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# BIM-BASED SAFETY FRAMEWORK FOR MANAGING SIMOPS IN BRIDGE CONSTRUCTION PROJECTS

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# 1. INTRODUCTION

To introduce the problem, context, and motivation behind developing a BIM-based safety framework to manage simultaneous operations (SIMOPS) in bridge construction.

## 1.1 BACKGROUND AND CONTEXT

Modern bridge construction is characterised by high complexity, large scale, and the involvement of multiple contractors working on concurrent activities. Typical safety challenges in such projects include crane lifts, deck assembly, welding, concrete pouring, and exposure to adverse weather conditions. The growing role of digitalisation and Building Information Modelling (BIM) in construction management offers new opportunities to enhance safety coordination and risk mitigation, particularly in environments where simultaneous operations (SIMOPS) are common.

## 1.2 PROBLEM IDENTIFICATION

Current safety management systems in bridge construction often lack real-time coordination between safety routines and on-site operations. Existing approaches are frequently static and paper-based, which limits their ability to visualise and communicate overlapping hazards that arise during SIMOPS. This disconnect can lead to increased accident risks, inadequate hazard awareness, and reactive rather than proactive safety management.

## 1.3 RESEARCH GAP

There is limited integration between BIM data and safety management processes in bridge construction. Furthermore, there is a notable absence of user-centred digital safety tools that provide actionable, real-time safety information to on-site personnel. This gap hinders the effective management of SIMOPS and reduces the potential of BIM as a preventive safety instrument.

## 1.4 PROBLEM STATEMENT

How can a BIM-based safety framework, combining a practical, user-friendly digital tool and structured safety routines, be implemented in bridge construction projects to deliver real-time, task-

specific safety information and reduce accident risks during simultaneous operations (SIMOPS), while ensuring compliance with relevant standards and regulations?

## 1.5 RESEARCH OBJECTIVES

1. Identify key SIMOPS-related risks in bridge construction.
2. Determine which BIM parameters are essential for hazard visualisation and control.
3. Develop a framework that aligns BIM-based safety data with existing regulatory requirements.
4. Propose improvements to safety routines, such as the Permit-to-Work system and daily briefings.

## 1.6 SUB-QUESTIONS

- SQ1: What SIMOPS risks and BIM parameters are critical for preventing on-site errors?
- SQ2: How can a human-centred digital interface effectively communicate real-time safety risks?
- SQ3: How can BIM safety tools be formally integrated into existing safety protocols and regulatory frameworks?

## 2. METHODOLOGY

### 2.1 RESEARCH DESIGN

A qualitative case study approach was adopted, combining empirical data collection with technical BIM analysis. This design was selected due to its suitability for investigating complex, real-world contexts where multiple variables interact. Bridge construction was chosen as the case domain because of its inherent complexity, multi-trade operations, and frequent occurrence of simultaneous operations (SIMOPS), which present significant safety challenges.

### 2.2 DATA COLLECTION METHODS

Multiple data sources were utilised to ensure triangulation and enhance the validity of the findings:

Document Review: Analysis of safety documentation, including method statements, risk assessments, and permit-to-work records.

**BIM Model Analysis:** Examination of 3D and 4D BIM models to identify spatial and temporal overlaps in construction activities.

**Semi-Structured Interviews:** Interviews were conducted with safety managers, site supervisors, and BIM coordinators to gain insights into current safety practices, challenges, and digital tool usage.

**Regulatory Review:** Examination of relevant legal frameworks and safety standards, including EU directives, ISO standards, and Danish occupational safety regulations.

## 2.3 ANALYTICAL STRATEGY

The analytical strategy integrated regulatory compliance assessment with BIM model evaluation. The flow of safety information from BIM models to on-site workers was mapped to identify discrepancies between theoretical safety planning, regulatory requirements, and actual site practices. This approach enabled the identification of gaps and opportunities for integrating BIM into existing safety management systems.

## 2.4 LIMITATIONS

The study acknowledges certain limitations:

Access to full-scale BIM models and proprietary safety data was restricted, which may limit the generalisability of certain findings.

The research focuses primarily on the construction phase, excluding design, maintenance, and operational phases of bridge projects.

The findings are based on specific case studies and may not be directly applicable to all bridge construction contexts without adaptation.

# 3. THEORETICAL FRAMEWORK AND KEY CONCEPTS

This section outlines the main theoretical ideas and criteria that underpin the research. It establishes a shared comprehension of terminology connected to BIM, safety management, and risk evaluation, which are subsequently utilized in the analysis and creation of the framework.

## 3.1 KEY CONCEPTS

This section defines the central theoretical concepts that underpin the research, establishing a common understanding of terminology related to BIM, safety management, and risk assessment.

Simultaneous Operations (SIMOPS) refer to multiple work tasks occurring concurrently in the same or adjacent areas, where the activities of one may affect the safety or efficiency of another. In bridge construction, SIMOPS commonly occur during processes such as lifting, welding, concrete pouring, and formwork assembly. These overlapping activities increase the complexity of hazard management and require coordinated safety oversight.

Building Information Modelling (BIM) is a digital representation of a construction project that integrates design elements, schedules, and associated data. The inclusion of the time dimension, known as 4D BIM, enables the modelling of construction sequences and the visualisation of overlapping activities, which is essential for identifying SIMOPS-related risks.

Safety Framework denotes a structured system comprising procedures, tools, and assigned responsibilities to oversee safety. In this research, the framework involves the integration of BIM tools with established safety practices, such as the Permit-to-Work (PTW) system and daily safety briefings.

### 3.2 RISK MANAGEMENT STANDARDS

This research aligns with ISO 31000:2018, which outlines a systematic approach to risk management through the stages of identification, analysis, evaluation, and treatment. Additionally, ISO 12100:2010 provides guidance on hazard identification and principles for risk reduction. Risks are assessed using a qualitative matrix that combines potential severity and likelihood, with controls implemented according to the ALARP principle, keeping risks “as low as reasonably practicable.”

### 3.3 BIM AND INFORMATION MANAGEMENT

The study adheres to the ISO 19650 series, which provides a framework for managing information using BIM. This includes standardised approaches to file naming, metadata, version control, and data coordination within a Common Data Environment (CDE). BIM serves as an integrative platform that combines 3D geometry, time (4D), and safety information, enabling the early identification of hazardous overlaps and supporting timely decision-making.

### 3.4 HUMAN-CENTRED DESIGN

In accordance with ISO 9241-210:2019, a human-centred design approach ensures that digital safety tools are usable, accessible, and aligned with user needs. Effective interfaces should employ clear layouts, colour-coded hazard zones, and real-time notifications to help on-site personnel, such as crane operators, welders, and supervisors, quickly comprehend risks without experiencing cognitive overload.

### 3.5 REGULATORY FRAMEWORK

The legal and practical foundation for safety management in this research is informed by several key regulations and standards:

- EU Directive 92/57/EEC: Establishes minimum safety and health requirements for temporary or mobile construction sites.
- ISO 45001:2018: Specifies requirements for occupational health and safety management systems.
- ISO 19650: Guides digital information management using BIM.
- Danish Working Environment Act and Executive Orders (e.g., BEK 1516): Provide national regulatory context for construction safety in Denmark.

These instruments collectively shape the compliance landscape and inform the development of a BIM-integrated safety framework.

## 4. ANALYSIS AND FINDINGS

### 4.1 SIMOPS RISK MAPPING AND CLASSIFICATION

Simultaneous operations (SIMOPS) constitute a pervasive and high-consequence safety challenge in complex bridge construction projects. Characterised by the concurrent execution of multiple high-risk activities within spatially constrained and temporally overlapping workspaces, SIMOPS introduce compounded hazards that extend beyond those of isolated tasks. Common concurrent operations in bridge construction include but are not limited to: heavy lifting of prefabricated segments, welding and hot works, concrete placement and curing, formwork assembly and stripping, reinforcement fixing, and the operation of heavy machinery and marine vessels. Each activity entails distinct energy sources, kinetic, electrical, thermal, gravitational, and associated exposure mechanisms, which, when combined, create non-linear risk amplifications and emergent hazards do not present in singular task execution.

The inherent complexity of bridge construction, marked by multi-contractor involvement, interdependencies among trades, and stringent project timelines, necessitates a systematic approach to SIMOPS risk classification. This study adopts a tripartite categorisation framework, distinguishing between:

1. Compatible operations – activities that may occur concurrently without significant risk interaction.
2. Partially compatible operations – activities that require specific controls or spatial separation to mitigate interaction risks.

3. Incompatible operations – activities that must be temporally or spatially segregated to prevent catastrophic interactions.

This classification is not merely descriptive but operational, enabling the integration of SIMOPS risk data into BIM-enabled safety planning tools. It aligns with the hazard identification principles of ISO 12100:2010 and provides a structured basis for subsequent spatial-temporal analysis within a BIM environment. (ISO 12100, 2010)

## 4.2 SPATIAL AND TEMPORAL OVERLAP ANALYSIS USING 4D BIM

The advent of 4D Building Information Modelling (BIM), integrating three-dimensional geometry with construction scheduling, provides an unprecedented capability for the proactive identification and management of SIMOPS-related hazards. In bridge construction, where activities are densely packed both horizontally and vertically, 4D BIM facilitates a multi-layered analytical approach:

- **Spatial Analysis:** Identifies physical conflicts between operational envelopes, exclusion zones, access routes, and temporary works. For instance, the swing radius of a tower crane may intersect with the work envelope of a deck welding team, creating a collision or strike-by risk.
- **Temporal Analysis:** Detects scheduling conflicts where the duration of one task overlaps with another in the same or adjacent space. This is critical for tasks with time-sensitive safety constraints, such as concrete curing periods during which formwork must remain in place.
- **Resource-Based Analysis:** Maps the utilisation and conflict of shared resources, including cranes, personnel, access platforms, and marine vessels, across the construction timeline.

The integration of these analytical layers within a unified BIM environment transforms static design models into dynamic safety coordination tools. By linking the BIM model with project scheduling software (e.g., Primavera P6, MS Project), the 4D simulation can be updated in near real-time to reflect schedule adjustments, weather delays, or resource reallocations. This enables safety managers and planners to conduct “what-if” analyses, visualise evolving risk scenarios, and implement pre-emptive controls before hazardous overlaps materialise on site.

## 4.3 RISK ASSESSMENT: SEVERITY AND FREQUENCY EVALUATION

Following the identification of spatial and temporal overlaps, a structured risk assessment is conducted to evaluate and prioritise SIMOPS hazards based on their potential consequences and likelihood of

occurrence. This assessment aligns with the ISO 31000:2018 risk management framework and employs a semi-quantitative matrix approach.

Severity (S) is assessed on a scale from 1 (negligible) to 10 (catastrophic), considering potential outcomes such as:

- Fatalities or life-altering injuries.
- Major structural damage or collapse.
- Significant environmental contamination.
- Project delays exceeding critical milestones.
- Reputational damage or regulatory sanctions.

Frequency (O) or likelihood, is estimated based on historical data, expert judgement, and schedule analysis within the BIM environment. Factors influencing frequency include:

- Task duration and repetition within the project lifecycle.
- Dependency on weather or tidal conditions.
- Level of human intervention and coordination required.
- Historical incident rates for similar activities in comparable settings.

