulate the CoP process and homologation and set standards. This includes defining the legal framework and regulations that vehicles must meet to be approved for the market. Especially on the Chinese market, the homologation of CoP parts must be listed in a control plan. As part of the annual audit, the authorities check this assurance in production. Any changes to the part safety must be communicated to the authority accordingly [3, 4, 36, 37].
	Suppliers: Suppliers of parts that are components of the homologated product could be affected by changes in the automation of the homologation process. Such changes could impact the requirements for supplied parts.
	Development department: Teams responsible for the development of CoP-relevant products may be affected by the impact of the new technology on the CoP process. Adjustments to development processes and product requirements may be necessary.

Identification of the stakeholders:	**IT department:** The IT department plays an important role as a stakeholder since the implementation of the new technology in connection with the CoP process depends on the support of the IT department. This concerns the integration into different systems as well as other internal processes of the BMW Group.
	Customers: Customers could be indirectly affected by the changes, as homologation standards have a direct impact on the quality and safety of products. Automation could affect the availability and introduction of new products to the market.

Table 1: Identification of the stakeholders.

In a workshop, relevant requirements were defined by a team of CoP experts at the BMW Group with the involvement of the above-mentioned stakeholders. The requirements are presented in Table 2.

Define the requirements:	The technology must be able to flexibly consider all regulatory requirements of the different countries [3, 4, 36, 37]. A concrete example is the Chinese implementation regulation CNCA C11 01:2020, which requires the assurance of up to 300 parts [35]. Therefore, the technology should be able to efficiently inspect a large number of parts with different properties in order to be able to meet the regulatory requirements.
	The BMW Group agrees with its suppliers different limits on the number of defects that are acceptable [38, 39]. The limits are specified in the service specifications agreed between the BMW Group and the suppliers. Due to the critical nature of CoP parts [35], a strict range of 0.001 % (10 ppm) to 0.01 % (100 ppm) was agreed upon between the BMW Group and the suppliers [36]. The technology must ensure that the part marking complies with the CoP data within these agreed tolerances. Within BMW, there is a standard for "quality monitoring using image processing" that must be adhered to. The underlying formula is: ñ ppm × 10 % × 100 % = maximum number of allowable defects. Here, ñ represents the acceptable defect specification limit for the supplier. Thus, maximum allowable error values in the measurement method are from 1 ppm to 10 ppm [38]. For the CoP technology, this value is to be applied to the false-positive identifications. This means that a part with a false ID is nevertheless detected as correct.
	DIN EN 12464-1 (German Institute for Standardization European Norm specifies) [39] that the illumination level in production environments be between 500 and 750 lux [41, 42, 43]. In the BMW Group's production facilities, this value varies between 500 and 850 lux, depending on the day and night shifts [42]. The technology must be able to handle these variations and be usable under different lighting conditions. It should also be scalable to reliably capture part markings on CoP parts of different sizes.

Define the requirements:	The technology had to have an intuitive and user-friendly interface to allow smooth operation by different employees of the BMW Group without the need for extensive training. The user interface should be easy to understand and to navigate to ensure efficient use of the technology. Clear feedback and instructions should be an integral part of the application in order to promote successful acceptance and application of the technology by the staff [43].
	In the production and logistics areas of the BMW Group, various fluctuations in temperature, humidity, dust, dirt and vibration can occur. The production environment in the automotive industry is regulated according to various standards. Section 8.5.6.1.1 of IATF 16949 (International Automotive Task Force) regulates aspects of the production environment [44], while Section 7 of ISO 26262 (functional safety) makes corresponding specifications [45]. A complete avoidance of the mentioned influences is not possible within the production. For this reason, it is necessary that the technology also performs correctly under these influences.
	The need for rapid responsiveness of the technology is to provide near real-time feedback as soon as a CoP deviation is identified. This allows not only the immediate detection of potential violations of compliance policies, but also a rapid response and immediate remediation of the detected deviations [46]. Such rapid response can be achieved through automation. In the automotive industry, the degree of automation refers to the share of automated functions in the overall functionality of a production system. It serves as a measure of a company's equipment with independently operating machines or devices and is expressed as a percentage. A higher value indicates a more advanced level of automation. For example, according to DIN IEC 60050-351 (International Electrotechnical Commission), a system is only called "automated" if its degree of automation is 100 % [47]. Therefore, the requirement for the technology to have a high degree of automation is an important prerequisite.
	The seamless integration of CoP technology is essential to ensure optimal synergies in existing structures. Particularly in the context of the BMW Group, where all homologation data is managed in the central "Approve" database, the technology must be seamlessly embedded in existing IT systems [48]. This enables the efficient exchange of information between different systems, avoids redundancies, and ensures the integrity of sensitive data, especially in official communication. Integration aims to prevent isolated solutions and to integrate CoP technology holistically into the corporate environment.
	The 300 CoP parts [35] are placed at different positions in the vehicle with different distances in the production and logistics area of the BMW Group. The technology must be able to reliably read the part IDs of the CoP parts [35] at different positions, in different material environments and at different distances. This is necessary because a constant distance for reading the part IDs or homologation-relevant markings is not always guaranteed in production. It is important to ensure safety distances in accordance with safety regulations. The spatial requirements and safety standards for production facilities with regard to distances are specified in the European Union's Machinery Directive (Directive 2006/42/EC) [49]. In BMW Group production, the usual distances are between 10 cm and 200 cm [50].

Define the requirements:	Homologation data is highly sensitive information that must be transmitted to the competent authority in accordance with regulations [3, 4, 37]. At the BMW Group, the security and protection of data is a top priority. The European Union's General Data Protection Regulation (GDPR) [51] sets out strict requirements for the protection and processing of data. The storage and archiving of sensitive data sources is regulated by DIN 66399 [52]. It is crucial that the technology complies with the data processing requirements of the GDPR and the archiving requirements of DIN 66399.

Table 2: Define the CoP requirement profile.

The requirements defined for the CoP process include technical, functional, regulatory or other aspects that are critical to the success of the CoP process and technology. The focus is on ensuring that the developed solution meets the actual requirements and expectations of all relevant stakeholders.

The next step is to define the evaluation criteria. These criteria will consider both the stakeholder requirements (Section 4.1) and the current state of the art. The determination of the current state of the art for the evaluation criteria and the derivation of the specific evaluation criteria are described in the following Section 4.2.

4.2 Determination of the Current State of the Art and Derivation of the Specific Evaluation Criteria

In addition to the definition of the requirement profile, research into standard criteria should serve as a reference for the definition of the evaluation criteria.

Rummel's contribution focusses on the evaluation of the suitability of different technologies. Different criteria are discussed, including cost, flexibility, ease of use, accuracy, susceptibility to error, degree of automation, degree of integration, and range [30].

Bauer evaluates technologies with regard to logistically relevant criteria. These are supplemented by usability/application, degree of integration, and security and data protection with regard to the underlying research questions in this contribution [8].

Identification technologies in logistics must meet various operational requirements. According to Hompel, these requirements include ensuring read reliability, sufficient read speed, and read distance [13].

In **Rossouw's** report "10 Factors for the Comprehensive Evaluation of Technologies", essential criteria for the evaluation of new technologies are discussed and considered in relation to autonomous driving. In the automotive industry, especially in the area of homologation, safety and data protection are important [53].

Schuh and Klappert explain how to conduct a value benefit analysis and integrate their research criteria. Some selected aspects are summarized in the present list of criteria, such as "low production costs" and "low investment costs" [28].

Messerle structured criteria for the evaluation of innovations in technical, economic and other effects in order to define a comprehensive overall benefit [54].

Heubach categorized the criteria into several aspects, encompassing functional criteria, operational requirements, design requirements, manufacturing requirements, environmental considerations, measures for environmental impact reduction, testing methods and equipment, market introduction requirements, ergonomic suitability, and economic feasibility [55].

Kröll developed evaluation criteria that include cost, quality, flexibility, and technological maturity [56].

The evaluation criteria identified in the literature largely correspond to the criteria defined in the requirement profile in Section 4.1 and are shown in Table 3 as a summary overview.

	Rummel, 2014 [30]	Bauer, 2019 [8]	Rossouw-Nel, 2019 [53]	Schuh / Klappert 2011 [28]	Messerl, 2016 [54]	Heubach, 2008 [55]	Kröll, 2007 [56]
Cost	x	x	x	x	x	x	x
Flexibility	x	x					x
Usability / application	x		x			x	
Accuracy	x	x				x	x
Degree of automation	x	x					x
Degree of integration	x		x	x		x	x
Range	x	x					
Safety and data protection			x				x

Table 3: Summary of evaluation criteria based on the state of the art.

Together with the previously defined requirement profile and the results of the state-of-the-art analysis, the evaluation criteria are derived. Section 4.3 presents and explains the evaluation criteria.

