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SUPPORTING CONSTRUCTION SITE H&S INSPECTIONS WITH COMPUTER VISION: A BPMN PROCESS FORMALISATION

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Abstract

Routine construction site Health and Safety (H&S) inspections remain manual, experience-driven, and weakly digitised. While Computer Vision (CV) has advanced construction safety, particularly for real-time monitoring, it has rarely been investigated to support everyday inspection practices. This paper addresses this gap by analysing a routine inspection process and formalising current practice using Business Process Model and Notation (BPMN) 2.0 to make roles, decisions, and information exchanges explicit and expose key limitations. The study then proposes a CV-enabled inspection process that structures the collection and interpretation of visual evidence and suggests compliance-related observations to the H&S Manager, while preserving their assessment responsibility.

Introduction

In recent years, rapid advances in Artificial Intelligence (AI) have accelerated its adoption in the Architecture, Engineering, Construction, and Operations (AECO) sector, with applications demonstrating practical benefits across a wide range of use cases. However, despite the growing availability of mature technologies, their implementation in everyday workflows often remains limited (Abioye et al., 2021; Khan et al., 2024). This is partly due to the construction industry's fragmented nature, which hinders the acquisition and retention of the data required for AI solutions, thereby constraining effective deployment. Furthermore, evidence indicates that adoption among Small and Medium-sized Enterprises (SMEs) remains comparatively limited and slower than in other sectors (Khan et al., 2024; Regona et al., 2022).

This implementation gap is particularly evident during the construction phase in site Health and Safety (H&S) management, where most applications currently focus on hazard detection and real-time monitoring (Pandithawatta et al., 2024), leaving AI's potential to support other routine activities of H&S managers unexploited. In this regard, construction site H&S inspections remain largely manual and weakly digitised, despite their central role in monitoring on-site conditions (Lin et al., 2025; Natasha Mohamad Shubqizam et al., 2025). In practice, effective AI support is constrained by the limited structure and poor quality of available data and the costs of integrating AI tools into established procedures. Among these, Computer Vision (CV) stands out as one of the most mature, accessible, and readily applicable options (Liu et al., 2021). Nonetheless, its adoption in H&S inspection is still hindered by the absence of shared, clearly defined, and actionable processes that translate CV outputs into operational decision support for H&S managers (Daniel et al., 2025), as well as by socio-legal constraints related to liability and on-site data collection and use (Agapiou, 2024). H&S inspections rely on the professional's experience of the individual manager or organisation, with compliance assessment and information management heavily dependent on unintegrated textual documentation (Forteza et al., 2023; Hussamadin et al., 2023). Without a structured understanding of inspection practices, efforts to develop and integrate AI tools into these workflows risk producing solutions that do not address real operational needs. To this end, this study aims to explore and provide a structured basis for the use of innovative CV-based approaches in construction site H&S inspections. Specifically, current inspection processes are analysed and modelled using the Business Process Model and Notation 2.0 (BPMN) to formally represent activities, decisions, and interactions among the involved actors (OMG, 2013). By clarifying how information is currently generated and shared, and by identifying bottlenecks and repetitive manual tasks, the paper discusses where and how CV can be integrated to systematise the collection, interpretation, and management of visual evidence. The proposed perspective is intended to support compliance assessment and reporting activities while accounting for the H&S manager's responsibility. On this basis, the study provides a process-oriented and structured interpretation of H&S inspections to guide the development and adoption of CV-based tools that support H&S managers' everyday operational practice on construction sites.

Background

This study bridges current manual H&S inspection practices and CV-enabled decision support by synthesising inspection limitations, BPMN workflow modelling, and AI/CV applications, moving beyond hazard detection toward process-driven support.

Site H&S inspection: current practice and limitations

Internationally, Health and Safety (H&S) management is increasingly recognised as a cornerstone of sustainable work, with Occupational Health and Safety Management

System (OHSMS) standards such as OHSAS 18001 and ISO 45001:2018 promoting structured cycles of planning, implementation, monitoring, and review to ensure compliance and continuous improvement, particularly in high-risk sectors such as construction (Arévalo Sarrate et al., 2024; Marhavilas et al., 2022). In the European Union, this systemic approach is embedded in a comprehensive regulatory framework centred on the Framework Directive 89/391/EEC and the construction-specific Directive 92/57/EEC for temporary or mobile construction sites, which establish core obligations for risk assessment, prevention, coordination, and the allocation of responsibilities among project actors.