The product of Severity and Frequency yields a preliminary risk score, which is further refined by considering Detectability (D), the ease with which a hazardous condition can be identified before it leads to an incident. Low detectability (high D value) significantly increases risk priority, as latent hazards are more likely to escalate undetected.

This tripartite evaluation ( $S \times O \times D$ ) forms the basis for the Risk Priority Number (RPN) utilised in the Failure Mode and Effects Analysis (FMEA) presented in Section 5.

## 4.4 BIM DATA ARCHITECTURE FOR SAFETY MANAGEMENT

### 4.4.1 RELEVANT BIM DATA LAYERS AND ATTRIBUTES

The efficacy of BIM as a safety management tool is contingent upon the richness, structure, and interoperability of its underlying data. This analysis identifies the following critical data layers for SIMOPS risk management in bridge construction:

Data Layer	Description	Safety Relevance
Object Geometry	Detailed 3D representation of permanent and temporary elements.	Enables clash detection, spatial conflict analysis, and accurate zone definition.
Safety Zones	Digitally delineated areas (exclusion, lifting, hot work, access).	Provides dynamic, visually communicated boundaries for high-risk activities.
Work Sequences (4D)	Time-phashed construction activities linked to model elements.	Allows simulation of task overlaps and proactive scheduling of mitigations.
Resource Assignments	Allocation of plant, equipment, and personnel to tasks.	Identifies resource conflicts and over-allocations that may create SIMOPS.
Environmental Parameters	Wind speed, temperature, visibility, precipitation (via GIS integration).	Supports weather-dependent risk assessments and operational decision-making.
Regulatory Attributes	Links to permits, inspection records, and compliance documentation.	Ensures traceability and integrates legal requirements into the digital workflow.

(Collinge et al. (2022))

#### 4.4.2 COMPLIANCE WITH ISO 19650 (NAMING, METADATA, VERSION CONTROL)

Building Information Modelling (BIM) and digital tools in general are becoming increasingly common in the construction industry because they offer clear advantages throughout all phases of a project. However, this also places high demands on how data is managed and structured, and BIM must handle this information in an efficient and reliable way. The international standard for information management in construction, ISO 19650, provides the framework for this. In the following section, the focus is therefore on three key elements highlighted in the **standard**: naming, metadata, and version control. The aim is to clarify what ISO 19650 requires and then assess whether BIM complies with these requirements or if there are areas where improvements are needed.

(ISO 19650-1:2018) outlines several fundamental principles for information structure. In section 3.3, the standard defines essential concepts that create the basis for naming, metadata and version control. Section 3.3.1 states that data must be represented in a form that can be communicated, interpreted and processed. In practice, this means that information is only usable if it is structured, verifiable and linked to clear documentation. The standard also emphasizes that information must always be defined by “what, when and for whom,” ensuring that data cannot be released or shared before its scope and purpose are fully documented. The same section also introduces the need for process control and versioning, which regulates how information containers are created and exchanged throughout a project.

A central reason for these requirements is the concept of the “information model,” defined in section 3.3.8 as a set of structured and unstructured information containers. The information model represents the complete and continuously updated collection of all project data, including models, documents and numerical information. Without a consistent information structure, this model would not be reliable. Section 3.3.12 further defines information containers as named, permanent collections of information retrieved from a file, system or application hierarchy. These must be managed throughout the project, and the naming of containers must follow agreed naming conventions to ensure consistency and traceability. All of this takes place within the Common Data Environment (CDE). (ISO 19650-1:2018)

Metadata also plays a critical role. Within the CDE, metadata identifies responsibility, approval status, version history and how information is intended to be used. ISO defines these status codes in section 3.3.13 as metadata describing the suitability of the container’s content. EFCA, the European Federation of Engineering Consultancy Associations, expands on this by emphasising that metadata is essential for traceability, accountability and real-time insight. Without metadata, information cannot be controlled or validated properly (EFCA, 2020, p. 16).

Metadata naturally leads to the concept of version control, which ISO describes as the process ensuring that information is handled and exchanged correctly throughout the project. Version control ties together containers and metadata so that all information remains traceable. ISO explains that information in the CDE passes through four stages: Work in Progress (WIP), Shared, Published and Archive. Each stage represents a control point where information is checked and approved before moving to the next level. This structure ensures that information is gradually validated and kept up to date. (ISO 19650-1:2018)

Figure 1 (ISO 19650-1, section 12) illustrates how version control governs the movement of information through these four stages. In the WIP phase, only the responsible team can access the information. Once validated, it moves to Shared, where other parties can review and coordinate their work. Even at this point, changes may still occur, allowing collaboration and refinement. When the information reaches the Published stage, it is ready for final use. Eventually, older

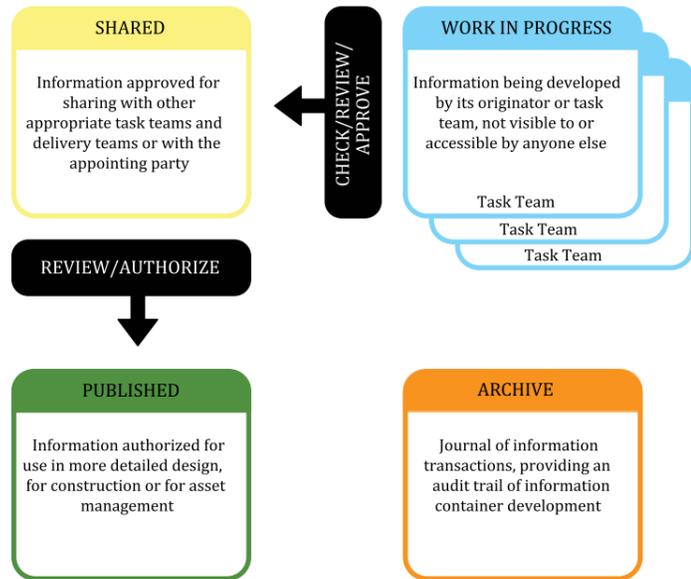


Figure 1

versions are stored in the Archive, ensuring continual traceability. This model clearly shows how the CDE supports reliable version control across the entire project lifecycle.

Given these requirements, it becomes essential to evaluate to what extent BIM actually complies with ISO 19650 in practice. EFCA provides a practical perspective on this by examining how BIM is used across real projects. Their report highlights several strengths. BIM significantly reduces the risk of data loss, the CDE provides a structured and controlled environment, and information is exchanged with traceability instead of through informal methods like email. This shows that BIM largely supports ISO’s expectations regarding data structure and information handling.

However, EFCA also notes that compliance is not only a technical issue. On page 24, they point out that despite BIM’s strong capabilities, new risks arise due to human behaviour rather than technology. A shared information structure loses value if project participants store files locally or follow internal habits instead

of agreed procedures. For full ISO compliance, project teams must actively maintain discipline and responsibility in their daily workflows (EFCA, 2020).

This pattern is also seen in the area of naming. ISO requires clear and consistent naming to maintain traceability, and EFCA confirms that BIM systems are capable of supporting this. They refer to containers as a “named persistent set of information retrievable from within a file, system or application storage hierarchy” (EFCA, p. 15). However, differences between software platforms, for example Revit’s internal naming habits, can create inconsistencies when project teams do not follow shared conventions. This means that naming failures are typically due to users rather than BIM itself.

A similar issue occurs in metadata handling. BIM is technically well equipped to provide automatic metadata, including who can access information and which version is the most recent. But EFCA notes that coordination problems often arise when BIM interacts with other tools such as Revit or Dalux (EFCA, p. 25). A study on BIM-based model checking supports this, stating: “errors and losses occur during the design, modification, and conversion processes of BIM models, due to human negligence or conflicts between heterogeneous data” (Li, Jiang & Xu, 2025). For example, when drawings created in Revit are transferred to the CDE, detailed metadata may be lost, requiring manual corrections. The problem is therefore not BIM, but the lack of alignment between tools and the human errors that arise in these transitions.

Finally, version control also presents challenges. While BIM can meet ISO’s requirements, including revision codes defined in ISO 19650-2, many CDE platforms rely on internal naming practices instead of automatically following ISO’s conventions. This leads to confusion when new file versions are uploaded, making it unclear which version is the current one. In such cases, version control loses its intended purpose and becomes dependent on project teams manually maintaining order (DS/EN ISO 19650-2:2018).

Overall, ISO 19650 establishes clear, detailed requirements for information structure, naming, metadata and version control. BIM systems are fundamentally capable of meeting these requirements and can do so at a high level. However, full compliance depends heavily on how the system is used in practice. The technology performs well, but the human factor remains decisive. To achieve optimal results, project participants must follow consistent procedures and maintain a disciplined approach throughout the project. As the analysis shows, BIM and ISO align well, but complete compliance ultimately depends on the organisation rather than the tool itself.

#### 4.5 HUMAN-CENTERED INTERFACE EVALUATION FOR BIM-BASED SAFETY SYSTEMS

A fundamental determinant of the efficacy of any Building Information Modelling (BIM)-integrated safety system is its capacity to communicate risk information in a manner that is intuitive, actionable, and accessible to the diverse spectrum of personnel operating on a construction site. While advanced data integration within a BIM environment enables the real-time identification of hazards, the practical utility and adoption of such a system are contingent upon the clarity, relevance, and usability of its user interface (UI). The interface must effectively translate complex, data-rich safety analytics into straightforward guidance for end-users, including crane operators, welders, steel fixers, site supervisors, and project engineers, each with varying levels of technical literacy and site responsibilities.

Bridge construction sites are dynamic, high-tempo environments where operational conditions and risk profiles can change rapidly due to factors such as shifting weather, revised schedules, and the concurrent execution of multiple tasks (SIMOPS). In such contexts, conventional safety communication modalities, including static 2D drawings, paper-based checklists, and verbal briefings, are often inadequate for conveying the spatial complexity, temporal urgency, and evolving nature of interrelated hazards. These traditional methods can fail to foster a shared and accurate situational awareness across the workforce, creating gaps between planned safety measures and on-the-ground reality.

A human-centered digital interface, embedded within the BIM ecosystem, addresses these limitations by presenting risk information contextually and visually within the user's operational frame of reference. Instead of relying on abstract data or technical notations, the interface visualises hazards directly within a digital representation of the worksite. For instance, a mobile BIM viewer deployed on ruggedised site tablets can render a 3D model of the bridge structure, with work zones dynamically colour-coded to reflect real-time risk levels: red for zones experiencing high-risk SIMOPS (e.g., active lifting over occupied areas), amber for areas with moderate or controlled risks, and green for safe access or low-activity zones. This immediate visual coding allows personnel to assess site safety intuitively, without requiring interpretation of complex reports or schematics.

The interface's effectiveness is significantly enhanced through integration with real-time data streams from onsite monitoring systems. By connecting to Internet of Things (IoT) networks, such as RFID or GNSS-based personnel location tags, crane load moment indicators (LMIs), anemometers, and vibration sensors, the BIM interface can transition from a passive visualisation tool to an active alerting system. Practical applications include:

**Proximity Alerts:** If a worker wearing an RFID tag enters a geo-fenced exclusion zone beneath an active crane lift, the interface can trigger an immediate visual warning on nearby tablets and a haptic alert (e.g., vibration) on the worker's wearable device.