4.3 Determination of Evaluation Criteria Considering the Requirement Profile and Evaluation Using the SMART Method

This section describes the criteria derived from the requirements and evaluates them using the SMART method to ensure that they are clearly formulated, measurable, achievable, and realistic [57]. The evaluation of these criteria refers to technologies and considers the requirement profile of the BMW Group. The SMART method provides a framework for the precise formulation of measurable and verifiable objectives. The criteria are evaluated based on the five attributes of the SMART method: specific, measurable, achievable, realistic, and time-bound [17, 59]. In this context, the SMART method is used to evaluate criteria and not to set goals. Since the implementation maturity level is still in the distant future, the "time-bound" evaluation criterion is not considered in the evaluation.

Costs [58]

The costs refer to the financial resources required for the implementation of new technologies in the CoP process, including acquisition costs and ongoing operating costs. A clear identification and definition of the costs associated with the implementation of new technologies must be made, with specific metrics defined to evaluate the implementation costs and operating expenses, which are measurable in Euros. These criteria are achievable and realistic if the allowable costs are clearly defined and can be reconciled with the actual costs of implementing the technologies to ensure that they are within the available budget and the implementation is financially feasible. Additionally, the costs are evaluated in terms of the realistic financial capabilities of the BMW Group and the long-term economic viability of the technology.

Flexibility [59]

The new technology must be sufficiently flexible for the future automation of the CoP process to capture the multitude of IDs of different CoP components, including different materials, regardless of material, size, texture, or color (see Table 2: requirement profile). It should reliably function under various lighting conditions, whether natural or artificial, to meet the production requirements of the BMW Group (see Table 2: requirement profile). In the event of changes to the CoP requirements, such as the addition of new features, the technology must be quickly adaptable without disrupting the production line or compromising the capture quality (see Table 2: requirement profile).

Usability / Application [59]

The new technology must have an intuitive and user-friendly interface so that various BMW employees can operate it without extensive training (see Table 2: requirement profile). The specificity of the technology requires that it be designed such that production employees can operate it alongside their regular tasks without causing additional effort. Additionally, the cycle times within the BMW Group must not be extended by the use of the technology (see Table 2: requirement profile). The measurability of usability is evaluated through specific metrics such as the number of steps required to perform tasks with the technology and the time an employee needs to learn and effectively use the technology. The realism of usability is assessed in relation to the actual working conditions and the technical infrastructure of the BMW Group to ensure seamless integration and application (see Table 2: requirement profile).

Accuracy [60]

The technology must operate within defined tolerances to ensure quality monitoring for the homologation of up to 1,500 vehicles per day in the production facilities of the BMW Group [61]. To this end, it is essential to determine a maximum allowable error rate of the technology based on predefined tolerances [37–39] (see Table 2: requirement profile). The Overall Equipment Efficiency (OEE) defines these tolerances [64, 65]. The OEE is calculated based on availability, performance, and quality, and is expressed as a percentage. The BMW Group requires an OEE of over 92 % [64, 65] (see Table 2: requirement profile). The measurability of accuracy is evaluated based on a maximum allowable error rate, an OEE target of over 92 , and the proportion of successfully monitored parts [64, 65]. The achievability of the technology requires that it is capable of maintaining its performance within the specified tolerances (see Table 2: requirement profile). It is important that the technology accurately assigns the component identification and homologation markings. This means correctly identifying both erroneously and accurately marked component IDs. For the CoP technology, this implies that parts falsely identified as correct must be maintained within a stringent tolerance range of 0.001 % (10 ppm) to 0.01 % (100 ppm). The technology must ensure that the part marking complies with the CoP data within these agreed tolerances (see Table 2: requirement profile).

Degree of Automation [47]
The technology must be able to react quickly to deviations in the CoP (see Table 2: requirement profile). Section 4.1 of the requirement profile defines the degree of automation according to DIN IEC 60050-351 [64]. This means that the part ID or homologation marking, especially the precise reading and comparison of the target homologation data, must be carried out in a short time (see Table 2: requirement profile). The measurability of the degree of automation encompasses the number of automatically conducted steps relative to manually performed ones. The feasibility of the requirements for the degree of automation must take into account the actual production conditions and the existing technological infrastructure (see Table 2: requirement profile).

Degree of Integration [65]
The technology to be introduced must be seamlessly integrated into the existing infrastructure of the BMW Group. It is necessary that the technology is compatible with the internal BMW systems and functions without any interruptions or impairments (see Table 2: requirement profile). The measurability of the degree of integration is based on the smooth integration of the technology into the BMW internal systems and the undisturbed functionality after the integration (see Table 2: requirement profile).

Range [66]
The technology must be able to reliably capture the 300 CoP parts at different positions within the production and logistics areas of the BMW Group, while complying with the safety standards for production facilities as outlined in Directive 2006/42/EC [49] and the tolerances defined by the BMW Group [50] (see Table 2: requirement profile). The technology must be capable of reliably capturing the 300 CoP parts at different positions and with varying ranges while adhering to the safety standards of Directive 2006/42/EC (European Union) and the BMW Group tolerances [49] (see Table 2: requirement profile). The measurability of the range is based on the number of successfully captured CoP parts at various positions, compliance with range tolerances, and the number of errors due to insufficient range [50] (see Table 2: requirement profile). The achievability requires that the technology has the technical capabilities to ensure the capture of CoP parts despite varying ranges and positions, meeting the prescribed safety and tolerance standards [50] (see Table 2: requirement profile). The realism of the range requirements must consider the actual conditions in the production and logistics areas to ensure effective implementation of the technology under real-world operational conditions (see Table 2: requirement profile).

Security and Data Protection [67]
The technology must ensure that the results of the CoP selection and data are securely stored after the part ID/marking inspection and comparison with the CoP data to remain meaningful in the event of regulatory inquiries. Given the sensitivity of these data, adequate protection is crucial. When introducing new technologies, it must be guaranteed that the comparison of CoP data with the part is protected against unauthorized access. Similarly, access to the new technology should be granted only to authorized personnel based on the stored CoP data (see Table 2: requirement profile). The specificity requires that the CoP selection results and data are securely stored and protected from unauthorized access, while complying with the requirements of the GDPR [51] and DIN 66399 [52] for the storage and archiving of sensitive data sources (see Table 2: requirement profile). The measurability of the effectiveness of the security measures can be assessed by the number of successfully prevented data protection incidents, compliance with the GDPR and DIN 66399 standards [53, 54] and the number of blocked attempts of unauthorized access (see Table 2: requirement profile). The achievability requires that the technology is capable of implementing robust encryption, secure storage mechanisms, and access controls to protect the CoP data from unauthorized access and ensure the integrity and confidentiality of the data [51] (see Table 2: requirement profile). The security and data protection requirements should be pragmatic and feasible within the existing technological infrastructure of the BMW Group. This ensures effective implementation without disrupting the existing workflows (see Table 2: requirement profile).
The application of the SMART method [57] to the specific criteria of the CoP process, such as cost, flexibility, usability/application, accuracy, degree of automation, range, and safety and data protection, offers a structured approach to evaluate these aspects. The results demonstrate that each criterion is made measurable through clearly defined specifications. Finally, it is necessary to weight the different

evaluation criteria. This is described in Section 4.4.

4.4 Pairwise Comparison of Evaluation Criteria Weightings

The previously defined evaluation criteria are now weighted by a pairwise comparison [68].

Subsequently, a percentage is calculated by dividing the sum of the ratings by the number of raters. In this way, the individual criteria are weighed against each other to allow a systematic evaluation by several people. After the comparison, the sums for the respective options are formed and the result is expressed as a percentage. The example of the calculation of "cost vs. flexibility" shows the procedure: the pairwise comparison involved 45 CoP experts. In the survey, 32 people voted 0 and 13 people voted 1. The sum of the ratings is 13, divided by the total number of 45 results in a value of 0.3 (see Table 5). For each evaluation criterion, a sum is calculated and related to the total number. This results in a percentage that reflects the weighting of the metric.

The evaluation was carried out by the BMW Group's CoP expert team, with the average of the individual evaluations serving as the basis for the weighting factor of the value benefit analysis. The survey among all CoP experts was conducted three times with the same group of participants, with the survey being repeated identically in each iteration.

As part of the pairwise comparison of criteria, all CoP experts were presented with identical questions to assess the importance of the criteria. The comparison of criteria was done through a survey. The CoP experts had the opportunity to classify the importance of each criterion using a nominal scale: lower (0), equal (1), or higher (2). A total of up to 37 different questions were to be evaluated in the survey.

An example of a question was: "In relation to the digitization of the CoP process, is flexibility more important, less important, or equally important compared to costs?"
The results of the pairwise comparison is shown in Table 4. Each criterion's importance was calculated by averaging the scores provided by the experts. This average score was then used as the weighting factor in the value benefit analysis.

	Cost	Flexibility	Usability / application	Accuracy	Degree of automation	Degree of integration	Range	Safety and data protection	Total	%
Cost		0,3	0,3	0,4	0,9	0,7	1,3	0,3	4,2	7 %
Flexibility	1,7		0,6	0,4	1,3	1,0	1,7	0,3	7,0	13 %
Usability / application	1,7	1,4		0,57	1,4	1,3	1,7	0,6	8,7	16 %
Accuracy	1,6	1,6	1,4		2,0	1,9	2,0	0,9	11,3	20 %
Degree of automation	1,1	0,7	0,6	0,0		0,9	1,3	0,4	5,0	9 %
Degree of integration	1,3	1,0	0,7	0,1	1,1		1,1	0,3	5,7	10 %
Range	0,7	0,3	0,3	0,0	0,7	0,9		0,1	3,0	5 %
Safety and data protection	1,7	1,7	1,4	1,1	1,6	1,7	1,9		11,1	20 %
								Total:	56	100 %

Table 4: Pairwise comparison of rating criteria weighting.

