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Capturing the system requirements for adopting Industry 5.0 in quality inspection: an evidence-based approach

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Abstract

Manufacturers face the challenge of adopting digital solutions to maintain competitiveness in the era of flexible manufacturing. The human remains a crucial asset in ensuring this flexibility. Industry 5.0 strongly emphasizes human-centric approaches to achieve sustainability and resilience in the industry. Notably, in-line quality inspection stands out among the assembly operations to minimize waste and ensure quality. With the increasing trend toward high-mix low-volume manufacturing, the reliance on operators' traditional tools and cognitive skills for quality inspections is no longer sufficient. Complexity escalates when manual assemblies involve components of varying sizes. Technologies such as augmented reality and computer vision can potentially support quality inspection in manual assembly. However, successful implementation depends on comprehending the specific requirements of the end users. We propose a qualitative approach to refining the requirements in applied research projects that aim to implement human-centered technologies. The approach was applied in a research project for in-line quality inspection with 18 professionals from two manufacturing companies. We instantiated the method using qualitative methods including questionnaires and focus groups with diverse stakeholders with demonstrations. We further investigated the verification and implementation of our method.

Keywords: Manual assembly; quality inspection; human-centered design; Industry 5.0

1. Introduction

Industry 4.0 has played a leading role in the transition of automated factories into smart ones. This has been made possible through the integration of cyber-physical systems (CPS), the Internet of Things (IoT), machine learning (ML) algorithms, Computer Vision (CV), and augmented reality (AR). Industry 4.0 places data and intelligent machines at its core, aiming to enhance the intelligence of manufacturing processes while reducing dependence on human labor. This evolution has led to the achievement of higher key performance indicators (KPIs) that were previously unattainable [1, 2]. However, Industry 4.0 has also brought a set of challenges, particularly in high-mix low-volume manufacturing. To remain competitive in this dynamic landscape, manufacturers must adapt to the demand for customized products. Developing intelligent systems for each product variant can be prohibitively expensive. Manufacturers should reassess the central role of their employees, leveraging their adaptability and problem-solving skills to swiftly and effectively address specific needs. This underscores the significance of Industry 5.0, which emphasizes human collaboration with smart machines rather than competition [3]. Both scholars and policymakers endorse Industry 5.0 as a means to foster sustainability, human-centricity, and resilience in industry. Transitioning from Industry 4.0 to Industry 5.0 requires manufacturers to embrace new technologies and sustainability while emphasizing circular economic principles and societal well-being [4].

Quality inspection emerges as one of the most challenging and crucial aspects of high-mix low-volume manufacturing. As

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products exhibit variations, quality procedures become diverse and necessitate variant-specific processes. The complexity intensifies when manual assemblies incorporate subassemblies and components of varying sizes. Consequently, traditional tools and the cognitive skills of operators alone are no longer sufficient for quality inspections. In this context, employees at the heart of high-mix low-volume manufacturing must be accompanied by advanced technologies such as AR, CV and IoT to effectively perform quality inspections. Although these argumentations can build up a conceptually well-defined use case to work on, the question of "*What is truly required on the shop floor?*" often remains ambiguous unless project executors are directly involving employees and relevant stakeholders from use case companies to identify and rectify critical requirements throughout the execution of the project implementation of those technologies [5].

This paper introduces an evidence-based methodology within the framework of Industry 5.0 to identify pertinent requirements for an industrial research endeavor involving universities, industrial research organizations, technology providers, and use case companies. We evaluate the effectiveness of this approach in accurately identifying requirements that offer value to stakeholders in leveraging new technologies for quality inspection of large-scale products.

2. Background

Quality inspection remains one of the most labor-intensive tasks in manufacturing. In the 1980s, total quality management (TQM) emerged as a comprehensive approach integrating various tools to aid employees in this process, leading to significantly enhanced product quality and widespread adoption worldwide [6]. Fast forward almost four decades, mass customization and high-mix low-volume manufacturing have become integral to the industry. However, adapting work instructions and quality procedures to each variant is time-consuming and labor-intensive. Hence, there is a growing necessity for intelligent technologies to support shop floor employees, particularly in complex assembly operations involving large components. Despite this need, current practices and literature are limited. A recent review found only four research papers exploring digital industrial solutions, such as AR, IoT, and CV, for quality improvement in manufacturing [7]. As of 2022, there has been no systematic review of these technologies' efficacy in enhancing quality inspection in manufacturing [8]. Addressing contextual and technological challenges is crucial for validating these technologies before their implementation on the shop floor.