**Condition-Based Notifications:** Supervisors can receive automated push notifications when critical equipment thresholds are breached, such as wind speeds exceeding safe lifting limits or crane loads approaching certified capacities, prompting timely intervention decisions.

**Contextual Awareness:** The system can filter and prioritise alerts based on the user's role and location, ensuring that a crane operator receives information pertinent to lifting operations, while a deck foreman is alerted to hazards in their immediate work area.

Such contextual and role-specific alerting reduces cognitive load, mitigates information overload, and enhances situational awareness by delivering only the most relevant safety information in a clear and timely manner.

To ensure the interface meets the practical needs of its end-users, its design must be guided by a structured evaluation framework rooted in Human-Centered Design (HCD) principles, as outlined in ISO 9241-210:2019. This evaluation should encompass the following key activities:

**Examination of User Requirements:** Conduct task analyses and stakeholder interviews with distinct user groups, field operatives (e.g., welders, riggers), supervisors, and engineers, to identify their specific information needs, workflow patterns, literacy levels, and device interaction preferences.

**Analysis of Information Display Modalities:** Investigate and prototype display strategies designed to minimise cognitive overload and maximise comprehension. This includes:

The use of colour-coded hazard zones and universal symbols for rapid recognition.

The implementation of tiered alert systems (informational, warning, critical) with distinct visual and auditory signatures.

The employment of 3D visual cues and augmented reality (AR) overlays to provide an immersive understanding of spatial risks.

The evaluation of suitable device platforms, such as site tablets for supervisors, smart helmets with heads-up displays for hands-free operatives, and AR glasses for engineers, considering factors like durability, usability in outdoor environments, and connectivity.

Evaluation of Prototypes Using HCD Principles: Develop iterative interface prototypes (e.g., wireframes, interactive mock-ups) and subject them to usability testing with representative users. Evaluation should focus on the core principles of ISO 9241-210, including:

- The extent to which the design is based upon a comprehensive understanding of users, tasks, and environments.
- How actively users are involved throughout the design and development process.
- How the design is driven and refined by user-centred evaluation.
- The iterative nature of the design process.
- The addressal of the complete user experience.

By adhering to this rigorous, human-centered design process, the resulting BIM safety interface can transcend being a mere data visualisation tool. It can become an integral part of the site's safety culture, effectively bridging the gap between the digital safety model and the human operators on the ground, thereby reducing misinterpretation, improving compliance with safety controls, and ultimately mitigating the risk of incidents during complex SIMOPS.

#### 4.6 INTEGRATION WITH SAFETY PROTOCOLS AND REGULATIONS

The successful implementation of a BIM-based safety framework is contingent not only upon its technical capacity to identify and visualise hazards but equally on its systemic integration with the existing safety management systems that govern construction projects. Within the domain of bridge construction, characterised by intricate, high-risk, and frequently simultaneous operations (SIMOPS), the principal advantage of BIM lies in its potential to augment and modernise entrenched safety protocols. These include Permit-to-Work (PTW) systems, daily safety coordination meetings (e.g., Toolbox Talks), and the statutory record-keeping mandated by regulations such as the **EU Directive 92/57/EEC** on temporary and mobile construction sites. By creating a digital thread that connects planning, authorisation, and execution, BIM can bridge the persistent gap between digital design intent and onsite operational reality. This integration transforms traditionally static, document-centric safety procedures into a dynamic, real-time management strategy that enhances regulatory compliance, improves communication fidelity, and fosters a proactive safety culture. (Chen et al., 2020a)

##### 4.6.1 BIM-ENHANCED PERMIT-TO-WORK (PTW) SYSTEM

A primary and impactful integration point is the digitisation and enhancement of the Permit-to-Work (PTW) system. The PTW process is a formal administrative control designed to ensure that high-risk tasks, such as heavy lifting, hot works, or working at height, are subjected to prior planning, risk assessment, and

managerial authorisation before commencement. In conventional practice, this process is predominantly manual, relying on paper-based forms, physical signatures, and fragmented communication channels. This methodology is inherently susceptible to delays, transcription errors, version control issues, and a disconnection from the live site context.

Integrating the PTW work flow within the BIM environment directly addresses these vulnerabilities. A BIM-integrated PTW system can perform automated validation checks by cross-referencing each digital permit application against the project's 4D (time-sequenced) model and current schedule. For instance, when a permit is requested for a crane operation, the system can instantly analyse the 4D simulation to detect spatio-temporal conflicts with other authorised activities in the same zone, such as concurrent welding or formwork stripping. If a conflict is identified, the system can generate an alert, preventing permit approval until mitigating actions, such as task resequencing, the establishment of additional physical barriers, or revised method statements, are digitally recorded and validated. (ISO 45001, 2018)

This automation yields multiple critical benefits:

- **Error Reduction:** It minimizes reliance on human memory and manual cross-checking, reducing omissions and oversights.
- **Decision Support:** It provides safety officers and supervisors with a visually intuitive basis for authorisation decisions, directly within the spatial context of the model.
- **Regulatory Alignment:** It ensures work authorisation is explicitly linked to the most current project information, satisfying the requirements for operational control and documented information as stipulated in **ISO 45001:2018** (Clauses 8.1.2 and 7.5).
- **Enhanced Traceability:** It creates an immutable digital audit trail linking each permit to its specific location in the model, the responsible parties, and the associated risk assessments.

In the spatially constrained and task-dense environment of bridge construction, such a system ensures that permits are not only administratively correct but are also contextually safe, rendering the authorisation process both more reliable and more efficient.

#### 4.6.2 AUGMENTATION OF DAILY SAFETY COMMUNICATION AND COORDINATION

Beyond formal permit systems, BIM can significantly enhance daily safety communication routines, such as Toolbox Talks and pre-shift briefings. These forums are vital for maintaining situational awareness among a diverse and often multi-contractor workforce, particularly in fast-changing project environments. Traditionally, these sessions rely on verbal descriptions, 2D paper drawings, or whiteboard sketches, which

can struggle to convey the three-dimensional complexity, precise locations, and dynamic nature of overlapping hazards.

BIM offers a transformative communication medium by enabling the visualisation of daily risks within an interactive 3D or 4D model. Updated to reflect the day's planned activities, the model can highlight active high-risk zones, for example, areas where steel erection will occur simultaneously with concrete delivery vehicle movement. Projecting this model on a shared display or accessing it via tablets during safety meetings allows the entire team to visualise hazards in their precise spatial and temporal context. This visual approach transcends language barriers and varying levels of technical literacy, enabling all workers to develop an accurate, shared mental model of the day's risks and the corresponding control measures. Consequently, safety instructions become more concrete, memorable, and actionable.

#### 4.6.3 DIGITAL TRANSFORMATION OF THE SAFETY AND HEALTH FILE

A profound regulatory integration opportunity lies in the digital management of the Safety and Health File, a comprehensive dossier mandated by EU Directive 92/57/EEC. This file serves as the central repository for all safety coordination documents, risk assessments, and records of implemented preventive measures throughout the construction phase. Conventionally, compiling and maintaining this file is a laborious, paper-intensive process involving the manual aggregation of reports, checklists, and certificates from multiple contractors. Its static nature often results in a document that lags behind the actual, evolving state of the worksite, undermining its utility for real-time safety management and future facility maintenance.

BIM enables a paradigm shift from a static document to a living, digitally integrated Safety and Health File. By linking all safety documentation directly to the relevant components of the BIM model, a dynamic and continuously updated record is created. Each physical element of the bridge (e.g., Pier P3, Deck Segment D-12, Temporary Scaffolding S-4) can be associated with a digital "dossier" containing its relevant hazard assessments, inspection reports, method statements, certificates, and photographic evidence. As the project progresses, through design revisions, schedule updates, or the completion of safety actions, these linked records are automatically versioned and remain intrinsically connected to their respective model elements. This BIM-based approach delivers substantial improvements:

- **Accuracy and Currency:** The file perpetually reflects the as-built and as-maintained state of the structure.
- **Enhanced Accessibility and Traceability:** Project managers, auditors, and safety coordinators can perform spatially intelligent queries. For example, selecting a specific pier in the model instantly retrieves all related lifting permits, crane lift studies, and inspection certificates for that location, eliminating the need to sift through voluminous paper files.

- **Streamlined Compliance Audits:** The provision of immediate, organised access to all corroborating evidence simplifies the verification of compliance with internal procedures and external regulations such as the Danish Working Environment Act (Executive Order BEK 1516) and ISO 45001:2018.

#### 4.6.4 SYNTHESIS: TOWARDS A UNIFIED, PROACTIVE SAFETY MANAGEMENT SYSTEM

The integration of BIM with core safety protocols ultimately facilitates the consolidation of disparate manual processes into a unified, intelligent data environment. Traditional safety management often suffers from fragmentation, with different contractors and departments maintaining separate records, leading to inconsistent data and a lack of a holistic, real-time safety overview. BIM dissolves these silos by embedding safety data directly into the shared digital model, creating intrinsic links between every task, control measure, inspection, and authorisation.

This connectivity enables instantaneous compliance verification and performance monitoring. Auditors and supervisors can interrogate the model not as a mere geometric representation but as an interactive safety management dashboard. The result is a transformation of BIM from a passive data repository into an active safety governance tool that unifies design intelligence, construction sequencing, and operational risk control on a single, collaborative platform.

In summary, for bridge construction projects where SIMOPS are endemic and risk profiles are fluid, the integration of BIM with established safety and regulatory frameworks represents a significant strategic advance. It directly addresses the core research problem by demonstrating how a practical, user-centric digital tool can institutionalise regulatory compliance while simultaneously delivering real-time, context-aware safety intelligence. This capability fundamentally shifts the paradigm of construction safety management from a reactive, document-driven obligation to a proactive, integrated, and collaborative process, one that enhances decision-making, fosters transparency, and robustly reinforces the safety culture essential for the successful execution of complex modern infrastructure projects.

#### 4.7 DATA INTEGRATION AND REAL-TIME DECISION SUPPORT IN BIM-BASED SAFETY MANAGEMENT

The progressive digitalisation of construction management has catalysed significant opportunities for embedding safety processes directly within Building Information Modelling (BIM) environments. In the context of bridge construction, characterised by frequent Simultaneous Operations (SIMOPS) within spatially confined and logistically intricate work zones, access to real-time, data-informed safety

intelligence is no longer a mere enhancement but a critical prerequisite for accident prevention and sustained regulatory compliance. Traditional safety management, reliant on periodic inspections and static documentation, is fundamentally reactive and often misaligned with the dynamic risk landscape of a live construction site. The integration of live data streams into a centralised BIM framework therefore represents a pivotal advancement in digital safety oversight, enabling a paradigm shift from post-incident response to anticipatory and preventative risk management.