The values of the individual criteria can be derived from the " pairwise comparison". The most important criteria are "accuracy" and "safety and data protection" with 20 %. The values of the criteria reflect above all the importance of compliance with technical requirements in the area of type approval. Based on the determination of the criteria, the value benefit analysis will be performed in a later step.

5. Methodology for Identification of Potential Technologies

In order to determine the most appropriate technology, an argument evaluation is first performed, taking into account all relevant arguments and aspects, followed by a value benefit analysis, in order to make a final decision based on quantitative data.

5.1 Summary of Arguments for the Discussion of Potential Technologies

The creation of the argument balance [68] is done under consideration of the state of the art and in co-operation with the CoP experts of the BMW Group.

The structure of this balance is based on the categories of optoelectronic systems and transceiver systems. The evaluation of the arguments is shown in Tables 5 and 6, where the different technologies and their identified advantages and disadvantages in the context of the CoP automation are presented.

Techno-logies	Advantages	Disadvantages
	Optoelectronic systems	
QR code	**High data storage capacity** [71, 72]: Can store a large amount of data, including text, URLs, and binary data. <u>CoP assurance process:</u> Allows comprehensive storage of all CoP-related data. **Robust functionality** [71, 72]: QR codes remain functional even if the code is partially unreadable due to damage or contamination. <u>CoP assurance process:</u> According to requirement profile 4.1, the readability and correct matching of the CoP data of all parts must be 100 % guaranteed.	**Challenges of QR code scanning on round and thin objects** [70]: Scanning QR codes on round and thin objects, such as a lambda probe, is often difficult. <u>CoP assurance process:</u> According to requirement profile 4.1, the readability and correct matching of the CoP data of all parts must be 100 % guaranteed. **Coded part identification** [69]: Disadvantage: The part identification is only available in coded form and remains hidden on the part. <u>CoP assurance process:</u> Certain country regulations [71] require that the CoP data must be visibly displayed on the part.

Barcode	**Low dependence on various scanning devices** [71, 74, 75]: Barcodes are compatible with various scanning devices and can be captured and decoded by simple handheld scanners, laser scanners, cameras, and other barcode readers. CoP assurance process: Various scanning devices can be used to read the part marking. **Fast modification of stored data** [69]: Refreshment of stored information CoP assurance process: In case of a change of the component ID / homologation marking data, a fast modification of the stored data is possible with an easy creation of new barcodes.	**Limited data capacity** [71, 74, 75]: Barcodes have a limited capacity of storing information. CoP assurance process: Storage of all CoP-related data is not possible. Limited flexibility [71, 74]: Barcodes contain only numeric data and are less flexible in the representation of information. CoP assurance process: According to requirement 4.1, it must be possible to flexibly read the part identification, regardless of the material, color, size or content of the CoP specifications. **Coded part identification** [69]: Disadvantage: The part description is only available in coded form and remains hidden on the part. CoP assurance process: Certain country regulations [71], however, require that the CoP data must be visible on the part. **Ruggedness** [72]: Sensitivity to external influences. CoP assurance process: According to requirement profile 4.1, the readability and correct matching of the CoP data of all parts must be 100 % guaranteed.
OCR	**Text recognition of printed documents** [71, 76, 77]: OCR enables the precise recognition and extraction of text information on parts. CoP assurance process: In accordance with requirement profile 4.1, the legibility and correct matching of the CoP data of all parts must be 100 % guaranteed. **Extraction of different forms of identification** [71, 76, 77]: OCR can extract different types of information, including text and numbers, from part identifiers. CoP assurance process: The country regulations [71] on the visibility of part markings can be met. OCR can automate the process of data entry. **Applicability to different material**s [71, 76, 77]: OCR can work on a variety of materials, regardless of the surface finish, color or size of the parts.	**Sensitivity to fonts and styles** [71, 77, 78]: This can lead to inaccuracies when reading the part identification. CoP assurance process: In accordance with requirement profile 4.1 (accuracy), the legibility and specific comparison of the CoP data of all parts must be 100 % guaranteed. **Impairment due to poor image quality** [71, 77, 78]: If the image quality is poor, due to any soiling or blurred images, the performance of the OCR technology may be impaired. CoP assurance process: According to requirement profile 4.1 (accuracy) **Limited ability to recognize handwritten text** [71, 77, 78]: OCR specializes in handling printed text and may have difficulty recognizing handwritten or engraved content. CoP assurance process: According to requirement profile 4.1 (accuracy)

OCR	CoP assurance process: See requirement profile 4.1 (flexibility) **Scalability** [71, 76, 77]: The OCR technology can be easily scaled to meet the requirements in different production environments. If different parts place different demands on the OCR technology, for example due to their size, shape or surface, the OCR technology can be adapted to deal with these differences. CoP assurance process: See requirement profile 4.1 (flexibility).	**Dependence on optimal lighting conditions** [71, 77, 78]: OCR systems often rely on optimal lighting conditions, and difficult lighting conditions can affect recognition performance. CoP validation process: According to requirement profile 4.1 (flexibility) **Need for training data** [71, 77, 78]: To achieve accurate results, OCR often requires an extensive training phase with specific data sets, which can mean additional effort. CoP assurance process: according to requirement profile 4.1 (usability).
ICR	**High accuracy (handwritten text recognizable / engraved part identification recognizable)** [71, 79, 80]: ICR can precisely recognize and extract handwritten text and engraved content. CoP assurance process: According to requirement profile 4.1 (accuracy) **Adaptability to different writing styles** [71, 79, 80]: ICR can adapt well to different writing styles and variants, enabling reliable results in text recognition. CoP assurance process: According to requirement profile 4.1 (accuracy) **Improved processing of unstructured data** [71, 79, 80]: Effective at processing unstructured data. CoP assurance process: In accordance with requirement 5.1 (flexibility), there is a requirement that the new CoP technology should be able to process unstructured data. **Integration with OCR for comprehensive text recognition** [71, 79, 80]: ICR can be integrated with OCR technologies to enable comprehensive text recognition for both printed, handwritten or engraved content. CoP assurance process: According to requirement 5.1 (accuracy, level of integration and flexibility).	**Complexity of handling** [71, 80, 81]: Processing handwritten or engraved content as well as different writing styles can be more challenging due to their complexity. CoP assurance process: According to requirement profile 4.1 (flexibility and user-friendliness) **Higher effort regarding requirements for training data** [71, 81, 82]: ICR requires more extensive and specific training data to ensure accurate detection. CoP assurance process: According to requirement 5.1 (accuracy, level of integration and ease of use) **High computing power required** [71, 81, 82]: ICR may require higher computing power, especially if large amounts of handwritten or engraved content are to be processed. CoP assurance process: According to requirement profile 4.1 (degree of Integration) **Costs for implementation and training** [71, 81, 82]: Implementation of ICR technologies can be costly and the training of systems may require additional resources. CoP assurance process: According to requirement profile 4.1 (costs), the cost-benefit ratio of the potential technology should be considered. In relation to training costs, the potential technology should be designed to be intuitive and user-friendly in accordance with requirement profile 4.1 (user-friendliness).

Table 5: Argument balance – optoelectronic systems.

Techno-logies	Advantages	Disadvantages
	Transmitter-receiver systems	
RFID passive	**Automation and efficiency** [83, 84]: RFID enables automatic identification of parts without direct visual contact. <u>CoP assurance process:</u> In accordance with requirement profile 4.1, flexible reading of part identification must be possible. **Contactless identification** [83–85]: As passive RFID tags do not have their own energy source, they are activated by the electromagnetic energy of the reader. <u>CoP assurance process:</u> This enables contactless identification of the CoP parts, which meets the requirements of profile 5.1 (flexibility/user-friendliness). **Power supply** [69]: Passive tags do not require their own power source and are therefore maintenance-free in terms of battery replacement or charging. <u>CoP assurance process:</u> In accordance with requirement profile 4.1 (user-friendliness). **More compact dimensions and lightweight design** [83–85]: Passive RFID tags are characterized by their compact and lightweight design, as they do not require their own power source. This makes them particularly appropriate for applications with limited space or weight restrictions. <u>CoP assurance process:</u> In accordance with requirement profile 4.1 (flexibility).	**Costs** [71, 86]: It is necessary to check up to 300 parts [35] for their part IDs or homologation-relevant labels. In the production plants of the BMW Group, up to 1,500 vehicles are produced every day [61]. This means that a total of 300 different parts per vehicle, multiplied by 1,500 vehicles per day, must be tracked. This requirement implies that each individual part must be equipped with a passive RFID tag, which is associated with considerable costs [84]. <u>CoP assurance process:</u> According to requirement profile 4.1 (costs) **Limited reading range** [71, 83, 84]: Passive RFID systems have a limited reading range and may therefore have difficulty identifying multiple items at the same time. <u>CoP assurance process:</u> According to Requirement 4.1 (range) **Coded part identification** [71, 83, 85]: Disadvantage: The part identification is only available in coded form and remains hidden on the part. CoP validation process: Certain country regulations [71] require that the CoP data must be visible on the part. **Reduced data transfer rates** [71, 83, 85]: Passive RFID tags have lower data transfer rates active. <u>CoP assurance process:</u> As per requirement 4.1 (flexibility). **Dependence on external reduced performance in demanding environments** [83, 84]: Passive RFID tags can be affected in areas with high metal content or other interfering materials. <u>CoP assurance process:</u> According to requirement profile 4.1 (error susceptibility/accuracy).