Comparative studies consistently characterise construction as a high-risk industry that requires robust preventive measures, formal H&S planning, and continuous supervision to ensure that dynamic site conditions remain aligned with regulatory requirements (González García et al., 2021). Within this context, the H&S manager assumes a central coordinating role, bearing significant responsibility for organising prevention activities, assessing compliance, and monitoring site conditions through routine inspections. However, these inspections largely rely on manual, experience-based practices: checks are predominantly visual and non-standardised, and observations are often recorded inconsistently across individuals and organisations, reflecting tacit knowledge rather than a structured process logic (Ramos-Hurtado et al., 2022; Saurin, 2016). Fragmented or paper-based data collection further weakens reporting, traceability, and follow-up. At the same time, inspection programmes are frequently irregular and insufficiently risk-based, leading to under-coverage of recurrent high-severity hazards and delayed corrective actions (Rey et al., 2021). Moreover, inspection outputs are rarely leveraged as leading-indicator datasets; reports are commonly archived rather than analysed to identify patterns, systemic weaknesses, or recurring causal mechanisms, limiting their contribution to prevention and continuous improvement (Saurin, 2016).

BPMN for process analysis and improvement

Despite their central role, H&S inspections have so far benefited only marginally from the broader digitalisation efforts underway in the AECO sector, where BIM, digital twins, and AI-based solutions are increasingly adopted to support design coordination, information management, and operational decision-making. Adequate digital support for routine practices, however, requires explicit formalisation of the underlying processes, so that activities, responsibilities, information flows, and decision points are transparent, comparable, and amenable to systematic assessment and continuous improvement (Häußler et al., 2021). This need is particularly acute for H&S inspection workflows, where inconsistent practices and fragmented documentation hinder accountability and limit learning across projects.

Process modelling approaches offer a structured means to capture such workflows and identify opportunities for standardisation and automation. Among these, BPMN provides a widely adopted, domain-agnostic standard for representing processes in a shared and interpretable form (OMG, 2013) and is increasingly supported by executable workflow engines that enable process enactment and monitoring (Geiger et al., 2018). In this sense, BPMN can act as a bridge between manual inspection practices and future digital solutions by supporting both the analysis of current workflows and the design of improved scenarios.

Several studies have applied BPMN to formalise construction inspection workflows, primarily for quality control and information exchange. Tsai and Hsieh (2016) use BPMN in combination with BIM to plan and rehearse inspection tasks in advance, structuring on-site activities and data capture. Similarly, Comai et al. (2022) adopt BPMN to model document- and data-intensive inspection and quality assessment processes, positioning process formalisation as a prerequisite for coherent digital information exchange and workflow execution. Complementarily, Shin and Cha (2023) highlight the lack of actionable process models as a barrier to the adoption of smart inspection technologies and propose a BIM-based quality inspection workflow supported by smart devices. However, these approaches largely focus on quality inspections and do not address routine H&S inspections in a way that clarifies how AI-based solutions can be integrated or how their outputs support H&S managers' decision-making.

AI/CV-based approaches in construction site H&S

In dynamic, visually complex construction site environments, images and videos provide a rich source of safety-relevant evidence that can be automatically analysed, making CV one of the most mature and widely investigated AI-based approaches in this domain (Fang et al., 2020; Guo et al., 2021). As a result, extensive research has focused on the use of CV to enhance situational awareness and automate parts of safety monitoring that are traditionally performed through first-hand visual assessment. Most CV applications address routine tasks such as worker and equipment detection, personal protective equipment (PPE) compliance checking, and recognising unsafe behaviours or hazardous interactions on site (Paneru and Jeelani, 2021; Seo et al., 2015). Recent advances in deep learning have significantly improved detection accuracy, enabling near real-time identification of safety-related conditions even in unstructured construction environments. Accordingly, CV is mainly applied for continuous or real-time safety monitoring via fixed cameras, mobile devices, or surveillance systems, focusing on detecting safety-relevant objects, conditions, and behaviours to improve awareness of on-site risks (Zhang et al., 2020). Although these approaches demonstrate the technical feasibility of CV for construction safety, they largely remain monitoring- and detection-centric, with limited use of CV outputs to support routine inspection workflows. As a result, CV is often deployed as an isolated solution rather than embedded in coherent, process-driven H&S practices, reinforcing the gap between advanced monitoring systems and established inspection routines. In response,