One of the main reasons behind this lack of maturity is the formulation of misleading requirements and priorities driven by developer interests rather than the genuine needs of the industry. A recent study, investigating the applicability of spatial AR for operator guidance and training, indicated that two out of five use case companies did not proceed with the technology uptake after the project, despite convincing results and user acceptance. High system cost, technical development time and required expertise were mentioned as the main hurdles to discouraging the use case companies [9]. Product-centered design frameworks were heavily practiced in manufacturing proposing innovative and hybrid technologies from tracking systems to digital twins while aiming to overcome technical challenges on the shop floor [8, 10].

A shift from product-centered to human-centered methodologies is crucial to deliver successful projects [11]. To determine real-world case studies that evolve toward industrial needs – especially the needs of employees, developers should first extract requirements through human-centered research methodologies using qualitative and quantitative tools [5]. From the very beginning, it is essential to engage end-users, such as operators, and all other relevant industrial stakeholders from various levels to properly identify and address their specific needs [7, 12, 13, 14]. Besides, iterative prototyping methodologies are highly recommended throughout the execution of the project, from conceptualization to requirements to validation of the end product [8, 14, 15]. Linear and waterfall-like research methodologies often result in incomplete requirements, subsequently resulting in low technology adoption at the end of the projects [12].

3. Research method

The overall method applied in this research is structured toward a design thinking approach as illustrated in Fig. 1. By crafting empirical data and best practices available in the literature having a similar context to our research, we developed an evidence-based approach to practice the design thinking in human-centered industrial projects, as can be seen in Fig.2. Following part of this section presents details on each component applied in this research.

3.1. Theoretical framework

Design thinking, depicted in Fig. 1, is widely embraced as an agile framework for human-centered design projects in product development. Its recent integration into manufacturing helps identify crucial requirements and foster technological adoption, prioritizing human-centered solutions tailored to users' needs [16]. Holistic methodologies like design thinking are known to foster innovation more effectively than product-centered approaches. Specifically, the double diamond method is popular for its structured approach, emphasizing divergent and convergent thinking stages to promote creativity and idea refinement [17]. However, its direct application in human-centered projects within Industry 5.0 is limited. Hence, in alignment with Industry 5.0 objectives, we adopt the doable diamond design thinking model for our methodology, featuring two diamonds, each with two steps.

The first diamond focuses on *"designing the right thing"*, comprising two key steps: discovery and definition. Discovery involves activities to thoroughly understand the problem and explore potential solutions, crucial for stakeholders to grasp their role. Divergent thinking is central, encompassing market research, proof-of-concept demonstrations, interviews, and partner observations. Definition, following a convergent approach, delineates the challenge and requirements, refining the use case with measurable indicators. The processing of discovery data and ongoing discussions with end-users and stakeholders are essential to converge on a specific problem.

Unlike the first one, in **the second diamond,** a specific solution should materialize to "*design things right*". Develop and deliver are two steps to produce tangible components that pave the way through design-driven solutions. The former adopts divergent thinking to ideate, develop, and primarily test possible opportunities that may turn into specific solutions. It is crucial to directly involve end-users to confirm the directions. The latter is about testing a variety of solutions to determine what will work and how to enhance it with iterative test and validation procedures.

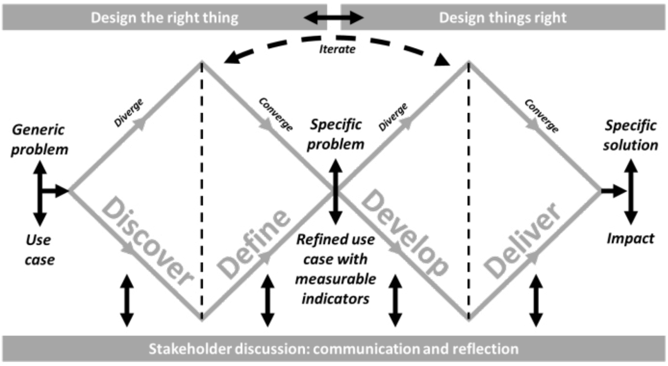

Fig. 1. Overall method to develop an evidence-based approach using the double diamond design thinking. Grey arrows and components represent the fundamental components, while black components are the processes and states applied in this research.