RFID active	**Greater reading range** [83, 84]: Active RFID tags have a greater reading range. This enables the tracking of objects over greater distances. <u>CoP assurance process:</u> According to requirement profile 4.1 (range). **Higher data rates** [83, 84, 85]: Active tags can support higher data transfer rates, which is particularly important in applications with extensive data requirements. <u>CoP assurance process:</u> Complies with requirement 4.1 (automation, level of integration). **Improved performance in metal-rich environments** [83, 84]: Active RFID tags are more powerful in metal-rich environments because they can transmit stronger signals due to their active power source. <u>CoP assurance process:</u> According to requirement profile 4.1 (accuracy, flexibility, and error susceptibility).	**Costs** [81, 84]: Each part must be tagged with a passive RFID tag, which adds significant cost [84]. <u>CoP assurance process:</u> According to requirement 4.1 (cost) **Larger size and weight** [81, 83]: Active RFID tags are larger in size and heavier in weight, making them less appropriate for applications where size and weight play a role. <u>CoP assurance process:</u> According to requirement profile 4.1 (flexibility). **Coded part identification** [69, 81, 82]: Disadvantage: The part identification is only available in coded form and remains hidden on the part. <u>CoP assurance process:</u> Certain country regulations [71], however, require that the CoP data must be visible on the part.
NFC passive	**Integration options** [85, 86]: NFC technology is already integrated into numerous smartphones and other devices, allowing for easy integration. <u>CoP assurance process:</u> Meets requirement profile 4.1 (flexibility and level of integration). **No batteries required** [85, 86]: Passive NFD tags do not require their own power source and are therefore maintenance-free with respect to battery replacement or recharging. <u>CoP assurance process:</u> Requirement 4.1 (usability).	**Costs** [87, 88] Each individual part must be equipped with a tag, which leads to considerable costs [87, 88]. <u>CoP assurance process:</u> According to requirement profile 4.1 (costs) **Low reading range** [86, 89]: Passive RFID systems have a limited reading range and could therefore cause difficulties in the simultaneous identification of multiple parts. <u>CoP assurance process:</u> According to Requirement 4.1 (range) **Reduced data rates** [85, 86]: Passive NFC tags have reduced data transfer rates. <u>CoP assurance process:</u> According to requirement profile 4.1 (flexibility). **Security and privacy** [85, 86, 89]: A potential risk of NFC lies in the fact that unauthorized devices or persons could gain access to transmitted data. <u>CoP assurance process:</u> According to requirement profile 4.1 (security and privacy). **Encoded part identification** [89]: Disadvantage: The part identifier is only available in encrypted form and remains hidden on the part. <u>CoP assurance process:</u> Certain country regulations [71] require that the CoP data must be visible on the part.

NFC active	**No complex configuration required** [85, 86, 89]: See NFC passive. **Integration capabilities** [85, 86]: See NFC passive. **Higher data rates** [89]: Active NFD tags can support higher data rates, which is particularly important in applications with extensive data requirements. <u>CoP assurance process:</u> According to requirement profile 4.1 (automation, level of integration).	**Costs** [87, 88]: Each individual part must be equipped with a tag, which leads to considerable costs [87, 88]. <u>CoP assurance process:</u> According to requirement 4.1 (costs). **Security and privacy** [85, 89]: See NFC passive. Encoded part identification [69, 89]: See NFC passive. **Increased size and weight** [85, 86]: Passive NFD tags are larger in size and heavier in weight, making them less appropriate for applications where size and weight are important. <u>CoP assurance process:</u> According to Requirement 4.1 (Flexibility)

Table 6: Argument balance – transmitter-receiver systems.

The results of the argument balance are used in the following value benefit analysis, which is presented in section 5.2.

5.2 Value Benefit Analysis to Identify Potential Technologies

The purpose of the value benefit analysis is to evaluate different technology variants based on previously defined evaluation criteria (see Section 4.3). The weighting of these criteria is derived from the pairwise comparison (see Section 4.4).

The BMW Group's CoP experts conducted the value benefit analysis, considering the previously prepared argumentation. The benefit analysis is divided into the areas of optoelectronic systems and transmitter-receiver systems. The results are shown in Tables 7 and 8.

Evaluation criteria	WF (%)	Optoelectronic systems							
		QR code		Barcode		OCR		ICR	
		DF		DF		DF		DF	
Cost	4.2	5	20.8	5	20.8	3	12.5	3	12.5
Flexibility	7.0	3	21.0	2	14.0	4	28.0	4	28.0
Usability / application	8.7	4	34.8	4	34.8	5	43.6	5	43.6
Accuracy	11.3	5	56.5	5	56.5	3	33.9	5	56.5
Degree of automation	5.0	1	5.0	1	5.0	5	25.0	5	25.0
Degree of integration	5.7	5	28.6	5	28.6	5	28.6	5	28.6
Range	3.0	1	3.0	1	3.0	5	15.0	5	15.0
Safety and data protection	11.1	4	44.5	3	33.4	5	55.7	5	55.7
Total		214		196		242		265	
Rankings		**5**		**6**		**2**		**1**	

Table 7: Value benefit analysis – optoelectronic systems.

(WF = weighting factor, DF = degree of fulfillment, QR = Quick data encoding, OCR = Optical Character Recognition, ICR = Intelligent Character Recognition)

Evaluation criteria	WF (%)	Transmitter-Receiver System							
		RFID passive		RFID aktive		NFC passive		NFC aktive	
		DF		DF		DF		DF	
Cost	4.2	4	16.6	3	12.5	4	16.6	4	16.6
Flexibility	7.0	4	28.0	5	35.0	3	21.0	4	28.0
Usability / application	8.7	4	34.8	4	34.8	2	17.4	2	17.4
Accuracy	11.3	5	56.5	5	56.5	5	56.5	5	56.5
Degree of automation	5.0	5	25.0	5	25.0	1	5.0	2	10.0
Degree of integration	5.7	4	22.8	3	17.1	2	11.4	2	11.4
Range	3.0	2	6.0	4	12.0	1	3.0	1	3.0
Safety and data protection	11.1	4	44.5	4	44.5	4	44.5	4	44.5
Total		234		237		175		187	
Rankings		**4**		**3**		**8**		**7**	

Table 8: Value-benefit analysis – transmitter-receiver systems.

(WF = weighting factor, DF = degree of fulfillment, RFID = Radio-Frequency Identification, NFC = Near Field Communication)

The partial value benefit values are determined by multiplying the degree of fulfillment (DF) by the weighting factor (WF), where the DF indicates the extent to which a criterion is fulfilled and is rated on a scale of 1 to 5. The weighting factor (WF) originates from the previously conducted pairwise comparison according to Section 4.4, Table 5.

Based on the results, a transparent decision can be made by selecting the variant that provides the highest value benefit. As shown in Tables 8 and 9, the ascending ranking shows the technologies that provide the highest value in terms of the CoP process. ICR, OCR and RFID (active/passive) achieve the highest scores.

The next step is to evaluate the findings from the value-benefit analysis, especially those with the highest scores. The ICR achieved the highest score with 453 points and is therefore the focus of the evaluation. For this purpose, a PoC [33] will be conducted to demonstrate whether the identified technologies can be implemented in practice.

5.3 Conducting Inter-Rater Reliability to Assess Consistency of Results

In the process of evaluating survey results, the same CoP experts were interviewed on the same topics at different time points. To ensure the robustness of the results and minimize the potential effects of random variations or other influencing factors, the scenarios were repeated three times with the same CoP experts.

Subsequently, inter-rater reliability [90] was calculated to quantify the consistency of the evaluations and determine whether the experts tended to agree or diverge. Fleiss' Kappa was used to calculate the inter-rater reliability. Fleiss' Kappa measured the inter-rater reliability when multiple respondents (CoP experts) were involved in the assessment. In this case, Fleiss' Kappa was used to examine the agreement or discrepancies in the evaluations of the CoP experts. It assessed the level of agreement beyond what is expected by chance and provided insight into how well the CoP experts agreed in their evaluations. A higher Kappa value indicated stronger agreement in the evaluations (high inter-rater reliability), while a lower value suggested greater discrepancies between the evaluations (low inter-rater reliability) [90, 91].