recent research has combined CV with Large Language Models (LLMs) to translate visual evidence more effectively into inspection-ready narratives and decision support. In this regard, Hussain et al. have reported promising results, combining image-based object detection with regulatory rule checking and then feeding the resulting classification and rationale to an LLM for narrative generation and dialogue (Hussain et al., 2026). However, in their approach, safety knowledge is hard-coded as general regulatory rules rather than retrieved from project-specific safety documentation, so inspection outputs are not grounded in the safety requirements defined during project design and planning.

Research Objective & Methodology

Building on the gap identified in the previous section, this study focuses on defining a structured and generalizable representation of routine H&S inspections. Rather than introducing new technologies, the paper aims to organise inspection activities, information flows, and decision logic into a coherent process that makes implicit practices explicit and operationally interpretable. This structured representation is intended to enable a systematic linkage between on-site observations, relevant safety requirements, and subsequent actions, thereby supporting more consistent inspection outcomes and facilitating the integration of digital support mechanisms. Importantly, the proposed approach is conceived as a foundation for the future development of CV-based inspection-support systems, providing a structured reference framework that can be operationalised through different technological implementations.

To achieve this goal, this study adopts a process-modelling methodology grounded in the BPMN standard (OMG, 2013) to make routine H&S inspection work explicit, comparable, and ready for digital support. The modelling effort is informed by a focused review of regulatory requirements, established best practices, and typical inspection deliverables (e.g., reports, issues, and corrective-action records), with primary reference to the Italian construction context while maintaining alignment with internationally recognised H&S management system principles and regulatory frameworks. The resulting workflow is further informed by direct observations conducted at residential and infrastructural construction sites within the broader research framework underpinning this study, providing empirical grounding for the proposed process structure. BPMN is selected not only for its ability to communicate roles, tasks, information exchanges, and decision points in a shared and interpretable form, but also for its suitability as a foundation for implementation. In particular, BPMN models can be operationalised through workflow engines (i.e., process orchestrators) to coordinate activities across heterogeneous tools and information repositories, supporting traceable and consistent execution in fragmented settings such as construction sites (Dumas et al., 2018; van der Aalst, 2013).

The paper proceeds in three steps, following the methodology adopted in the study. First, it models the end-to-end current construction site H&S inspection process, explicitly capturing the involved actors, core activities, exchanged information, and key decision points. Second, it zooms into a recurring inspection task—i.e., the systematic checking of site features of interest such as ongoing activities, workers and equipment, and layout elements—analysing it at a finer level of detail to highlight friction points, bottlenecks, and repetitive manual operations. Third, building on these insights, it proposes an enhanced process model in which CV-enabled capabilities are integrated at well-defined points to support the structured collection and interpretation of visual evidence alongside other H&S information, and to streamline reporting while preserving the H&S manager's central role and responsibility. Together, these three steps provide a process-oriented basis to guide the informed development and adoption of CV-enabled decision support for routine construction site H&S inspections.