This section examines the technical and operational mechanisms through which the alignment of BIM with real-time data sources, including sensor networks, equipment telemetry, and personnel tracking systems, can enhance proactive hazard control and situational awareness during SIMOPS. By transforming the BIM model from a static planning tool into a dynamic Digital Twin of the construction site, project stakeholders gain an unprecedented capacity to monitor, analyse, and respond to evolving risks as they emerge.

#### 4.7.1 THE IMPERATIVE FOR REAL-TIME DATA IN SIMOPS ENVIRONMENTS

Bridge construction entails the concurrent execution of multiple safety-critical tasks, such as heavy lifting, structural welding, concrete placement, and temporary works assembly, within tightly constrained physical and temporal windows. These overlapping activities generate complex, non-linear risk interactions that evolve in real-time with changes in schedule, weather, resource deployment, and human movement. Conventional paper-based or spreadsheet-driven safety systems lack the temporal resolution and integrative capacity to monitor these fluid interactions, creating a latency between the emergence of a hazard and its recognition by the safety management team. This latency represents a critical vulnerability, as even brief periods of unmanaged risk exposure can precipitate catastrophic incidents in high-consequence environments.

#### 4.7.2 FRAMEWORK FOR BIM AND IoT INTEGRATION

The convergence of BIM with the Internet of Things (IoT) establishes the technological backbone for real-time safety monitoring. IoT refers to the network of physical devices embedded with sensors, software, and connectivity, enabling them to collect and exchange data. Integrating these data streams into a BIM environment involves creating a bidirectional link between the geometric and semantic data of the digital model and the live data generated on site. Key IoT data sources relevant to bridge construction safety include:

- **Equipment Telemetry:** Cranes and other heavy machinery equipped with Load Moment Indicators (LMIs), GPS, inclinometers, and pressure sensors can transmit real-time data on operational status, including load weight, boom angle, radius, and wind speed at the hook.

- **Personnel Location and Proximity Tracking:** Wearable devices incorporating RFID, Ultra-Wideband (UWB), or Bluetooth Low Energy (BLE) technologies enable the real-time location tracking of workers. This data can be used to monitor entry into predefined hazard zones (geofencing) and to assess proximity between workers and dangerous equipment or activities.
- **Environmental Monitoring Networks:** A suite of deployed sensors can continuously measure ambient conditions critical to site safety, such as wind speed and direction (via anemometers), temperature, humidity, visibility, and structural vibrations.

The technical integration of these heterogeneous data streams typically occurs through a middleware layer or a dedicated integration platform that aggregates, filters, and contextualises the raw sensor data before mapping it onto the corresponding elements within the BIM model. For instance, a crane's live load data is associated with the 3D crane object in the model, and a worker's UWB coordinates are plotted in real-time within the site's spatial framework.

#### 4.7.3 FUNCTIONALITY AND BENEFITS OF A LIVE-DATA BIM SYSTEM

Once integrated, this live data infusion empowers the BIM-based safety system with several advanced functionalities:

1. **Dynamic Hazard Visualisation:** The BIM interface transitions from showing planned or historical states to displaying the *current* site conditions. Hazard zones (e.g., crane swing radii, drop zones, hot work areas) are not static but can dynamically adjust based on real-time equipment positioning and environmental readings. These zones can be visually overlaid on the 3D model using colour-coding (e.g., red for active, high-risk zones), providing an instant, at-a-glance overview of the live risk landscape to supervisors in the site office or via mobile devices.
2. **Predictive Analytics and Proactive Alerts:** By applying predefined safety rules and thresholds to the incoming data stream, the system can automatically generate predictive alerts. For example:
  - If the integrated wind sensor data exceeds the safe lifting limit defined in the crane's load chart, the system can automatically flag all active lifting permits and notify the crane operator and lift supervisor.
  - If a worker's tracking data indicates they are approaching a geo-fenced exclusion zone around an active pile-driving operation, a proactive warning can be sent to the worker's wearable device and to the zone supervisor. (Teizer, Cheng & Fang (2013))
3. **Enhanced Situational Awareness and Decision Support:** Safety managers are provided with a unified, data-rich dashboard that synthesises information from multiple, previously siloed sources.

This holistic view supports more informed and timely decision-making. For instance, when deciding whether to authorise a critical lift, the manager can review not just the static lift plan but also the real-time wind conditions, the confirmed locations of all personnel in the vicinity, and the current status of overlapping activities in the 4D schedule.

4. **Automated Compliance Logging and Forensic Analysis:** All sensor data, system states, and triggered alerts can be automatically timestamped and logged within the BIM-connected Common Data Environment (CDE). This creates a comprehensive, auditable digital record of site conditions and safety interventions. In the event of an incident or a near-miss, this data trail provides an invaluable resource for forensic analysis, helping to accurately reconstruct event sequences and identify root causes far more effectively than traditional manual logbooks.

In conclusion, the integration of real-time IoT data into the BIM framework transforms the model into a living, breathing nerve centre for construction safety. It directly addresses the core challenge of managing evolving risks during SIMOPS by closing the information latency gap. This capability enables a fundamental shift towards predictive safety management, where hazards are identified and mitigated before they can escalate into incidents, thereby reinforcing the regulatory adherence and operational resilience required for the successful completion of complex bridge projects.

## 4.8 GAP AND OPPORTUNITY ANALYSIS

This section systematically identifies discrepancies between prevailing industry practices and established regulatory standards within bridge construction, with a specific focus on safety management during Simultaneous Operations (SIMOPS). Furthermore, it delineates critical opportunities where the integration of Building Information Modelling (BIM) can bridge these gaps, thereby enhancing safety outcomes, operational efficiency, and regulatory compliance.

### 4.8.1 IDENTIFIED GAPS BETWEEN CURRENT PRACTICE AND REGULATORY STANDARDS

Despite a general trend towards digitalisation in the construction sector, the adoption of BIM, and more specifically, Bridge Information Modelling (BrIM), remains inconsistent within bridge construction projects. This lag in technological adoption has precipitated significant disconnects between on-site safety practices and the requirements set forth by international regulatory and management system standards.

A prominent gap is evident in the management of the Permit-to-Work (PTW) process. As previously noted, PTW procedures in bridge projects frequently rely on manual, paper-based systems. This approach results in protracted approval cycles, fragmented documentation across multiple contractors, and considerable

challenges in maintaining an auditable trail of authorisations and checks. Such practices are fundamentally misaligned with the documentation and traceability mandates specified in (*ISO 45001*, 2018 Clause 7.5 p. 14) which require documented information to be controlled and remain available and suitable for use.

Integrating PTW within a BIM environment presents a direct solution to this discrepancy. By associating permit data directly with specific bridge elements within the digital model, documentation becomes centralised, automatically updated, and intrinsically linked to the spatial and temporal context of the work. This digital integration ensures consistency with both ISO 45001 requirements for hazard control and the information management principles of ISO (*ISO 19650-1*, 2018 Clause 5.1 p. 11-13), transforming PTW from a passive administrative task into an active, real-time coordination tool that helps prevent conflicting high-risk operations.

#### 4.8.2 OPPORTUNITIES FOR ENHANCEMENT THROUGH BIM INTEGRATION

##### 1. Risk Visualisation and Forecasting

Current risk assessment methodologies in many bridge projects depend on static 2D drawings and checklist-based evaluations. These tools are inadequate for modelling the dynamic, overlapping nature of work processes inherent in SIMOPS, often leading to the late identification of spatial and temporal conflicts. The implementation of 4D BIM, which integrates 3D geometry with construction schedules, enables the proactive simulation and visualisation of task sequences. This capability allows project teams to identify and analyse potential hazardous overlaps before they occur on site, facilitating the planning of preventive measures in alignment with the principles of (Clause 5(*ISO 31000*, 2018 Clause 5, p. 7-9) on risk management and (*ISO 12100*, 2011 Clause 5.3, p. 6) on hazard identification. Consequently, risk management evolves from a reactive, document-centric exercise to a proactive, data-driven process.

##### 2. Real-Time Communication of Hazards

On-site safety communication traditionally occurs through toolbox talks, physical notice boards, and paper-based reports. These methods suffer from significant latency and cannot keep pace with the rapid changes characteristic of a live construction site, leading to information asymmetry between different contractors and trades. The integration of BIM with real-time data sources, such as IoT sensors for monitoring weather conditions, equipment status, and worker location, enables the automation of hazard communication. A BIM-IoT system can generate and disseminate immediate warnings, for instance, alerting a worker entering a restricted zone or notifying supervisors of exceeding environmental limits, directly within the contextual

digital model. This approach aligns with the user-centric design principles of (*ISO 9241-210*, 2019 Clause 5.3, p. 6) and substantially elevates situational awareness across all project roles.

### 3. Compliance Reporting and Traceability

The manual, fragmented approach to safety documentation complicates compliance verification and obscures traceability. BIM offers the opportunity to create a unified, intelligent data environment where every safety action, inspection, and permit is digitally linked to the relevant component of the project model. This intrinsic connectivity allows for instantaneous compliance checks and provides a clear, auditable digital thread from planning to execution, satisfying stringent regulatory and standardised requirements for record-keeping.

#### 4.8.3 CROSS-CUTTING CONSIDERATIONS FOR BIM IMPLEMENTATION

- Data Interoperability and Information Management

Bridge projects typically involve multiple stakeholders employing diverse software platforms (e.g., Revit, Civil 3D, Tekla). The lack of efficient data exchange between these systems impedes collaboration and hinders the integration of comprehensive safety information. Adherence to open standards, such as those outlined in (*ISO 16739-1*., 2024 Clause 4.1, p. 2-4) and (*ISO 12006-2*, 2020 Clause 4.2, p. 6-7), is critical. The OpenBIM methodology, supported by these standards, ensures that critical safety data, including risk information, sensor feeds, and PTW documentation, can be seamlessly shared across software ecosystems without loss of fidelity or meaning.

- Data Quality, Security, and Human Factors

The efficacy of a BIM-based safety system is contingent upon the quality and security of its underlying data. Inaccurate or corrupted data can lead to flawed risk judgements. Implementing ISO 8000 (Data Quality) for validation and (*ISO/IEC 27001*, 2023 Clause 6.1.2, p. 5-7) alongside (*ISO 19650-1*, 2018 Clause 6.3.2, p. 10) is essential to ensure data integrity, protect sensitive project and personnel information, and maintain compliance with regulations such as the GDPR.

Successful implementation also hinges on addressing human and organisational factors. The rapid pace of digitalisation can outstrip the digital literacy of the on-site workforce, where BIM may be perceived as an engineering administrative tool rather than a practical safety aid. ISO 10018:2020 (Quality Management - Guidance on People Engagement) provides a framework for managing employee competencies and fostering engagement, which is vital for cultivating the necessary digital skills and promoting a positive safety culture conducive to adopting new technologies (*ISO 10018*, 2020 Clause 5.3, p. 3-4).

- Integration of Environmental and Sustainability Aspects

Traditional safety planning often focuses narrowly on personal risk, overlooking environmental factors such as dust, noise, and vibrations. A holistic risk management approach requires the integration of Safety, Health, and Environmental (SHE) considerations. BIM can serve as the consolidating platform for this integration, aligning with the requirements of (*ISO 14001*, 2015 Clause 6.1.2, p. 9-10) for identifying environmental aspects and enabling a more comprehensive, proactive management of all project-related risks.