Formula 1 displays the Fleiss' Kappa formula along with the computed values.

$$\kappa = \frac{p_o - p_e}{1 - p_e} \qquad \kappa = \frac{0{,}82 - 0{,}34}{1 - 0{,}34} \qquad \kappa = 0{,}73 \qquad (1)$$

(1) Formula: Fleiss' Kappa result for inter-rater reliability.

In the Fleiss' Kappa formula, "Po" represented the observed agreement among the CoP experts. It measured the frequency of actual agreement in their evaluations. "Pe" stood for the expected agreement due to pure chance. It indicated how often agreement was expected purely by chance. The difference between "Po" and "Pe" reflected the level of agreement beyond what is expected by chance and provided insights into how well the CoP experts agreed in their evaluations. In the Fleiss' Kappa formula, the value of "Po" was calculated as 0.82 and the value of "Pe" as 0.34. The Kappa value was obtained by dividing "Po" by "Pe". A higher Kappa value, closer to 1, indicated a higher level of agreement among the CoP experts. The calculated Kappa value of 0.73 suggested a good agreement among the CoP experts. There was solid consistency in their evaluations.

In order to obtain a preliminary assessment of the findings, a piloting was carried out on the best result derived from the utility analysis in Section 6.

6. Piloting of the Results of the Value Benefit Analysis

In the context of the value-benefit analysis (Section 5.2), ICR technology was identified as the most appropriate solution for the automation of the CoP process. In order to evaluate the practicability of this technology, a PoC [33] was performed. The aim was to evaluate the identified ICR technology in a realistic environment.

In the following section, the experimental description of the PoC in Section 6.1 was presented first. The results were then presented in Section 6.2 and discussed in Section 6.3 .

6.1 Description of the Experiment

At the beginning of the PoC, the experimental procedure was first described using a technical flowchart. Figure 2 illustrated the ICR technology flowchart.

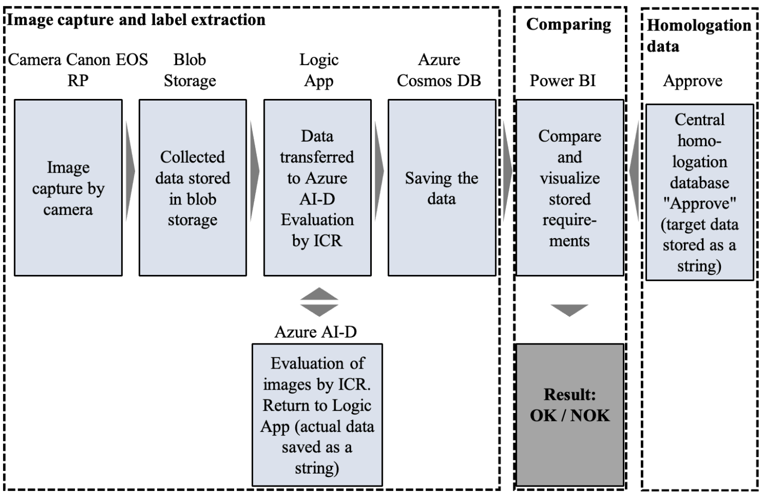
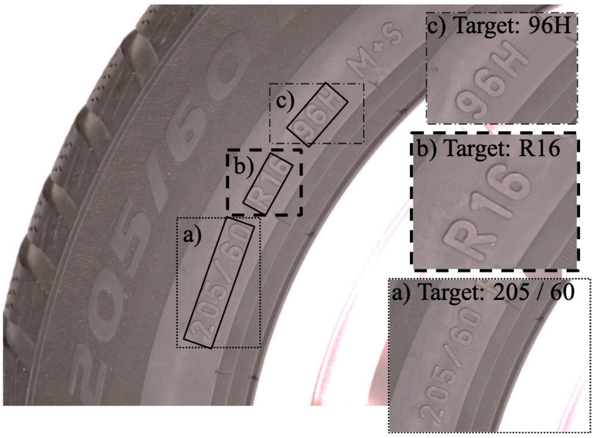


Figure 2: Presentation of the technological structure and the internal BMW tools (flow chart).

The process started with image acquisition using industrial cameras (Canon EOS RP). The collected image files were then stored in a blob storage (cloud storage by Azure). A "Logic App" (BMW internal naming) transferred the data to Azure AI Document Intelligence (Azure AI-D), where an analysis of the images was performed by the ICR. The results of this analysis were sent back to the Logic App. The processed information was stored in an Azure Cosmos DB (Azure Cosmos Database) as a string. This was called string 1. The "Approve" database served as the BMW Group's internal platform for transmitting all homologation requirements to the relevant authorities. The target data for the comparison came from this database. This data was also stored as a string. This was called string 2. In the final step, the stored data was compared to the requirements stored in the Approve homologation database using Power BI (Power Business Intelligence). Using Power BI, all results were marked in order ("OK") / not in order ("NOK"). In the PoC, only OK parts that were correctly marked were used for comparison. This meant that the parts had been correctly delivered by the supplier as well as produced by BMW and that the information in the homologation data matched the respective parts. Therefore, it was checked whether the ICR method marked the images as OK according to the specifications. If the images and their processing led to a result that was not OK, then there was an identification deviation in the technology. Identification deviations were not necessarily caused by a single element of the technological structure, but rather by the interaction of various elements in conjunction with the environment. The framework for the PoC, including the focus, test section, technical parameters, equipment, test series, experiment, and success criteria, was summarized in Table 9.

Framework	
Focus	The goal was to evaluate the ICR technology identified in the benefit analysis (Section 5.2) in a practical experiment. The focus was on the automatic extraction of part IDs and homologation-relevant designations and their comparison with the homologation data. The requirements and limitations from Section 4.1 of the requirement profile had to be considered.
Part	The CoP part identification test involved checking up to 300 different parts [35] for their part ID or homologation-relevant markings (see requirement profile 4.1). Various materials were used, including metal (by means of engraving, stamping, or casting), printed parts (e.g., labels), and plastic or natural and synthetic rubber. The PoC did not investigate all materials but focused on the part with the highest defect rate. Previous studies [5] conducted a statistical analysis of all CoP parts [37] to identify the most common CoP defects. The largest error category concerned tires, with most errors due to incorrect labeling (missing, incorrect, or poorly legible labeling) [5]. The part to be inspected, the tire, came from the manufacturer Pirelli and was made of a mixture of natural and synthetic rubber. The tire was flawless.
Technical parameters of the test part	The BMW Group bought tires from several manufacturers. The problems in the CoP were not specific to one particular supplier. The tire manufacturer was selected for the PoC based on availability. This selection did not represent a piloting of the quality of the manufacturer or its products. Specifications: Pirelli 205/60 R16 96H Tire width: 20.5 cm Tire diameter: 65.2 cm Flank height: 12.3 cm Tread height: 9.2 mm Width: 5.2 mm Character depth: 0.8 mm Character Spacing: 8.9 mm Character or background color: Black Material: Natural and synthetic rubber

Technical parameters of the test part	The focus of the PoC was the marking of tires for the Chinese homologation market. Unlike other CoP parts, the Chinese authorities did not require a part ID specifically for tires. Instead, there was an obligation to verify markings such as tire dimensions, tire diameter, and speed index [35]. The measurement ranges of the parts to be inspected were divided into three different categories. The scope of testing was shown in Figure 3 below:  Figure 3: Measuring range of test part. The indication "205/60" represented the tire dimensions and indicated the ratio between the height and the width of the tire, "R16" the tire diameter and "96H" the load and speed index. These test ranges had to comply with the homologation requirements [3, 4, 34, 35].
Equipment	• Camera (Canon EOS RP + RF 24-105mm F4-7.1 IS STM lens [92]): The camera was operated in automatic mode, which automatically adjusted the exposure time, ISO film sensitivity, exposure compensation, aperture, and shutter speed. • 2 industrial flashes (SLV 1004076 NUMINOS PHASE [93]): with 10 different settings • Tripods for mounting lamps and camera • Lux meter: For measuring brightness (Sauter lux meter SO 200K [94])
Test series Number of measurements	A total of 400 measurements were performed. The design is shown in Table 10.
Experiment	The CoP parts were currently inspected manually on the final vehicle or directly on the production line at the BMW Group plant. In the PoC project, the manual assurance was to be automated by ICR technology. For the implementation in the production environment, it was crucial to ensure a smooth process through the **optimal adjustment of illumination intensity, illumination angle,** and **range**. **Adjustment of illumination intensity:** At the BMW Group, the limits for illuminance in the production environment were specified in Section 4.1 of the requirement profile. According to this standard, the ICR technology had to function perfectly at illumination levels between 500 and 750 lux [40], [41]. In the PoC, an attempt was made to reproduce the real production conditions as accurately as possible. For this purpose, two industrial lamps [93] used to simulate the illumination level in a production environment.