Construction site H&S inspection process

This section presents the analysis and BPMN formalisation of a routine construction site H&S inspection process (Figure 1), modelled from the perspective of the H&S manager. The model focuses on the on-site phase of the inspection and considers the two main participants: the H&S manager, acting as the inspector and responsible for safety coordination, verification, and control during the construction phase, and the contractor, representing one or more contracting organisations operating on site. While the model covers only on-site inspection activities, these are situated within the broader construction site H&S management process, which, prior to the start of site operations, includes planning and verification steps involving both participants and the H&S manager's review of the contractor's documentation. To this end, the contractor is required to submit detailed, site-specific documentation, including Safety Operating Procedures (SOPs) for the activities to be performed, records of workers' general and task-specific training, and technical and administrative specifications for equipment and other planned resources. The construction site safety plan, developed by the H&S manager, defines the overarching site organisation and preventive measures. The contractor's documentation is assessed against this plan for compliance, complementarity, and formal validity—particularly with respect to regulatory requirements, safety procedures, and the validity of training and authorisations. Where gaps or inconsistencies are identified, revisions are requested from the contractor; otherwise authorisation to commence works is issued, concluding this preliminary phase.

Although heterogeneous and largely unstructured, the safety plan, together with the contractor's submission, is archived in a local or shared repository and provides the

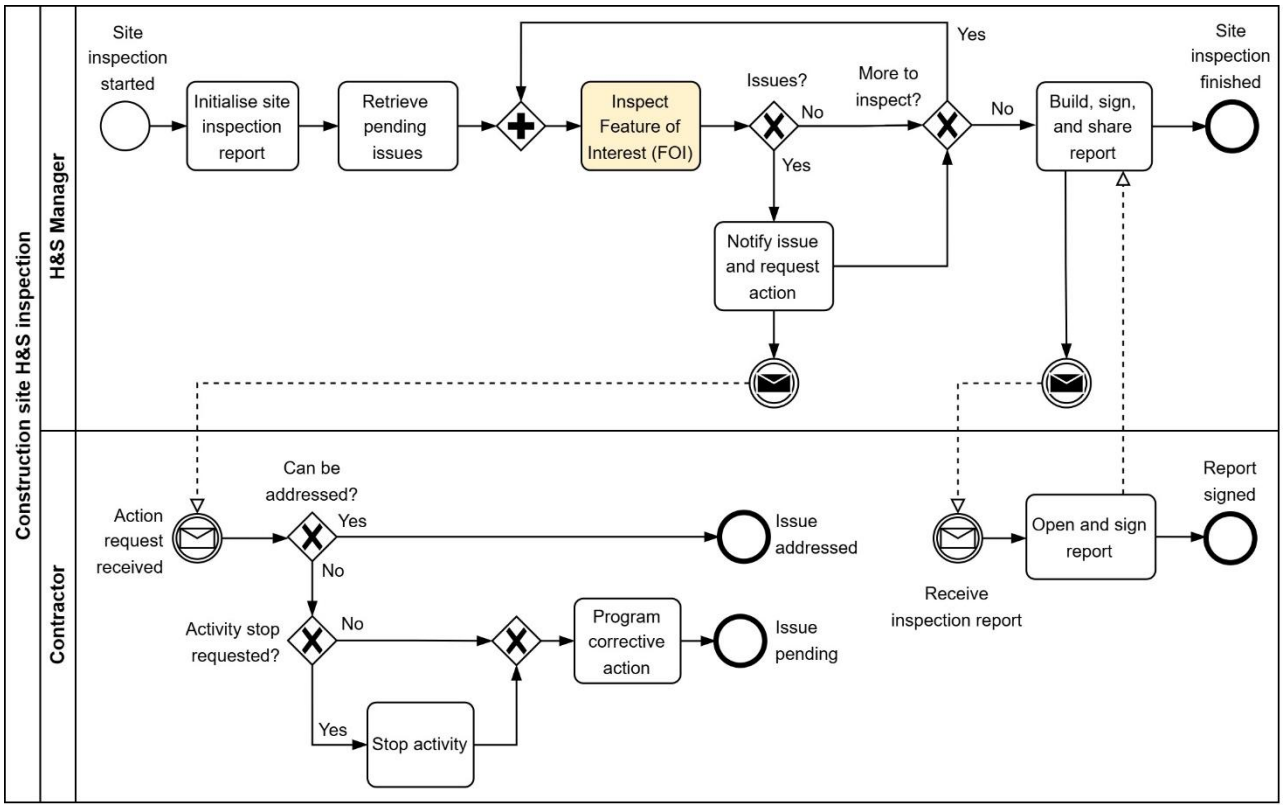

Figure 1: Routine construction site H&S inspection process model (BPMN).

basis for understanding site organisation and involved resources, and for defining the scope of safety inspection activities.