#### 4.8.4 SYNTHESIS AND VISUAL REPRESENTATION

The confluence of these technical, procedural, and human factors underscores the necessity for a structured, multi-faceted safety management framework. The Bow-Tie model referenced in Figure 2 provides a pertinent visual synthesis of this analysis. It graphically maps the key threats arising from current in practice, illustrates how their realisation could lead to a loss of safety control during SIMOPS, and identifies both preventive and recovery barriers. These barriers are explicitly linked to the implementation of BIM-enabled solutions and adherence to the relevant ISO standards discussed, demonstrating a systematic approach to risk minimisation or elimination.

##### 4.8.4.1 VISUAL SUMMARY: BOW-TIE MODEL

The following Bow-Tie model provides a visual summary of the gaps and control measures discussed in this analysis. It illustrates how key threats inherent in current bridge construction practices can precipitate a loss of safety control during SIMOPS, and delineates how preventive and recovery barriers, founded on BIM implementation and the application of relevant ISO standards, can systematically minimise or eliminate these risks.

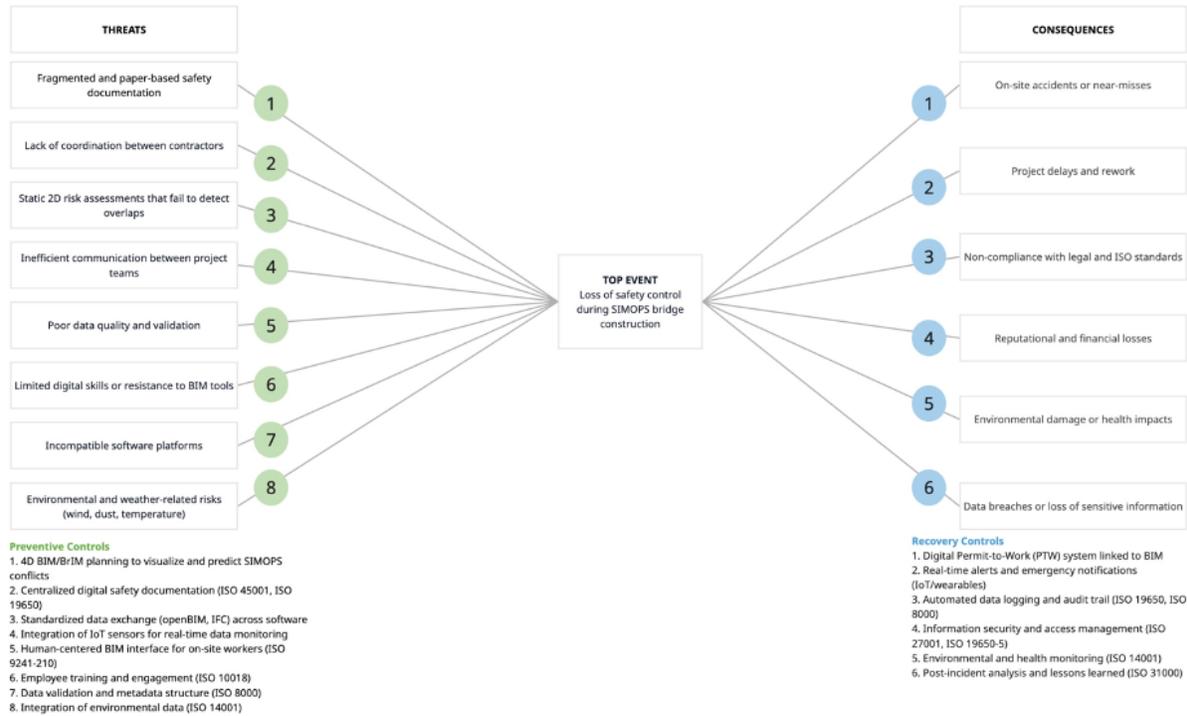


Figure 2 – Visual summary of the Bow-Tie model

As shown in Figure 2, the model translates the preceding analytical findings into a coherent visual structure, explicitly linking identified threats, proposed barriers, and potential consequences in a clear and actionable overview.

#### 4.8.5 PRACTICAL IMPLEMENTATION CHALLENGES

Notwithstanding its significant potential, the practical implementation of BIM-based safety management in bridge projects faces considerable challenges that must be strategically addressed.

**Training and Digital Competence:** A fundamental barrier is the varying level of digital experience among on-site personnel. A prevalent perception views BIM as an engineering or administrative tool rather than a daily safety instrument. This gap between system capability and user comfort necessitates substantial investment in targeted training programmes and the development of genuinely user-friendly interfaces. Proactive change management, guided by principles such as those in (*ISO 10018*, 2020), is crucial for building user confidence and competence.

**Data Governance and Standardisation:** The multi-contractor nature of bridge projects often results in disparate data handling practices, ranging from proprietary software use to informal methods like emailing PDFs. This heterogeneity leads to inconsistent information quality and obstructs collaboration. Establishing robust data governance protocols based on standards like (*ISO 19650-1*, 2018) and ISO 8000 (Data quality)

is imperative. These frameworks provide the necessary rules for data ownership, validation, exchange, and version control, ensuring a reliable and shared information foundation.

Management Commitment and Cultural Change: Implementation represents a significant investment of time and resources. Without sustained and visible commitment from senior management, BIM initiatives risk being perceived as ancillary administrative burdens rather than core safety investments. Securing this commitment often requires demonstrable proof of concept, showcasing tangible benefits such as reduced incident rates, fewer delays, enhanced documentation quality, and improved safety performance metrics.

In conclusion, the identified gaps between practice and standards reveal a clear pathway for innovation through BIM. However, realising this potential is not merely a technological exercise. It demands a holistic strategy that concurrently addresses technological integration, procedural standardisation, human factor development, and strong leadership. Failure to adequately confront these practical barriers may result in even the most sophisticated BIM framework remaining an underutilised theoretical concept, failing to deliver substantive safety improvements on the construction site.

## 5. CASE STUDIES

### 5.1 PELJEŠAC BRIDGE: A CONTEMPORARY CASE IN SIMOPS MANAGEMENT

#### 5.1.1 INTRODUCTION AND SYSTEM DEFINITION

This case study examines the construction of the Pelješac Bridge to assess safety challenges associated with Simultaneous Operations (SIMOPS) in major bridge projects. Constructed between 2018 and 2022, the project entailed significant prefabrication, large-scale heavy lifting, complex maritime logistics, and intricate elevated work tasks. These characteristics establish it as an exemplary context for investigating how concurrent construction activities can precipitate hazardous interactions and for evaluating the potential role of a Building Information Modelling (BIM)-based safety framework in mitigating associated risks.

The analytical scope of this study is delimited to the construction phase, encompassing all activities related to structural assembly, erection of temporary works, lifting operations, and waterborne material transport. Design, maintenance, and post-construction evaluation phases are excluded from this analysis. The system under investigation includes the key human agents integral to site safety during this phase: crane operators, reinforcement (rebar) placement teams, marine vessel crews, deck assembly workers, site supervisors, safety managers, and BIM coordinators. Their interactions within the shared physical and temporal workspace form the basis for assessing SIMOPS complexity.

### 5.1.2 SIMOPS ENVIRONMENT AND OPERATIONAL COMPLEXITY

SIMOPS scenarios are defined as situations where two or more potentially conflicting operations occur concurrently within the same or adjacent operational zones. On the Pelješac Bridge project, SIMOPS were an inherent and necessary consequence of a segmented construction methodology and the imperative to execute multiple critical path activities in parallel to meet ambitious project timelines.

The operational environment was characterised by several layers of complexity that amplified SIMOPS-related risks:

1. **Marine-Based Lifting SIMOPS:** The deployment of large floating cranes for positioning prefabricated deck segments created dynamic, mobile exclusion zones. These zones frequently intersected with stationary work areas allocated for activities such as rebar installation and welding, necessitating meticulous spatial and temporal coordination.
2. **Vertical SIMOPS:** Construction activities were distributed across multiple elevations, including pylon tops, deck levels, and temporary platforms beneath the superstructure. This vertical stacking led to scenarios where work conducted at higher levels inherently created risks, such as falling objects or tools, for personnel working below, demanding stringent vertical separation and protection measures.
3. **Horizontal and Maritime SIMOPS:** A continuous flow of marine vessels supplying materials operated in the same maritime space as crane activities, often passing directly beneath or in close proximity to lifting zones and temporary platforms. This resulted in horizontal spatial conflicts between marine logistics and structural erection operations.
4. **Schedule Volatility and Weather-Induced SIMOPS:** The exposed maritime location made the construction schedule highly susceptible to variability. Frequent adjustments due to changing wind, wave, and weather conditions often compressed tasks or caused unexpected rescheduling, leading to unplanned and potentially hazardous overlaps between activities that were initially sequenced separately.

Collectively, these factors established a complex web of interdependent tasks operating within a dynamic and constrained environment. In the absence of real-time situational awareness and robust cooperative protocols, this complexity created significant vulnerabilities: personnel could inadvertently enter hazardous zones, unrelated tasks could collide with unsafe consequences, and management could struggle to maintain an accurate, integrated overview of all concurrent activities, thereby increasing the potential for safety incidents.

### 5.1.3 HAZARD IDENTIFICATION (HAZID)

A systematic Hazard Identification (HAZID) study was conducted to identify and evaluate the principal dangers associated with Simultaneous Operations (SIMOPS) during the construction of the Pelješac Bridge. This structured assessment, aligned with established risk management methodologies, revealed a series of recurrent high-risk scenarios intrinsically linked to task overlap within the project's constrained spatial and temporal parameters.

The analysis identified several critical hazard themes. A predominant risk involved load drops during crane operations, particularly during the lifting of heavy prefabricated segments while other teams were concurrently active on or beneath the deck. Contributory factors to this hazard included deficiencies in real-time coordination, the inadvertent intrusion of personnel into dynamically changing lifting zones, and sudden variations in wind conditions. The reliance on verbal communication and static, paper-based diagrams for disseminating spatial information often resulted in ambiguous or outdated awareness of active exclusion zones, thereby increasing the likelihood of positional conflicts.

Furthermore, SIMOPS introduced significant maritime interface risks. Conflicts between marine vessels and crane operations occurred when supply boats navigated beneath or in close proximity to active lifting areas. These operations were predominantly coordinated via radio communication, rendering them vulnerable to miscommunication, signal failure, or procedural non-compliance. Any breakdown in this coordination could precipitate collision incidents or result in loads being dropped onto vessels, with severe consequences for personnel safety, structural integrity, and marine environment.

To formalise and synthesise these findings, a systematic HAZID process was employed to catalogue risks stemming from concurrent operations. The outcomes are summarised in Table 5.1, which delineates the primary SIMOPS scenarios, their underlying causes, potential effects, and the existing mitigation measures in place during the project.