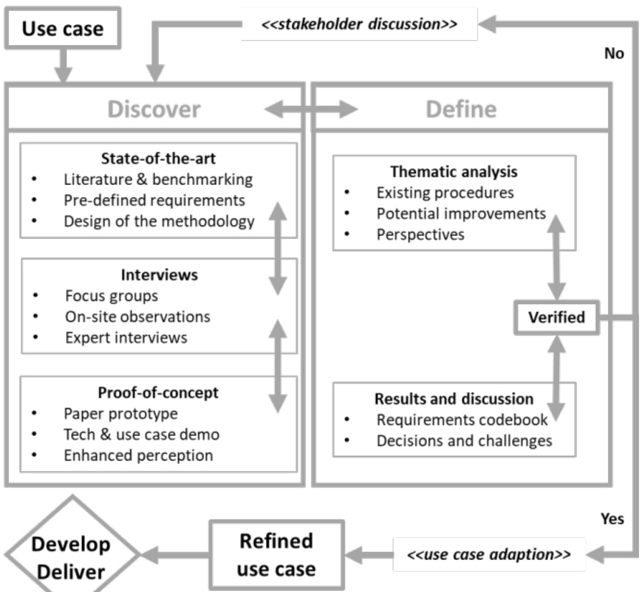

Fig. 2. Details of the applied components in the double diamond design thinking that are practiced in this research.

3.2. Conceptual framework

We developed a method building upon the double diamond design thinking approach, integrating empirical data and literature best practices, as shown in Fig. 2. Our research aims to identify specific problems and refine use cases with critical requirements, formulating measurable indicators in human-centered projects, concerning both quantitative and qualitative methods such as optimizing latency in real-time vision based quality inspection to assessing the task load with NASA Task Load Index, respectively. Therefore, in this phase, we only detailed tools used to practice the first diamond, as requirements are the very first task in industrial research projects to determine "*the right thing to design*" as a part of design thinking. Nevertheless, a thorough perspective is presented to usher the future work.

In **the discover** step, we opted for the three components to exercise divergent thinking to discover the main aspects of the use case:

- *State-of-the-art:* We did a literature survey to comprehend the current state of practices to utilize new technologies in quality inspection in Industry 5.0. It guided us to find best practices and challenges to adopt such technologies.
- *Proof-of-concept:* Offering industrial stakeholders hands-on technology experiences is crucial. Utilizing relevant demos from existing solutions or similar alternatives helps inexperienced end-users grasp potential solutions effectively. Introducing proof-of-concepts early in stages is vital for extracting industry-relevant requirements [8]. Thus, we utilized paper prototypes and interactive AR demonstrations to enhance stakeholder perception.
- *Interviews:* Essential for understanding technology users, interviews aim to grasp stakeholders' needs, strengths, and aspirations, fostering a shared problem understanding. Focus group interviews yield rich, interactive requirements, with 80% of themes identified in two to three sessions [5, 15]. Each session typically involves 10 to 12 questions. On-site observations further validate requirements [14]. Danielsson et al. [15] suggest starting with operators, then involving stakeholders, and finally engaging experts to refine use case requirements.

The components in **the define** step were purposefully formed to converge to a specific problem:

- *Thematic analysis:* The use case is in the project proposal, which most likely involves developing a novel quality inspection technique by incorporating new technologies in manual assembly with large products. In terms of feedback about quality, we aim to determine the types of information operators need to better understand the issue, how they can rectify them, and how they can prevent them. This encompasses existing procedures, potential improvements, and various perspectives.
- *Results and discussions:* This section includes the requirements codebook, decisions, challenges, and the verification conducted through stakeholder discussions.