As shown in Figure 1, these are conducted by the H&S Manager as site walkthroughs and begin with creating a new inspection record, including entering site identification information and listing workers and resources (e.g., machinery) present on site. During this formal initialisation, the H&S manager also reviews previously recorded pending issues—especially missing or non-compliant documentation from earlier inspections—to assess corrective actions and identify items that require follow-up during the walkthrough.

Following these preliminary steps, the inspection proceeds to the practical on-site walkthrough, carried out zone by zone across the construction site in accordance with the zonal organisation specified in the construction site safety plan. For each zone, the H&S manager evaluates the compliance of the ongoing activities, relevant site layout elements (e.g., temporary works, access routes, protections, signage), and the workers and equipment present (see Figures 2–3).

These three categories constitute the H&S Features of Interest (FOIs) considered in the process model. For each encountered FOI, the H&S manager directly assesses the observed conditions against the prescribed safety requirements and documents the outcome as a recorded observation, indicating whether they are compliant (e.g., prescribed protections and signage in place), partially non-compliant (e.g., minor deviations from requirements), or critically non-compliant (e.g., severe violations requiring immediate attention). This evaluation and recording represent a core, non-delegable responsibility of the H&S manager, who subsequently manages identified issues by requesting corrective actions from the contractor. Where an observation indicates non-compliance, the process branches to involve the contractor. The contractor is notified of the identified issue and is requested by the H&S manager to implement a corrective action. If the correction is feasible and carried out immediately, the resolution is recorded in the inspection report; otherwise, the contractor programs its implementation, and the issue is registered as a pending item to be verified during subsequent inspections. In cases where the non-compliance is critical—i.e., it constitutes a serious breach of the prescribed safety requirements or poses an immediate risk to workers—the H&S Manager may issue a stop-work order for the affected activity or restrict access to the relevant area until the condition is resolved (e.g., missing mandatory training or authorisation, non-compliant equipment, absence of required permits/ documentation). Once all FOIs within a given area have been assessed, the process iterates to the next zone until the entire construction site has been inspected. The inspection report is drafted and signed by the H&S Manager, then shared with the contractor for acknowledgement and signature. Following this, the on-site inspection concludes. The final report is archived, serving as a formal record of the site's safety at the time and guiding future inspections.

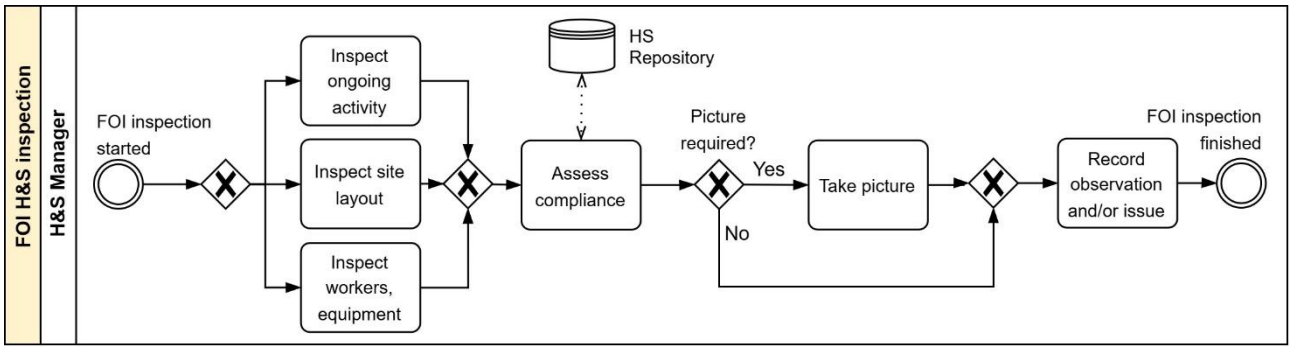

Figure 2: Routine H&S feature of interest inspection sub-process model (BPMN).