## TABLE 5.2 – HAZID FOR PELJEŠAC BRIDGE SIMOPS SITUATIONS

Scenario	Hazard	Causes	Consequences	Existing Controls	BIM Opportunities
<b>Crane lifting + rebar installation</b>	Falling load	Poor coordination, wind gusts, schedule overlap	Fatality, structural damage	Lift plan, radio comms	4D clash detection, real-time alerts
<b>Concrete pouring + formwork adjustment</b>	Formwork collapse	Early removal, timing conflicts	Worker injury, delays	PTW, supervision	BIM-linked curing time data
<b>Work at height + workers below</b>	Falling objects	Tools/material unsecured	Serious injury	Safety nets, PPE	Live hazard zones on tablets
<b>Marine vessel supply + crane ops</b>	Vessel-crane collision	Miscommunication	Equipment damage, drowning	Marine procedures	BIM logistics mapping
<b>Cable installation + deck welding</b>	Fire hazard	Hot works near flammable materials	Burns, fire	PTW	BIM proximity rules

Table 1 -Hazid for Peljesac bridge

### 5.3 BOW-TIE ANALYSIS

To better understand how accidents can unfold when tasks overlap, a Bow-Tie analysis was conducted for the most serious risk identified earlier: a load being dropped while lifting heavy deck segments. This scenario was chosen not only because of its potentially fatal consequences but also because it was a familiar and recurring challenge on the Pelješac Bridge site, where changing winds and tight schedules made such events more likely.

The Bow-Tie diagram helped map out the various ways this accident could happen. On one side, it showed the everyday threats that could trigger the event:

- Plans that didn't fully account for how tasks overlapped in time and space.
- Crane lifts scheduled in the same area where other crews were working.
- Communication gaps between the crane operator and the ground team.
- Sudden wind gusts that could swing a load unexpectedly.
- A worker accidentally walking into a restricted lifting zone because they weren't aware it was active.

Many of these threats stemmed from a simple but critical problem: no one had a clear, real-time picture of what was happening where. Teams relied on paper plans, radio calls, and memory, tools that couldn't keep up with the fast-changing reality of the site.

The existing safety measures, detailed lift plans, pre-work meetings, and paper permits, were all managed by people doing their best under pressure. While these steps are essential, they leave room for human error: a missed detail in a plan, a misunderstood radio message, or a permit that wasn't updated after a schedule change.

If these preventive measures failed, the consequences could be severe:

- Loss of life or life-changing injury.
- Major damage to the bridge or equipment.
- Projects delays affecting everyone on site.
- Legal and reputational fallout for the companies involved.

Emergency procedures and rescue plans were in place to respond, but these are, by nature, actions taken *after* something has gone wrong.

The Bow-Tie analysis also pointed toward solutions. It showed that a BIM-based safety system could support, not replace, the people on site by providing tools that address the root causes of these risks:

- **Visual Lift Planning:** A 4D BIM model could show the crane team *and* the welding crew how their tasks overlap in time and space *before* work begins, making the plan easier to understand and follow.
- **Live Zone Alerts:** If a worker with a site badge stepped into a restricted area, the system could alert them immediately, and notify their supervisor, preventing a dangerous situation before it happened.
- **Weather-Aware Notifications:** Real-time wind data integrated into the BIM platform could automatically warn the crane operator when conditions become unsafe, supporting better real-time decision-making.
- **Smarter Permits:** A digital permit system linked to the BIM model could flag conflicts automatically, like approving a welding job directly under a planned lift, before the permit is signed.

In short, the Bow-Tie analysis reveals that many risks arise from gaps in information and awareness, gaps that affect real people making real-time decisions. A well-designed BIM system can fill those gaps, not by removing human judgment, but by giving teams the clear, current information they need to work safely together.

## Bow-Tie Breakdown Sequence

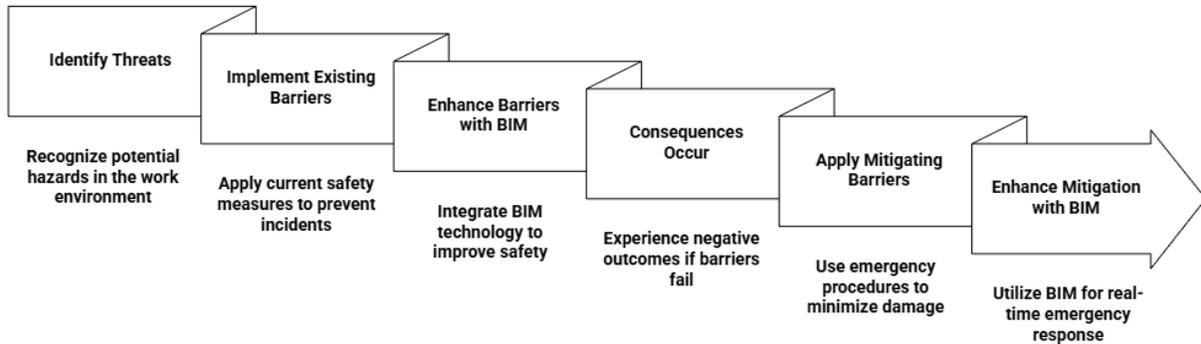


Figure 3 – bow tie sequence

Figure 3 outlines the entire process from spotting risks to taking steps to reduce them, emphasizing how BIM can enhance proactive and responsive safety strategies. The journey starts with the detection of risks and the acknowledgment of possible dangers in the workplace. Subsequently, current safety measures, including Permit-to-Work protocols, oversight, and lifting strategies, are put in place to avert these risks from causing an accident.

### 5.4 FAULT TREE ANALYSIS (FTA)

To better understand the chain of events that could lead to a major accident, a Fault Tree Analysis (FTA) was conducted for the most serious scenario identified earlier: a load dropping from a crane and striking a worker during a deck segment lift. This event was chosen because it represents the highest level of danger, where human life is at risk, and because it is a realistic possibility in the complex, overlapping work environment of the Pelješac Bridge.

The FTA shows that this tragic event doesn't happen by chance. It only occurs when two things go wrong at the same time:

1. The load being lifted falls, *and*
2. A worker is in the wrong place at the wrong time.

This “AND” relationship sits at the top of the fault tree and reveals a crucial insight: accidents in SIMOPS are rarely caused by a single failure. Instead, they happen when multiple smaller problems, often in different parts of the system, line up.

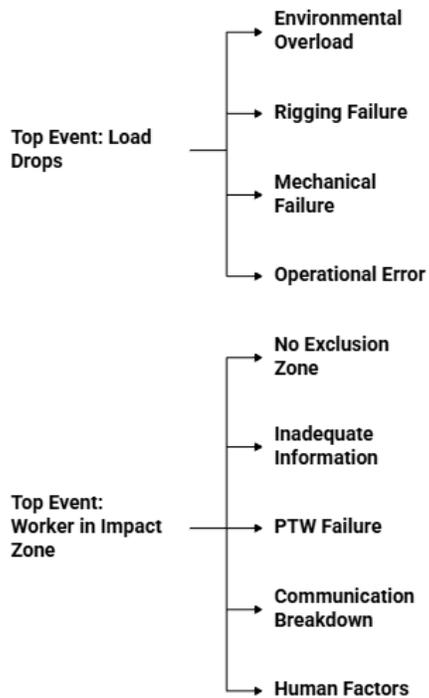


Figure 4 – FTA model

#### Why a load might fall

The first branch of the tree breaks down the reasons a crane load could drop:

- Environmental factors, like a sudden gust of wind stronger than the crane’s safe limit.
- Equipment issues, such as worn rigging, a mechanical failure in the crane, or using the wrong sling for the load.
- Human or procedural errors, like the operator lifting outside the safe working radius, a miscommunication during the lift, or a missed inspection.

These are connected by “OR” gates in the fault tree, meaning that *any one* of these problems could be enough to cause the load to fall.

#### Why a worker might be in the danger zone

The second branch examines why someone could be in harm’s way during a lift:

- Unclear or missing boundaries, if the lifting zone isn’t clearly marked or physically blocked, a worker might not realize they’re entering a danger area.
- Outdated or confusing information, if schedules change but aren’t communicated clearly, teams might not know a lift is happening nearby.

- Breakdowns in communication or procedure, if a permit wasn't checked, a safety briefing was rushed, or radios weren't working, people can be left unaware.
- Human factors, even with good procedures, distraction, fatigue, or taking a shortcut can put someone at risk.

These are also linked by “OR” gate, just one communication gap or procedural slip can place someone in danger.

A clear pattern emerges

Looking across both branches, a common theme stands out: many of these failures happen because people don't have a clear, real-time picture of what's happening on site. Information is delayed, visual cues are missing, and teams are often working with different understandings of the plan. This lack of shared situational awareness is a core vulnerability in fast-moving, multi-team environments like bridge construction.

How BIM can help break the chain

A BIM-based safety system is designed to address exactly these kinds of informational and awareness gaps.

It can help prevent accidents by:

- Making hazards visible, showing real-time exclusion zones on a tablet or display so everyone can see where it's unsafe to go.
- Simulating lifts before they happen, using 4D models to walk through crane movements and identify conflicts during planning.
- Linking permits to live schedules, automatically flagging if a permit is issued for work that conflicts with a lift already in the plan.
- Sending smart alerts, warning crane operators when wind speeds rise, or alerting workers if they approach an active lifting zone.

In essence, the FTA shows us that preventing a serious SIMOPS incident means preventing multiple small failures from lining up. BIM offers a way to do that, not by adding more rules, but by giving everyone on site the clear, current, and visual information they need to make safer choices together.

## 5.5 FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

To build on the insights from the Bow-Tie and Fault Tree analyses, a Failure Mode and Effects Analysis (FMEA) was conducted. This method provides a structured way to evaluate specific things that could go

wrong during SIMOPS, not just what they are, but how serious they are, how likely they are to happen, and how hard they are to notice before it's too late.

The FMEA uses a simple scoring system to help prioritize risks:

- Severity (S): How bad would the outcome be? Scored from 1 (minor) to 10 (catastrophic, such as loss of life).
- Occurrence (O): How likely is this to happen? Scored from 1 (very unlikely) to 10 (almost certain).
- Detection (D): How easy is it to spot this problem before it causes harm? Scored from 1 (easy to detect) to 10 (very hard to detect).

These three scores are multiplied to give a Risk Priority Number (RPN). A higher RPN means a risk is more urgent, it's serious, likely, and hard to catch.

The FMEA helps move from general risk awareness to targeted action. It tells us not just *that* something is dangerous, but *why* it's dangerous and where to focus our safety improvements. In this case, the analysis highlights which SIMOPS failure modes would benefit most from digital tools like BIM.

One of the highest-risk scenarios identified was workers entering an active crane lifting zone during deck segment installation. This situation scored high in Severity because it could easily lead to a fatality. It also scored high in Occurrence because, on a busy site with overlapping tasks, people can easily lose track of where lifts are happening. Most importantly, it scored high in Detection, meaning under current manual systems, it's very hard to notice someone in the danger zone until it's too late.

This combination, high severity, likelihood, and poor detectability, makes it a critical priority for intervention. It's exactly the kind of risk where better information and real-time awareness could make a life-saving difference.