	To achieve a brightness range between 500 and 750 lux (for day and night shifts and different lighting levels in production), ten different lighting levels were alternated. One lamp was mounted at a height of 80 cm and the second lamp at a height of 55 cm to achieve the desired illumination. Optimal illumination was essential because tire assurance involved several criteria, such as 205/60 tire dimensions, R16 for tire diameter, and 96H for speed index.
	Illumination angle (compare α1 and α2 in Figure 12): In the PoC, the illumination angles were set such that the illuminance was within the requirement profile (see requirement profile 4.1). The goal was to match the illumination angles to the real production conditions. For Lamp 1, at a height of 80 cm, the illumination angle was 61°, and at a height of 55 cm, the illumination angle was 47°. For Lamp 2, the illumination angle was 46° at a height of 80 cm, and 31° at a height of 55 cm.
Experiment	**Range:** The 300 CoP parts [35] were placed at different ranges in the production and logistics areas of the BMW Group. The ranges were determined according to the safety and production distances from section 4.1 of the requirement profile [50]. The camera was positioned within a range of 70 cm to fulfill the requirements specified in the range of 10 to 200 cm as outlined in the requirement profile. The ranges from the measurement area to Lamp 1 and Lamp 2 were set to 33 cm and 65 cm, respectively.
	Approve Database: The Approve Database served as an internal BMW platform for the transmission of all approval applications to the responsible authorities. The target data for the comparison was taken from this database, and all results (OK/NOK) were visualized using Power BI.
	ICR-Technology: In the PoC, the ICR technology was based on a Microsoft Azure architecture [95, 96]. The technological process was shown in the flowchart in Figure 2.
	Storage Location: Azure Cosmos DB: BMW used Azure Cosmos DB [96] internally as a database for Microsoft Azure architectures. This NoSQL database from Microsoft allowed the flexible storage of data in different formats such as JSON, BSON, and others. In this PoC, the data was stored in a JSON file within the Azure Cosmos DB.
Success Criteria	In requirement profile 4.1, the identification error was defined according to the standard "quality control by means of image processing" [38]. Thus, the identification error could vary from 1 ppm to 10 ppm. The PoC analyzed how many part IDs were recognized correctly and incorrectly when the illumination intensity and angle were varied. The percentage found was compared to the defined limits to get an idea of whether the technology in the PoC could reach production readiness. The goal of the test was to verify that the ICR method marked the images as in order **(OK)**. If the images and their processing led to a not in order **(NOK)** result, this indicated an identification deviation in the technology. **Explanation of OK/NOK:** • **OK:** The method correctly detected and compared all part information (string 1 = string 2). • **NOK:** String 1 was not equal to string 2, which may indicate an identification error.

Table 9: Experimental description of the piloting.

To determine if the technology had limitations, tests were performed in a range from low illumination (approximately 30 lux) to high illumination (approximately 850 lux). This range was achieved by varying the lamp settings and the lamp height. Two lamps were used for illumination. Preliminary tests had shown that with setting 1 and a lamp height of 80 cm each, a lower lux range was possible. At setting 10, both lamps achieved a high illumination of over 850 lux. The corresponding values were shown in the test plan in Table 11.

During the experiment, several factors were examined. Among them were the variation of the lamp heights (55 cm and 80 cm), which resulted in four different lamp variations, and the adjustment levels of the lamps (10 levels). With the applied design, 400 measurements were made (4 adjustment variations x 10 adjustment levels for Lamp 1 x 10 adjustment levels for Lamp 2). The tests were carried out on a tire with the specification 205/60 R16 96H. A summary of the parameters was given in Table 10.

Lamp height variations	Brightness setting levels Lamp 1	Brightness setting levels Lamp 2	Tire specifications
55 cm / 55 cm	1 2 3	1 2 3	205 / 60 R16 96H
55 cm / 80 cm	4 5	4 5	
80 cm / 55 cm	6 7 8	6 7 8	
80 cm / 80 cm	9 10	9 10	

Table 10: Piloting, test variations of the experiment.

The schematic of the experiment is shown in Figure 4.

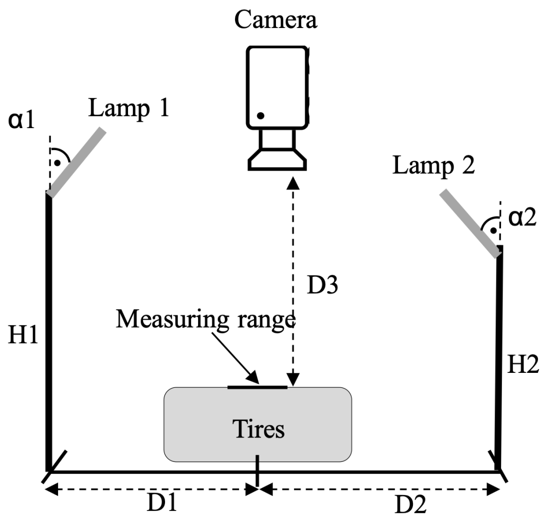


Figure 4: Schematic representation of PoC.

α 1 / 2	Illumination angle
H 1 / 2	Height of lamp
D 1 / 2	Range from lamp to part

The real experiment was shown in Figure 5.

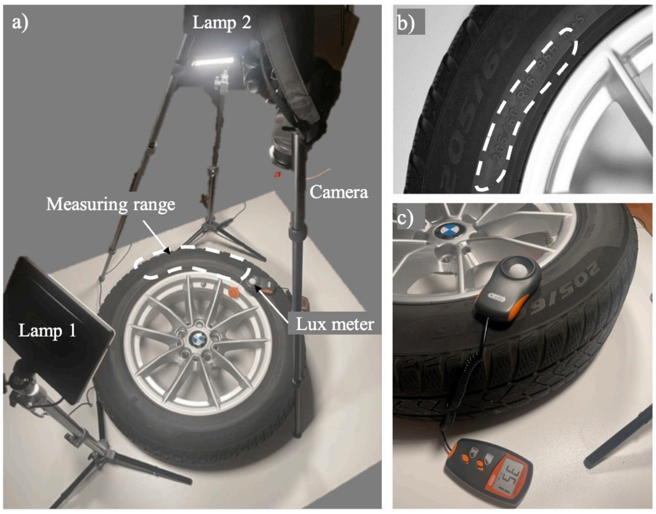


Figure 5: Real experiment of the PoC.

Figure 5 a) showed the overall view. Under b), the measurement range (205/60, R16, 96H) was encircled. In area c), you could see the lux meter for measuring different light levels.

6.2 Results of the PoC

The results of the PoC were shown in the following figures. An experiment was performed with a total of 400 results (OK/NOK). Illumination ranged from 30 to 925 lux. Figure 6 showed an example of image brightness at three different illumination levels over the full range (a, b, c).

Figure 6: Sample images at different levels of illumination.

a)	030 lux
b)	442 lux
c)	925 lux

The production lighting at the BMW Group was typically between 500 and 750 lux [42]. The variance of the illumination level was used to test the influence on the selection quality of the technology. Figure 6 a) showed a low image illumination of 30 lux. Figure 6 b) was approximately in the middle of the illumination levels with 443 lux, which made it easier for the human eye to recognize the measuring range, while 850 lux (Figure 6 c) led to high illumination. The focus was on investigating whether different illumination levels had a positive or negative effect on the selection result.

Figure 7 showed an OK/NOK comparison of the 400 tests performed using illuminances ranging from 30 to 925 lux.

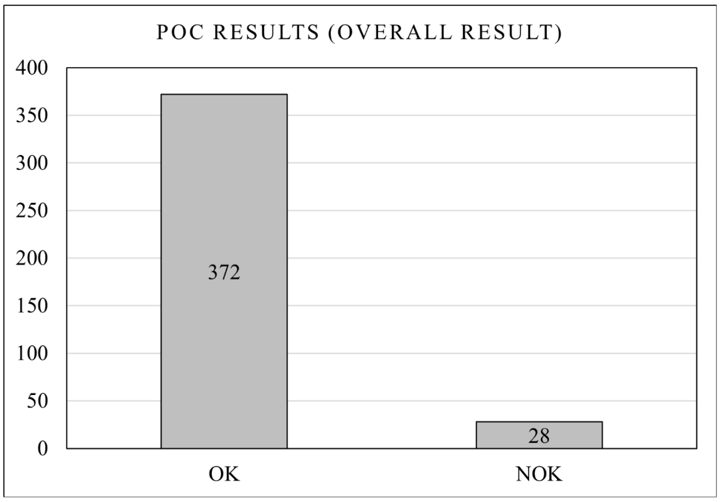


Figure 7: PoC result over the entire lighting value range (30 lux to 925 lux).

It was seen that the ICR technology correctly identified 372 of the CoP parts. However, the ICR technology caused identification errors for 28 parts by interpreting them as "NOK" when in fact they were correct. This represented an identification error rate of 7%. The following analysis was based on the 28 parts where the ICR technology caused an identification mismatch during readout. Figure 8 showed the identification errors that occurred at illumination levels ranging from 30 lux to 925 lux.