3.3. Instruments, data collection and data processing

After reviewing requirements and instruments in existing literature, we crafted 56 semi-structured questions categorized into 10 sections, including topics like the Current Quality Inspection Process in Assembly and Quality Inspection with CV. Stakeholders filtered and prioritized questions in alignment with project objectives, categorizing them by importance (high, mid, low, and out-of-scope) and target group (operators, method engineers, IT staff, etc.). The selected questions were divided into three groups, with approximately 10 to 15 questions each, focusing on critical requirements and technology adoption stages. These questions were provided in both English and Dutch languages. Additionally, we included a set of five questions using a five-point Likert scale to gauge operators' technology acceptance.

We asked the use case companies to recruit participants with experience and knowledge of assembly and quality processes. Participant recruitment was conducted internally by employers with explicit consent, without soliciting personal data for tracing or individual identification purposes. Thorough anonymization procedures were applied to the gathered data, potentially eliminating the need for ethical approval. Flanders Make initiated the ethical process for user interviews, informing participants about the procedures and their rights, including the option to discontinue participation at any point. However, in cases where personal data was collected during experimental procedures, adherence to ethical guidelines required approval from relevant research institutions.

It is important to recruit a diverse range of interviewees, including both experienced operators and those with limited experience, to capture a range of perspectives. In total, 18 employees from two use case companies participated in the experiments. First and foremost, we collected feedback using an online survey from all 18 participants to identify critical points during the focus group interviews. Then, we arranged on-site visits to perform focus group interviews.

Separate on-site visits showcased each company's manufacturing facilities, including assembly lines and quality processes. Proof-of-concepts, like augmented reality demos with HoloLens 2, were presented for employee testing in a meeting room. Subsequently, two focus group sessions, each with three participants ranging from operators to method engineers, were conducted. Notes and interviews were recorded and data was pseudonymized. Additionally, individual expert discussions were held with managers, IT experts, method engineers, quality engineers, and tech providers to complement focus group insights.

Responses from the online survey, interview transcripts, and participant notes were analyzed using thematic analysis to extract requirements. Qualitative data underwent thematic analysis, supported by a developed codebook for structuring interview responses. Themes and sub-themes were identified to capture requirements, with stakeholders refining the processed data. This process, similar to Ferrati et al [14], involved organizing themes based on work packages and project tasks due to multiple stakeholders. Work package members subsequently reviewed requirements related to expertise.

4. Results and discussion

Before diving into the thematic analysis, we provided an overview of the participants who partook in the qualitative research in Table 1. The participants hold different roles and have varying levels of experience in quality inspection, which assisted us in gathering diverse information on their needs.

To understand technology acceptance, operators completed a questionnaire featuring 5-point Likert questions, as can be seen in Fig. 3. They were comfortable using tablets for shop floor operations, likely due to familiarity with existing instruction and inspection systems. Mobile technologies, ubiquitous in daily life, were positively received. However, preferences for head-mounted displays (HMD) in quality inspection varied among operators, with concerns including ergonomics, integration into the shop floor environment, and individual-level technology acceptance.

Table 1. The participant profile based on role and experience in manual assembly and quality inspection; * indicating the ones responsible for the assembly line and quality procedures, such as quality engineer.

Role	Experience in manual assembly by years	Experience in quality inspection by years
Operator (n=6)	Below 1 year (n=2)	Below 1 year (n=1)
	1 to 5 years (n=1)	1 to 5 years (n=1)
	5 to 10 years (n=2)	5 to 10 years (n=2)
	Above 10 years (n=1)	Above 10 years (n=2)
Responsible (n=12)*	Below 1 year (n=0)	Below 1 year (n=2)
	1 to 5 years (n=2)	1 to 5 years (n=3)
	5 to 10 years (n=1)	5 to 10 years (n=1)
	Above 10 years (n=9)	Above 10 years (n=6)

All interview data and notes from stakeholder meetings during on-site visits were incorporated into the thematic analysis. One researcher created the first version, compiling all data into a codebook. Then, involved stakeholders reviewed and iteratively recategorized themes and sub-themes extracted from the coded data, which included quotes and phrases from interviews, as well as related tasks and work packages from the project proposal. We additionally identified common and distinctive requirements for the use case companies.