#	Process / SIMOPS Situation	Failure Mode	Effect	S	O	D	RPN	BIM-Based Action / Control
1	Deck segment lifting with simultaneous rebar work	Worker enters crane impact zone	Worker hit by falling load → fatality	10	6	6	360	Visual exclusion zones in BIM, 4D lift simulation, automatic alert when tasks overlap, BIM-linked PTW blocking conflicting work
2	Concrete pouring + formwork adjustment in adjacent segment	Formwork removed too early	Local collapse, worker injury, rework	8	5	5	200	BIM object parameters for curing time, PTW dependence on curing status, 4D sequencing to prevent early removal
3	Work at height above temporary platforms	Tools or materials not secured	Falling objects injuring workers below	8	6	5	240	Highlight vertical SIMOPS in BIM, mark drop zones, alerts when tasks scheduled above occupied platforms, safety briefings supported by 3D views
4	Marine vessel passing under active crane	Poor coordination of timing and route	Collision with crane or dropped load on vessel	7	4	6	168	BIM-based marine traffic corridors, integration of vessel routes into 4D model, dashboard showing “no-go windows” for vessels during lifts
5	Hot works near cable installation	Heat or sparks ignite nearby material	Local fire, burns, cable damage	7	3	6	126	BIM “hot work” zones with proximity rules, automatic clash check between hot-work tasks and sensitive components, BIM-supported PTW for hot works
6	Schedule changes not reflected in safety planning	Updated tasks overlap in same zone	Unexpected SIMOPS, all hazard levels increase	9	5	7	315	Live link between schedule (4D) and safety model, automatic re-check of conflicts after every update, notifications to supervisors

Table 2 – FMEA

The FMEA clearly highlights where attention is most needed. The highest-risk failure modes, those with the largest Risk Priority Numbers, are not necessarily the most technically complex, but they are the most *human* and *organizational* in nature:

1. Personnel entering crane impact zones during lifts (RPN ~360)
2. Unplanned schedule changes leading to unexpected SIMOPS (RPN ~315)
3. Objects falling from height (RPN ~240)

What these three have in common is that they are deeply connected to communication, awareness, and coordination, not just equipment failure. When schedules change without warning, when zones aren't clearly marked or understood, or when teams aren't fully aware of what's happening around them, risk increases dramatically.

A key insight from the FMEA is that detectability plays a major role. Many of these risks are hard to spot with traditional methods, like paper schedules, static signs, or radio calls. By the time someone notices a problem, it may already be too late.

This is where BIM can make a tangible difference. By integrating real-time data and visual tools, a BIM-based safety system can help *see* problems before they become incidents:

- Digital alerts can notify supervisors when someone approaches a restricted zone.
- 4D visualizations can show schedule conflicts *before* work begins.
- Live zone mapping can make hazardous areas clearly visible to everyone on site.
- Integrated permits can automatically flag unsafe overlaps.
- Automatic risk reassessment can occur whenever the schedule changes, keeping safety planning aligned with reality.

In short, the FMEA reinforces what the earlier HAZID and Bow-Tie analyses revealed: the greatest danger in SIMOPS is not the work itself, but the gap in shared understanding between teams working in the same space and time. BIM offers a way to close that gap, not by replacing human judgment, but by giving teams the clear, current information they need to work safely together. When people can *see* the plan, *see* the hazards, and *see* each other in real time, they can make better decisions, and that is how serious risks are reduced

## 5.6 SUB-CONCLUSION

The Pelješac Bridge case study shows us that the most serious risks during simultaneous operations don't come from broken equipment or flawed designs, they come from gaps in communication, awareness, and coordination among the people doing the work. Whether it's a major crane lift, work at height, or marine logistics, the danger increases when teams lose sight of what others are doing around them.

Through systematic analysis, using HAZID, Bow-Tie, FTA, and FMEA, we see a consistent pattern: incidents are often preceded by a breakdown in real-time awareness. Schedules change, but not everyone gets the update. Zones are marked on paper, but not visible in the field. Permits are approved, but without checking for conflicts with other active tasks. These are human and organizational challenges, not purely technical ones.

Traditional safety systems, built on paperwork, signs, and meetings, struggle to keep pace with the speed and complexity of modern bridge construction. They rely heavily on memory, vigilance, and flawless communication, things that are difficult to sustain in a dynamic, multi-team environment.

This is where Building Information Modeling (BIM) offers a meaningful shift. A well-integrated BIM safety framework doesn't replace people or procedures, it supports them. By providing:

- Visual, real-time awareness of who is working where and when,
- Automated checks that flag conflicts before permits are approved,
- Live alerts that warn teams of changing conditions or unsafe proximity,

BIM helps close the information gaps that so often lead to accidents. It turns safety from a reactive checklist into a proactive, shared understanding.

In short, the Pelješac Bridge experience underscores a clear need: in complex, fast-moving projects, safety must be seen, shared, and supported in real time. Digital tools like BIM are not just optional upgrades, they are becoming essential partners in building smarter, safer, and more connected construction sites.

## 6 GREAT BELT BRIDGE- DENMARK

### 6.1 PROJECT OVERVIEW

This case study examines the construction of the Great Belt Bridge in Denmark, a landmark project built between 1988 and 1998 (VisitDenmark, 2025). It serves as a historical example of the safety challenges inherent in large-scale bridge construction, particularly those arising from Simultaneous Operations (SIMOPS). The project involved extensive marine work, heavy lifting, and complex assembly at significant

heights, demanding careful coordination among multiple contractors who often worked side-by-side in overlapping zones.

Tragically, the construction was marked by serious safety incidents, including at least seven fatalities (Metalindustrien.dk, 2019). These events underscore the high level of risk present in projects of this magnitude and reveal limitations in the safety and coordination methods available at the time. Looking back, this case helps us understand why a more integrated, real-time approach to safety management, one possible today with digital tools like BIM, could have provided critical support to the teams on the ground. This analysis focuses specifically on the construction phase, covering activities such as cable installation, pylon erection, deck assembly, heavy lifting, formwork, marine logistics, and temporary works. It does not address operation, maintenance, or design-related stages. The work involved a diverse group of stakeholders: crane operators, marine crews, steel and cable installation teams, supervisors, safety officers, surveyors, and planning engineers, all of whom played a role in managing the complex, overlapping tasks that defined the project.

By revisiting this historical project through a modern lens, we can explore how a BIM-based safety framework might have provided real-time, task-specific safety information, helping to identify and reduce risky interactions during SIMOPS. This reflection is not about criticizing past practices, but about learning from them to improve how we support people's safety in today's construction environments.

## 6.2 HAZID – SIMOPS HAZARDS

The construction of the Great Belt Bridge was one of Europe's most complex infrastructure projects of its time. Work occurred simultaneously on land, at sea, and at great heights, making Simultaneous Operations (SIMOPS) not just likely, but unavoidable. Teams often worked in overlapping zones, and even small changes in schedule, weather, or logistics could shift how tasks interacted. The sheer scale of the site, from the tops of the pylons to the deck above the water and vessels below, added layers of spatial and operational complexity.

This analysis applies modern risk assessment principles, guided by ISO 31000's emphasis on systematic, proactive hazard identification (*ISO 31000*, 2018). Methods like HAZID, Bow-Tie, and FTA, aligned with (*ISO 31010:2019*, 2019) are used here to retrospectively examine the project's challenges. Many of these challenges relate directly to requirements in (*ISO 45001*, 2018), particularly concerning coordination, communication, and hazard control on multi-contractor sites.

### Vertical SIMOPS

Working at different elevations was especially hazardous. Pylon assembly and cable installation took place directly above teams working on the deck. This meant that tools, materials, or equipment could fall from one level to another, and cranes often operated both above and below work platforms. Escape routes were limited, worsening any emergency. Communication between levels was difficult, teams couldn't see each

other and relied on radios and incomplete updates. Without a real-time overview of who was where, unintended interactions were hard to avoid.

#### Maritime SIMOPS

Marine operations were vital to the project's logistics. Supply vessels regularly passed beneath the bridge deck, often directly below active crane lifts. This created horizontal SIMOPS where vessel routes and lifting zones intersected. Strong currents, poor visibility in fog or at night, and even minor navigation errors increased the risk of collision or near-misses. Radio communication was the primary coordination tool, but delays or misunderstandings could easily lead a vessel into a restricted zone.

#### Heavy Lift and Assembly SIMOPS

Lifting massive deck segments and steel structures was a critical, high-risk activity that often occurred alongside welding, bolting, and fitting work. These tasks created tight spatial and temporal conflicts. Even a small delay or change in one team's progress could ripple into another team's work area. Coordination relied on paper drawings, physical markings, and radios, tools that couldn't reflect real-time changes, making it difficult to spot conflicts as they developed.

#### Weather-Related SIMOPS

The exposed marine location meant weather was a constant factor. High winds could suddenly exceed safe lifting limits, fog reduced visibility for crane operators and vessel pilots, and ice in colder months made surfaces treacherous. Weather changes often forced work to stop and restart abruptly, compressing tasks and increasing the likelihood of unplanned overlaps just as teams rushed to resume.

#### Fragmented Communication and Lack of Real-Time Awareness

During the Great Belt Bridge's construction, digital tools like BIM did not yet exist (Revati Patil, 2024). Information flowed through radios, paper plans, meetings, and word of mouth. This often led to outdated, inconsistent, or incomplete information across teams. Supervisors and safety personnel struggled to maintain a clear, unified picture of all ongoing activities, especially with multiple contractors operating at once.

The 1991 caisson incident, where a work platform collapsed (Metalindustrien.dk, 2019), illustrates how simultaneous activities, limited oversight, and changing marine conditions could combine with severe consequences. While SIMOPS were not the sole cause, this event underscores how a lack of integrated, real-time awareness can allow risks to escalate unseen. Today, tools like BIM-based zone monitoring, live weather integration, and automated conflict alerts could help identify such developing hazards earlier.

Table 3 summarizes the key SIMOPS-related hazards identified during the construction phase, detailing their causes, potential consequences, and the controls available at the time.