Inspection of H&S Features of Interest (FOIs) sub-process

While the overall process includes record initialisation and the management of non-compliances, the most recurrent and information-intensive part of the workflow is the repeated inspection of individual FOIs during the walkthrough. Accordingly, the "Inspect Feature of Interest" sub-process is further detailed and analysed (Figure 2) to clarify current practices and to identify points of friction and opportunities for improvement.

Upon reaching a designated construction site area, the H&S manager assesses compliance with the safety requirements prescribed in the relevant safety documentation by examining FOIs across three complementary categories.

First, ongoing activities are assessed, including the evaluation of operations currently underway in the area and the verification of the authorisations or permits required to perform the specific tasks. Second, the site layout is inspected, focusing on the presence and adequacy of collective protective measures and the implementation of the site organisation and arrangements prescribed in the construction site safety plan and further specified in the contractor's SOP documentation. Third, the workers and equipment present in the area are checked by verifying the validity and completeness of their associated documentation, including workers' general and task-specific training records and machinery inspection and maintenance documentation.

By integrating on-site observations with the relevant safety documentation, the H&S Manager assesses safety compliance for each FOI and, where appropriate, captures photographic evidence to be attached to the recorded observation in support of the inspection outcome. The outcome of the FOI assessment determines the subsequent process flow previously described (Figure 1).

Limitations of current construction site H&S inspection practices

The analysis of the current FOI inspection process highlights several limitations that constrain its efficiency, consistency, and potential for systematic improvement.

Most notably, inspection outcomes remain strongly dependent on the H&S manager's individual practices, expert knowledge, and field experience. While the main tasks and decision points can be identified at the process level, their execution is largely situational and weakly standardised, which reduces replicability and comparability across sites and over time. Supporting the H&S manager in handling this operational complexity motivates the exploration of AI-assisted solutions to structure evidence collection and facilitate timely interpretation and reporting. However, the current process has structural and data-related limitations that complicate this approach, as discussed below. At FOI level, inspections are usually conducted separately: features of interest are evaluated individually without connections to other FOIs or past inspection data, limiting the ability to identify recurring patterns or systemic issues that could guide preventive actions in future inspections or projects. This limitation is reinforced by current recording practices, as FOI assessments are frequently expressed as unstructured natural-language statements, hindering interoperability, structured querying, and integration with other site- and project-related information. Similarly, visual evidence is often collected opportunistically and stored separately, rather than being embedded in a structured workflow and consistently associated with the corresponding observations. Reporting practices represent an additional bottleneck. Inspection reports are typically drafted after the walkthrough through manual consolidation of field notes and documentation, a time-consuming step that can lead to information loss and delayed communication. Reports are commonly archived as PDF documents, which limits their reuse as data sources for analysis and continuous improvement. Finally, documentation management is often fragmented across multiple repositories and formats, further reducing the efficiency and coherence of inspection activities.
Overall, while the inspection process remains central to site safety management, it remains mostly unstructured and poorly suited to systematic data exploitation and AI-assisted support.

Enhanced inspection of H&S Features of Interest (FOIs) with a CV-enabled decision support system

To address these limitations, the enhanced process retains the same underlying inspection workflow while introducing the intervention of a CV-based decision-support system intended to support the user in activities that, in the traditional process, are typically performed manually, interpretatively, and with limited operational structure.