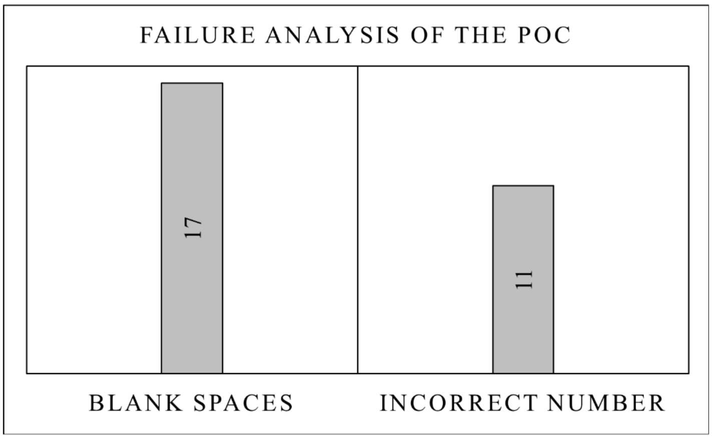


Figure 8: PoC identification deviation analysis over the entire lighting value range (30 lux to 925 lux).

The analysis revealed two categories of identification discrepancies. In 11 cases, the ICR technology misidentified numbers, while in 17 cases it misinterpreted spaces. Figure 9 showed an example of the "wrong number" category, while Figure 10 showed examples of the "space" category.

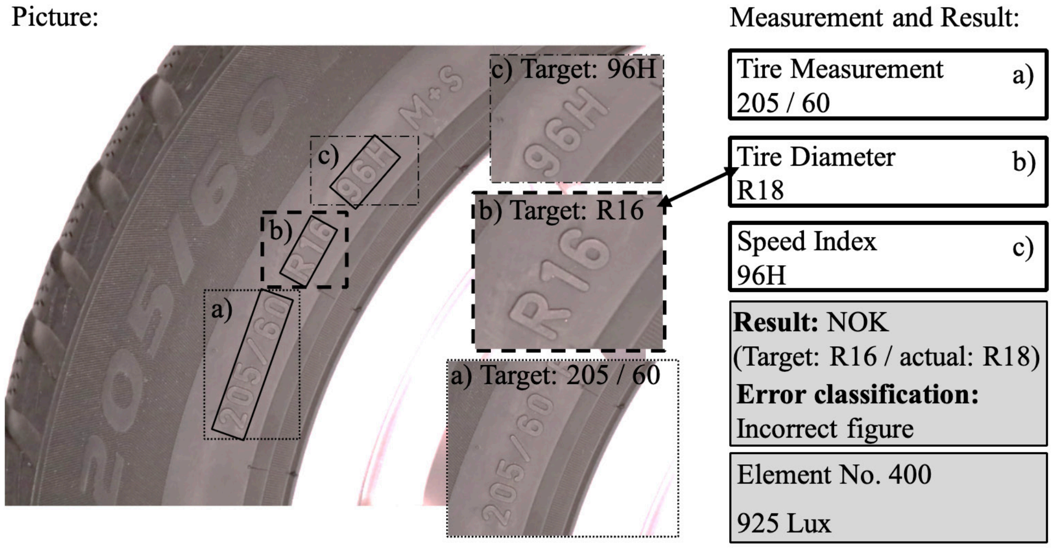


Figure 9: ICR-technology – incorrect figure (target: R16 / actual: R18).

In Figure 9, it was seen that the ICR technology identified the area b) for the tire diameter as R18 instead of R16 (target). An ICR technology identification error occurred in the range of 925 lux. Figure 10 showed the "Blank" category of identification error.

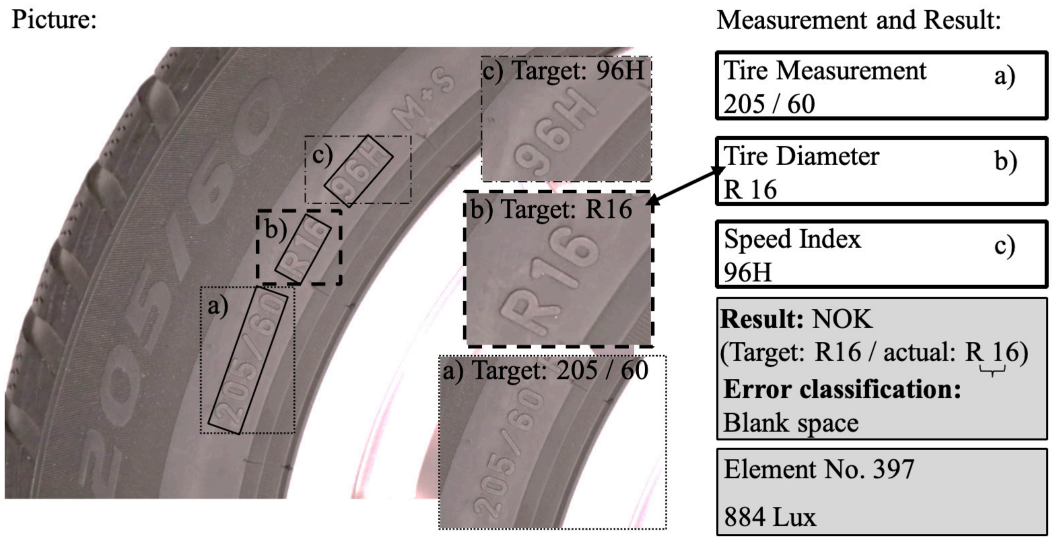


Figure 10: ICR technology – „blank space“ (target: R16 / actual: R16).

At an illumination level of 884 lux, the ICR technology detected and interpreted an additional blank space in area b) for the tire diameter "R16".

The piloting of the 400 results also included an analysis of the behavior of the ICR technology in the illumination range under production conditions (see requirement profile – 500 and 750 lux). These results were shown in Figure 11.

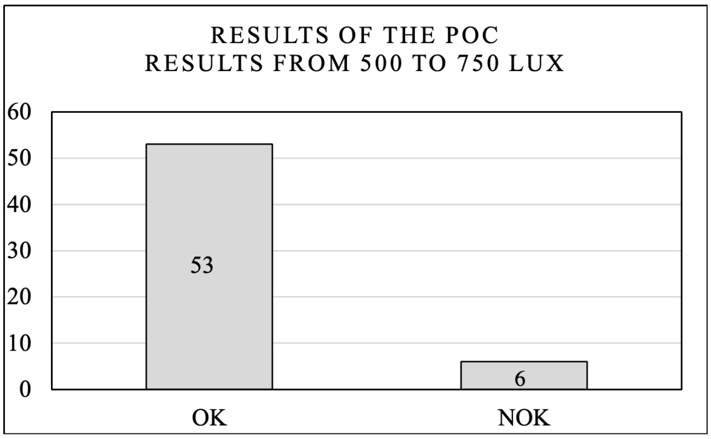


Figure 11: PoC result for the value range 500–750 lux (production conditions BMW Group).

The ICR technology correctly identified 53 of the 59 parts. However, in 6 cases, parts were declared "NOK" when they were in fact correct. This represented an error rate of 10.2%.

The following analyses focused on the 6 parts where the ICR technology caused identification errors during readout. The classification of ICR errors at illumination levels from 500 to 750 lux was shown in Figure 12.

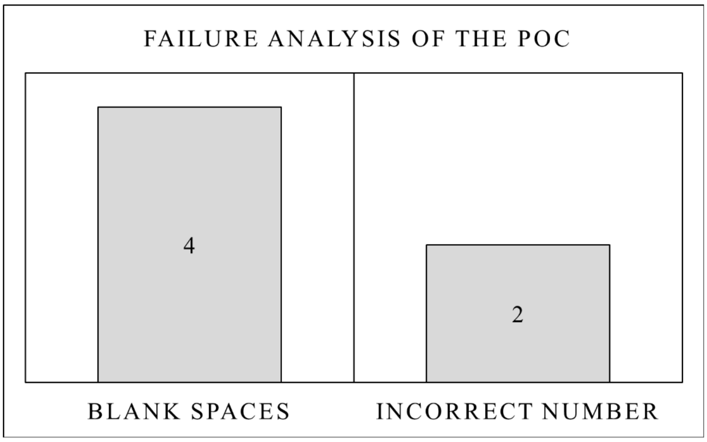


Figure 12: Identification deviation analysis over the value range of 500 to 750 lux (production conditions BMW Group).

The same categories of identification errors occurred as in the overall analysis (see Figures 7 and 8). The ICR technology misidentified numbers in two cases and misinterpreted spaces in four cases. Examples of the identification error categories were shown in Figure 9 ("wrong number") and Figure 10 ("space"). These 6 identification errors occurred within the illumination levels of 665 to 722 lux.

The next step was to analyze the potential causes of the identification discrepancies using ICR technology. Not only was the nature of the discrepancy investigated, but an attempt was made to identify patterns among the discrepancy cases. Particular attention was paid to the analysis of illumination levels to determine if specific lighting conditions affected the accuracy of the ICR technology. In conjunction with this, an analysis of the adjustment levels of the different lamp variants was also performed.

Figure 13 showed a piloting of the ICR technology's identification error in relation to the different illumination levels.