Codebook is made of a total of six themes with around 30 subthemes across as follows:

- *Current quality inspection processes:* actions, analog and digital tools, periodic procedures, registry, operator, Loctite application, training & follow-ups, processes and dataflow, and large assembly applications.
- *Documenting and reporting quality issues:* communication with stakeholders, procedures, and digital logging systems.
- *Typical problems and challenges in quality inspection:* human error, human violations, external factors, Loctite application, O-ring application, lack of knowledge, traceability, operator's behavior, and tools & operations.
- *Information helpful for quality inspection:* context-aware feedback, operator-centric, quality data from suppliers, lots of lessons learned, Loctite application, increased traceability, O-ring application, tools, and real-time data.
- *Operator inclusion:* usability, integration, training, work instructions, user interaction, and language.
- *Manufacturing systems to adopt:* quality tools, manufacturing systems, and user applications.

The themes and subthemes extracted from the interviews revealed the critical aspects of the current quality inspection processes, while highlighting the typical problems and challenges in existing practices. This helped us further specify the problem that can be addressed in our research. Likewise, the results showed that the effective communication of quality issues through digital tools and their seamless integration with existing manufacturing systems is of utmost importance for the adoption of such technologies on the shop floor. Besides, the human-centered aspects of the implementation were focal points, focusing on enabling an inclusive system that provides information helpful for quality inspection.

To translate thematic analysis results into system requirements, stakeholders discussed and verified a compiled list. These discussions revealed that themes and subthemes lacked specificity for outlining project tasks across work packages. Thus, we collaboratively structured a categorized requirements file based on themes and subthemes, each tagged with unique identifiers for clarity. For instance, UR_state_1: "The system shall handle multiple operators and determine ongoing operations in the work cell."

Our method aims to define a specific question and formulate measurable indicators by categorizing requirements into types and priorities. Functional requirements define validation criteria and tests, while non-functional requirements indicate qualitative system characteristics, which may be translated into functional requirements if necessary. Priorities, ranked from one to five, determine relevance and research effort: (1) urgent action requiring new research, (2) incremental steps building on existing research, (3) limited implementation effort, (4) minimal research or extensive implementation needed, and (5) extensive research outside the project scope. High priorities are subjectively rated by the project lead based on milestones, time, and effort, while low priorities are considered out of scope.

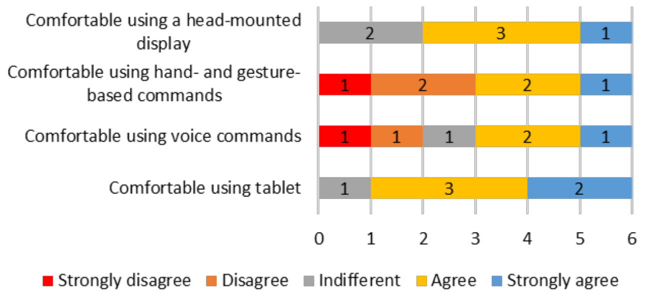

Fig. 3. Results from the technology acceptance questionnaire illustrate the preferences of operators (n = 6).

The interviews were also conducted to comprehend operators' perspectives and enhance the current practices on the shop floor. Operators came up with an interesting combination of technologies to improve the overall efficiency of the quality inspection procedure, summarized as follows:

- “Put sensors for part detection on Poka-yoke plate to register which parts are taken and to ensure that this is in line with assembly steps given in the digital instructions.”
- “Apply computer vision to verify Poka-yoke practices.”
- “Utilize a 3D scanner to detect sizes and missing or incorrectly mounted parts and give a message or alarm.”
- “Use an instruction card showing that if you do this wrong, that is what will happen.”
- “Integrate QR codes for traceability of non-conforming assembly parts.”
- “Integrate with a data lake platform is necessary to visualize the data afterward.”
- “Use a head-mounted flashlight to increase sight.”

Operators indicated the need for an in-line quality inspection procedure integrated into the current practices such as Poka-yoke. They mentioned sensors, computer vision, and 3D scanners to facilitate such assistance on the shop floor. Results showed that operators prefer non-invasive technologies that can assist them in verifying steps taken during manual assembly to reduce cognitive load. Besides, the implementation of quality instructions structured toward “what-if” scenarios was found intriguing by operators. This approach can be a convincing way to encourage operators to pay more attention to work instructions, as they can anticipate the potential consequence of a wrong action. Operators also mentioned the need for a transparent and traceable process, such as visualizing quality-related data in existing manufacturing systems and using QR codes for non-conforming assembly parts as examples. This can assist operators and their stakeholders in identifying the main source of quality-related issues promptly without examining the entire operation.