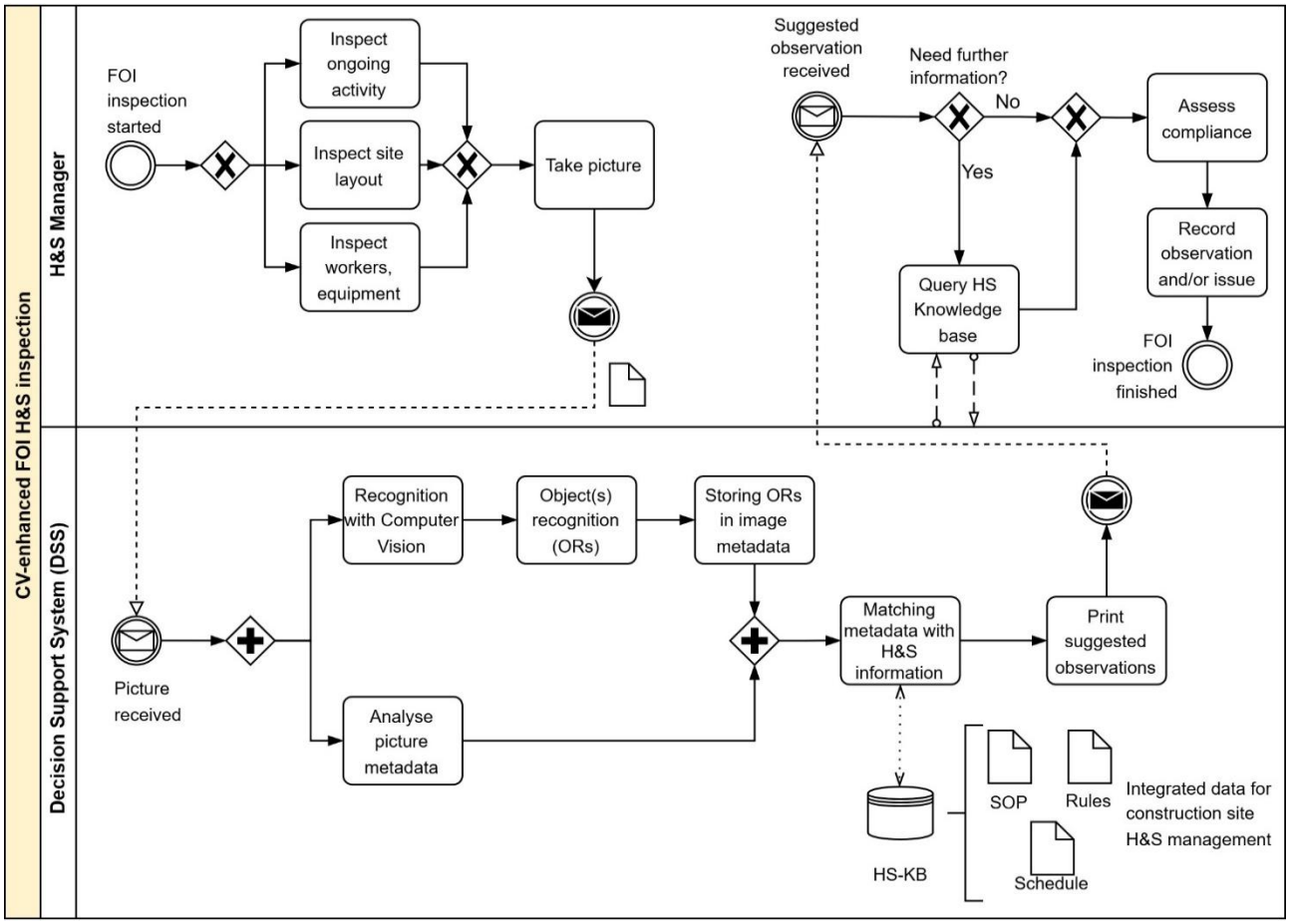

Figure 3: Sub-process model of H&S feature of interest inspection supported by a CV-based Decision Support System (BPMN).

In particular, it enables the real-time validation of on-site observations against project-specific safety requirements, establishing a more direct and actionable link between visual evidence and inspection criteria. Within this perspective, the enhanced workflow is conceived as part of a broader framework connecting inspections with safety planning and knowledge reuse.

As illustrated in Figure 3, the proposed approach intends to leverage existing safety design documents and contractors' safety documentation as primary knowledge sources for inspection planning and on-site control. Since these inputs are predominantly document-based and weakly machine-interpretable, they are first processed to transform H&S-relevant content into structured, queryable data suitable for integration within the proposed decision-support workflow.