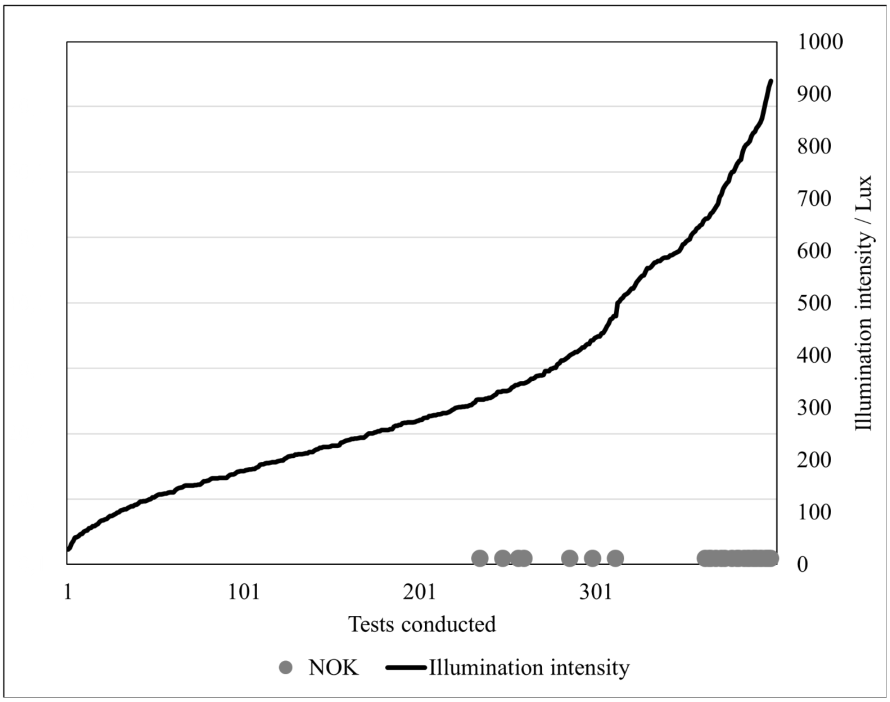


Figure 13: Statistical analysis of ICR technology identification errors related to illumination levels (lux).

The statistical results of the identification discrepancies with respect to the ICR technology showed that an increase was associated with a higher lux range. Up to 316 lux, there were no ICR discrepancies. More ICR discrepancies occurred in the 650 to 925 lux range.

Figure 14 showed a statistical piloting of the identification deviations in relation to the adjustment levels of the different lamp variants. The gray bar indicated the parts read as "OK" using ICR technology, while the red bar indicated the parts read as "NOK".

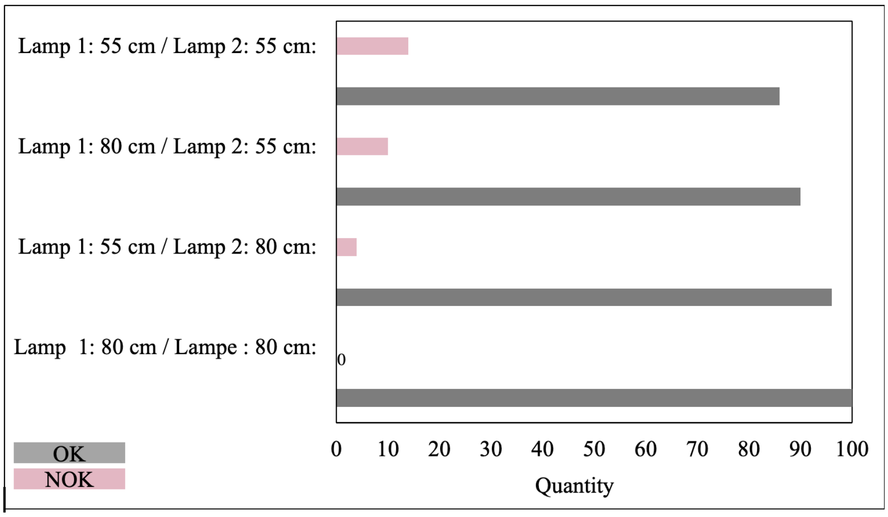


Figure 14: Statistical piloting of the ICR technology's identification deviations in relation to the lamp variations (Lamp 1 / Lamp 2 [cm]).

The piloting of the ICR identification deviations associated with the lamp variations was performed for the four different lamp settings as explained in Section 6.1, Table 11. The lamp settings 55/55, 80/55, and 55/80 showed ICR identification deviations. There were no identification biases at the 80/80 setting. It was noteworthy that most of the discrepancies occurred when the lamp setting was close to 55/55.

The following section discussed the results of the PoC.

6.3 Discussion of the PoC Results and Further Outlook

The results showed that the ICR technology worked, but not with the desired reliability. Since all parts were correctly marked during the PoC, these identification deviations resulted in a still needed manual step for the production workers, who had to perform additional visual checks to verify the marking.

During the PoC, there were two main identification deviations: first, the ICR technology incorrectly recognized the number, and second, it incorrectly interpreted voids as deviations. Blank spaces were not considered an official CoP discrepancy [2], [3], [4], so the ICR technology needed to be fine-tuned, especially when dealing with blank spaces. An example of such "blanks" was shown in Figure 10.

One focus was on the ICR identification variations as a function of illumination levels (lux). In particular, there were more ICR discrepancies in the 650 to 925 lux range (see the statistical analysis in Figure 13). This could be due to the increased occurrence of glare problems in images with higher lux values, leading to misinterpretation of certain numbers. This relationship was illustrated by the identification bias plots in Figures 9 and 10.

Another focus was on the ICR identification differences in relation to lamp variations (Lamp 1 / Lamp 2 [cm]). At the 80/80 setting, however, no identification deviations occurred. It was noticeable that at the close lamp setting of 55/55 the highest number of identification deviations occurred (see statistical piloting in Figure 14). Possible reasons for this could be the more intense light emission in this area, which could lead to over-illumination and reflections, thus affecting the recognition and interpretation by the ICR technology. Another possibility was that the specific light conditions of this setting might emphasize or diminish certain features of the parts, leading to misinterpretations.

It was necessary to perform a more in-depth analysis to understand the causes of the two types of identification errors (number error and void error) in ICR technology.

Since the ICR technology provided good results especially at low lux levels, possible solutions could include adjusting the lighting conditions, e.g., by targeted dimming. Further optimization could be achieved by fine-tuning the ICR technology, particularly in the handling of gaps, to improve the selection quality.

The PoC was conducted within the BMW Group under the given production conditions and processes. The aim of the PoC was to provide an initial assessment of the ICR technology. However, further investigations were necessary to evaluate the different CoP parts, optimize the technology, and assess other technologies identified in the utility analysis. Furthermore, ensuring a certain level of reproducibility was also crucial. These points constituted the objective of further scientific research.

7. Summary and Outlook

The increasing variety of vehicle variants and the more stringent regulatory requirements in the automotive industry pose a growing challenge for ensuring production conformity [1, 2]. Previous studies [5] have shown that part IDs or homologation-relevant markings do not always comply with legal standards, as manual spot checks cover only small quantities. Recall actions affect all automotive manufacturers who must ensure safety and quality according to legal requirements.

The aim of this contribution is to identify and evaluate an appropriate automation solution for the homologation process. The focus is initially on digitizing the reading process for part IDs and homologation-relevant markings. Sections 4 and 5 of the CoP technology analysis include an investigation of the CoP process. In section 4, a requirement profile is created, and the current state of the art is analyzed. The results are used to derive evaluation criteria, which are evaluated and prioritized using a pairwise comparison. In this pairwise comparison, the CoP experts had to assess the different criteria multiple times through a survey to determine their importance. The results of the criterion prioritization were presented in the pairwise comparison, which in turn influenced the benefit analysis.

Section 5 captures the advantages and disadvantages of technologies in the CoP process, followed by a benefit analysis to identify the optimal technology. The structure is based on the categories of optoelectronic and transmitter systems.

The results from the pairwise comparison, argument balance, and benefit analysis indicate that technologies such as ICR, OCR, and RFID have been identified as potential technologies for securing the CoP process. Therefore, further evaluations on practical application will exclusively focus on these technologies.

The initial practical evaluation of the ICR technology in Section 6 served as an initial assessment, but further analyses with appropriate statistical evaluations need to be conducted. Hence, the results provide an initial assessment but should not be generalized.

The practical evaluation of the different technologies in conjunction with the CoP parts, as well as the analysis of when the technology can be implemented in the BMW product development process, represent further research potential.

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List of Abbreviations:

AI:	Artificial Intelligence
AIQX:	Artificial Intelligence Quality Next
CoP:	Conformity of Production
DB:	Database
DF:	Degree of Fulfillment
DIN EN:	German Institute for Standardization European Norm
GDPR:	General Data Protection Regulation
GPS:	Global Positioning System
IATF:	International Automotive Task Force
ICR:	Intelligent Character Recognition
IEC:	International Electrotechnical Commission
OEMs:	Original Equipment Manufacturers
OCR:	Optical Character Recognition
OEE:	The Overall Equipment Efficiency
part ID:	Part Identification Number
PoC:	Proof of Concept
ppm:	Parts per Million
RFID:	Radio Frequency Identification
SDA:	Smart Data Analytics
WF:	Weighting Factor