Table 2. An overview of condensed requirements to refine use cases in human-centered manual assembly operations involving big components and high-mix low-volume productions.

Themes used to refine use cases	Sub-themes as requirements
In-situ quality inspection with vision systems	Real-time, components with varying sizes, taking images of completed steps, and components with different colours.
Quality instructions	Visual and audible error prompts, seamless integration with the available system for digital work instructions, navigation through quality steps, and personalization based on the context and experience level
Human factors and ergonomics	Not interfering with the operators’ manipulations, and not taking pictures of operators
Static hardware	Preferably using static cameras to perform a robust and reliable in-line quality inspection
Mobile hardware	Supporting long periods of operating times (e.g., eight hours) for mobile systems, preferably not head-mounted displays due to the concerns over ergonomics, operability, and maintainability, using body cam for continuous monitoring and quality inspections, and tablets for discrete quality inspection
Data storage and network	Using already available databases and network instances in line with the existing data logging system.

We compiled requirements, along with supplementary information, into a file for clarity on project targets. These were then disseminated among research partners, technology providers, and industrial use case companies for further validation and incorporation into refined use cases. Initial verification involved active participation from research partners and technology providers, with meetings held to gather additional input. This cycle helped us navigate complex tasks involving stakeholders from different organizations and align common goals with requirements. The second verification cycle engaged industry use case companies, whose experts and managers reviewed and refined the requirements, pinpointing preferred system requirements for enhanced use cases. Upon request, each company submitted a list of refined requirements. Bilateral discussions with technology providers and research partners facilitated the translation of user requirements into system requirements.

We found that use case companies are likely to address common requirements, as the problems on the shop floor share similar attributes, such as high-mix low-volume productions, human-centered manual assembly operations, and a strong emphasis on the improvement of the quality inspection process. Both companies already made proven progress in digitalization and Industry 4.0. In Table 2, we derived the following themes to refine use cases and align system requirements to deliver related solutions from the user requirements.

Through expert reviews of user requirements, we refined system requirements, pinpointing specific issues. The iterative verification process proved beneficial for stakeholders, aligning project objectives with industrial infrastructures, preferred user technologies, and human-centered solutions. Once refined use cases were defined, we began developing validation cases, representing the second diamond in our evidence-based approach. Often, industrial research projects overlook requirements, risking misdirection due to poorly defined or integrated requirements. Projects involving stakeholders from different sectors exacerbate this challenge, necessitating significant effort to bridge needs, roles, and responsibilities while formulating effective design strategies.

5. Outlook

The evidence-based approach received positive stakeholder feedback, improving requirement understanding. Employing a clear framework within an agile workflow boosted stakeholder engagement and emphasized requirement importance. However, refinements are needed in certain methodological aspects, such as qualitative methods. Stakeholders may prefer alternative technologies to refine design strategies. Proactively addressing new technology value through internal best practices could stimulate critical stakeholder thinking.

In projects integrating new technologies into human-centered manufacturing, identifying adoption challenges is vital. AR is seen as immature for quality inspection; however, industrial partners express skepticism due to non-robust solutions [5, 8]. Performance metrics are essential for objectively assessing effectiveness. Likewise, usability and usefulness are crucial metrics for supporting employees.

An unexplored aspect of the double diamond design thinking is the assumption that each step should take an equal amount of time [11]. Imposing time limits may hinder stakeholders from embracing an agile approach. Instead, stakeholders can invest time in learning how to implement agile methodologies while aligning the temporal dimension with the actual time needed.

6. Conclusion

In this study, we developed an evidence-based approach to extract requirements at the beginning of an industrial research project comprising stakeholders from academia, research organizations, and industry. The approach was explicitly practiced extracting system and user requirements on the implementation of new technologies to assist employees during the quality inspection process in manual assembly operations. We extracted and verified the requirements with an agile method to refine use cases to formulate measurable indicators. Our explicitly communicated approach convinced stakeholders to actively partake in the definition of specific problems to refine the use cases, as well as to think and propose solutions to solve these problems from the beginning of the project.

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