The extracted information is stored in a Health and Safety Knowledge Base (HS-KB), integrating safety design requirements, contractors' documentation, inspection observations, and their associated corrective actions. On this basis, a CV-enabled Decision Support System (DSS) is instantiated on demand to cross-reference inspection evidence with applicable safety prescriptions and project-specific requirements. Operationally, the enhanced FOI inspection process embeds this decision-support layer into the routine walkthrough by enabling the H&S Manager to capture photographic evidence via a mobile device and upload it to the DSS. Here, the FOI image is analysed using CV techniques to recognise relevant elements (e.g., guardrails/edge protections), whose labels are stored as photographic metadata together with contextual information such as timestamp and location.

These enriched metadata are used to query the HS-KB and retrieve the corresponding safety prescriptions defined during the design phase, which are then matched with the contractor's SOPs. Based on this matching process, the DSS provides the H&S manager with pre-compiled, context-specific observation suggestions aligned with the applicable safety and project documentation, thereby supporting professional judgement without replacing it. In fact, after receiving the DSS's suggested observations, the final compliance assessment remains entirely under the responsibility of the H&S Manager. The H&S Manager may interrogate the HS-KB in real time to validate the information provided by the system or retrieve additional specifications. FOI-related observations and any encountered issues are then recorded, supporting subsequent communication with the contractor, the request, and the management of corrective actions, as previously shown in Figure 1. Ultimately, this approach enables the production of structured inspection-report data alongside the conventional unstructured document form, supporting not only the H&S Manager's day-to-day inspection activities while enabling systematic reuse of inspection outcomes. The resulting information is stored in the HS-KB, where it can be queried and aggregated

across inspections and construction sites to support cumulative learning and continuous improvement of H&S management practices.

Conclusions and future developments

Despite the growing availability of AI-based technologies, they have not yet been systematically introduced to support routine construction site H&S inspections, which remain weakly structured and largely manual. By adopting a process-modelling approach based on the BPMN 2.0 standard notation, this study formalised current inspection workflows from the H&S Manager's perspective, explicitly capturing roles, activities, decision points, and information flows. The resulting model also highlights key limitations of current practice, including non-standardised observation recording, the need to retrieve relevant H&S information from heterogeneous, fragmented documentation, and the limited reuse of inspection data. Building on this analysis, the paper proposes a structured foundation to guide the development and informed adoption of CV-enabled decision support for routine construction site H&S inspections, integrating a CV-enabled DSS at defined points to support the structured collection and interpretation of visual evidence. Rather than automating compliance assessment, the proposed approach embeds CV within a coherent inspection workflow that preserves the H&S Manager's non-delegable responsibility while improving the consistency and efficiency of inspection activities. From a Human–Data Interaction (HDI) perspective, the proposed approach improves the legibility of inspection processes by structuring the collection and processing of visual evidence within an explicit workflow, supports the H&S Manager's agency by augmenting rather than replacing compliance assessment, and enhances negotiability by allowing system outputs to be interpreted, assessed, and acted upon in light of project-specific requirements and site conditions. These aspects motivate further investigation in future developments.

The process-based approach proposed in this study provides a general foundation for integrating a CV-enabled DSS into routine construction site H&S inspections, but it still requires further specification toward a viable conceptual and technical system architecture, followed by implementation and evaluation.

First, CV algorithms must be further tested and benchmarked in the context of construction site inspections to identify the most suitable approaches.

Future work will examine deep learning models against few-shot and zero-shot approaches, accounting for variability in construction environments, site elements, and routine walkthroughs. Developments will also include structured management of visual evidence and metadata in a HS-KB, such as extracting, storing, and persisting CV outputs and photographic metadata in a machine-interpretable form for integration with other project domains. In this perspective, the system is expected to process visual data potentially including workers present on site, thereby raising issues of data governance, privacy, and responsible data use that future developments will need to address explicitly.

Linking inspection data with safety design documentation, construction planning information, and broader project management data is expected to improve interoperability, support cross-domain reasoning, and promote reuse of inspection knowledge across projects. In this regard, significant challenges remain. A key open issue is defining data structures that align with existing construction and safety documentation practices while interfacing effectively with regulatory requirements.

Addressing these challenges will be essential to ensure that CV-enabled inspection support can be adopted in practice, remain interoperable, and remain aligned with regulatory frameworks and professional responsibilities in construction H&S management.

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