<b>Hazard</b>	<b>Causes</b>	<b>Potential Consequences</b>	<b>Existing Controls</b>	<b>SIMOPS Relevance</b>	<b>BIM Opportunities</b>
<b>1. Dropped load during lifting operations</b>	<ul style="list-style-type: none"> <li>• Sudden wind gusts</li> <li>• Rigging failure (worn wires, incorrect assembly)</li> <li>• Crane mechanical issues</li> <li>• Miscommunication</li> <li>• Workers entering lifting zone</li> </ul>	<ul style="list-style-type: none"> <li>• Fatality or severe injury</li> <li>• Damage to deck, pylons, temporary works</li> <li>• Impact on vessels below</li> <li>• Environmental spill</li> <li>• Delays, cost overruns, legal impact</li> </ul>	<ul style="list-style-type: none"> <li>• Manual rigging inspection</li> <li>• Wind limits for lifting</li> <li>• Permit-to-Work</li> <li>• Exclusion zones</li> <li>• Radio communication procedures</li> </ul>	Lifting occurred directly above and near deck works, platforms, and marine logistics: high potential for overlap	<ul style="list-style-type: none"> <li>• 4D lifting simulation</li> <li>• Real time zone monitoring</li> <li>• Automatic alerts for workers entering zones</li> <li>• Integrated weather data</li> <li>• Digital PTW</li> </ul>
<b>2. Falling objects during vertical SIMOPS</b>	<ul style="list-style-type: none"> <li>• Work at multiple heights</li> <li>• Poor tool securing</li> <li>• Cranes moving above active platforms</li> <li>• Limited visibility between teams</li> </ul>	<ul style="list-style-type: none"> <li>• Injuries / fatality</li> <li>• Damage to structures or platforms</li> <li>• Work stop</li> </ul>	<ul style="list-style-type: none"> <li>• PPE (helmets)</li> <li>• Tool lanyards</li> <li>• Physical barriers</li> <li>• Level separation when possible</li> </ul>	Pylon crews worked directly above deck teams: vertical interaction risk	<ul style="list-style-type: none"> <li>• 3D vertical zone mapping</li> <li>• Real time worker location tracking</li> <li>• Alerts when stacked work zones overlap</li> </ul>
<b>3. Vessel crane interaction (maritime SIMOPS)</b>	<ul style="list-style-type: none"> <li>• Strong currents and waves</li> <li>• Fog and low visibility</li> <li>• Miscommunication between vessels and crane operators</li> </ul>	<ul style="list-style-type: none"> <li>• Collision with structure or crane</li> <li>• Dropped load onto vessel</li> <li>• Crew injury</li> <li>• Environmental contamination</li> </ul>	<ul style="list-style-type: none"> <li>• Marine radio protocols</li> <li>• Marked navigation channels</li> <li>• Marine coordination team</li> </ul>	Vessel routes passed under crane lifting zones: horizontal SIMOPS overlap	<ul style="list-style-type: none"> <li>• AIS vessel tracking integrated with BIM</li> <li>• Automated entry into zone alarms</li> <li>• Weather and current prediction overlays</li> </ul>

<b>4. Spatial and temporal conflicts during heavy assembly</b>	<ul style="list-style-type: none"> <li>• Multiple teams working close together</li> <li>• Outdated schedule information</li> <li>• Manual coordination delays</li> <li>• Unexpected workflow changes</li> </ul>	<ul style="list-style-type: none"> <li>• Workers entering unsafe zones</li> <li>• Equipment collisions</li> <li>• Rework and delays</li> </ul>	<ul style="list-style-type: none"> <li>• Paper drawings</li> <li>• Toolbox talks</li> <li>• Supervisor coordination</li> </ul>	Assembly tasks overlapped with welding, bolt tensioning, lifting: time and space conflicts	<ul style="list-style-type: none"> <li>• 4D sequencing</li> <li>• Automatic conflict detection</li> <li>• Shared real-time schedule updates</li> </ul>
<b>5. Weather related operational instability</b>	<ul style="list-style-type: none"> <li>• Strong or shifting winds</li> <li>• Fog</li> <li>• Ice on platforms</li> <li>• Strong currents affecting vessels</li> </ul>	<ul style="list-style-type: none"> <li>• Swinging loads</li> <li>• Slip/fall accidents</li> <li>• Vessel instability</li> <li>• Emergency shutdowns</li> </ul>	<ul style="list-style-type: none"> <li>• Manual weather checks</li> <li>• Wind limits for cranes</li> <li>• Work stop procedures</li> </ul>	Weather affected all parallel work zones: unpredictable SIMOPS risk	<ul style="list-style-type: none"> <li>• Real-time weather integration</li> <li>• Automated stop-work alerts</li> <li>• Predictive modelling for planning</li> </ul>

Table 3 HAZID for Great Belt Bridge SIMOPS Hazards (developed by the author)

BIM was not available during the construction of the Great Belt Bridge, but looking back, many of the hazards identified could have been managed differently with today’s digital tools. For example:

- 4D simulations could have helped teams visualize how lifting operations, deck work, and marine traffic overlapped in time and space *before* stepping onto the site.
- Real-time zone monitoring might have alerted supervisors when vessels entered restricted areas or when teams worked too closely in vertical space.
- Integrated visual planning could have provided a shared, up-to-date picture of the work plan to all contractors, reducing reliance on memory, paper, and radio calls alone.

While we cannot change the past, we can learn from it. The following Bow-Tie and Fault Tree analyses will explore these opportunities in greater detail, showing how a BIM-supported safety framework could have provided an additional layer of awareness and prevention, helping people on site make safer choices in real time.

### 6.3 BOW-TIE ANALYSIS

One of the most significant risks during the construction of the Great Belt Bridge was the potential for a heavy load to fall during lifting operations, particularly when workers were present below, above, or nearby. Since large components were often lifted in close proximity to other ongoing tasks, on the deck, on temporary platforms, or at various heights, even minor shifts in schedule or workflow could create dangerous and unplanned overlaps. This scenario is well-suited for a Bow-Tie analysis, a method that helps clarify how various threats can lead to an incident and how barriers can prevent or mitigate harm.

In this analysis, the Bow-Tie model is used to reflect on how modern BIM-based safety tools might have strengthened both preventive and mitigative barriers. While BIM was not available at the time, this retrospective view helps us understand how digital tools could have supported the teams on site, providing clearer awareness and more responsive safety controls.

It is important to clarify that ISO standards such as 31000, 45001, and 31010 were published after the bridge was built. They are referenced here not to describe historical practice, but as a modern framework for understanding risk. During construction, safety relied on national regulations, contractor procedures, and industry standards. Using current ISO principles allows us to relate past challenges to contemporary risk management thinking and explore how BIM could enhance coordination in similar settings today.

#### Understanding the Top Event: Loss of Load

The event analyzed is loss of load during a lifting operation. This could occur due to a combination of factors:

- Technical issues: Worn rigging, incorrect assembly, or crane malfunction.
- Environmental factors: Sudden wind gusts, fog reducing visibility, or sea conditions affecting stability.
- Organizational and communication factors: Outdated lift plans, teams working in close quarters, schedule changes creating unplanned overlaps, or miscommunication between crane operators and ground crews.

In the dynamic environment of the bridge site, these factors often interacted in ways that were difficult to predict or control in real time.

#### Preventive Barriers in Historical Context

The preventive measures during construction were largely procedural and physical:

- Rigorous inspection of lifting equipment.
- Established rigging and lift procedures.

- Defined wind limits for safe crane operation.
- Physical marking or barricading of exclusion zones.
- Clear radio protocols and pre-lift briefings.

These barriers align with principles later formalized in ISO 31000 (systematic risk management) and ISO 45001 (controlled high-risk work), emphasizing structured processes and clear communication. ISO 31010 also recognizes Bow-Tie analysis as a suitable method for understanding how technical, environmental, and organizational factors can lead to an incident.

### How BIM Could Have Enhanced Prevention

If BIM had been available, many preventive steps could have been supported digitally:

- 4D simulations could have visualized lift sequences alongside other scheduled tasks, identifying conflicts during planning.
- Automated zone monitoring could have provided dynamic, visible boundaries, reducing reliance on static markings and verbal coordination.
- Integrated communication tools could have linked lift plans, permits, and live weather data, keeping all teams aligned.

Figure 5 below illustrates the Bow-Tie model for this scenario, showing how threats relate to the top event and where preventive barriers, both historical and BIM-enhanced, could intervene.

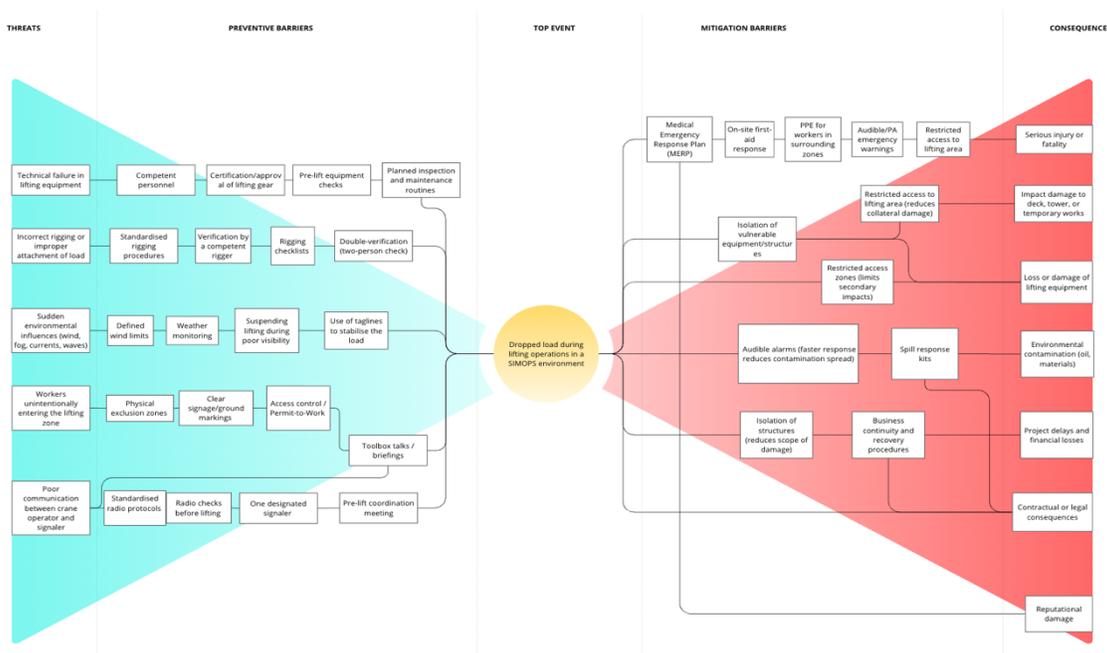


Figure 5 Bow-Tie model for dropped load during lifting operations - Developed by the author based on ISO 31010.

## **Vulnerabilities and Consequences**

Even with these controls, vulnerabilities remained. Many barriers relied on manual coordination, and changes in weather, schedules, or logistics could quickly make information outdated. Ensuring all teams had the same updated understanding of active zones and lift times was challenging, increasing the risk of someone unintentionally entering a hazard area.

If a load were dropped, the consequences could be severe:

- Serious injuries or fatalities.
- Damage to bridge components, equipment, or vessels.
- Environmental contamination from materials entering the water.
- Project delays, financial losses, legal issues, and reputational harm.

## **Mitigative Barriers and BIM's Role in Response**

Once an incident occurs, the focus shifts to mitigation, reducing harm and ensuring an effective emergency response. Historical mitigative measures included:

- Immediate first aid and use of PPE.
- Audible alarms and PA systems to evacuate areas.
- Isolating affected zones and equipment.
- Spill response kits and business continuity procedures.

These align with the emergency preparedness principles of ISO 45001.

BIM could have strengthened mitigation by providing:

- Real-time visualization of the site to support faster, safer evacuation.
- Automated alarms linked to spatial conflict detection.
- Digital logs to inform emergency teams about who was in the affected zone.
- Integrated data to help coordinate response and limit secondary impacts.

## **Conclusion: Learning for the Future**

The Bow-Tie analysis reveals that while the Great Belt Bridge project implemented robust safety practices for its time, many risks stemmed from gaps in real-time awareness and coordination, gaps that digital tools like BIM are designed to address. By providing a shared, visual, and up-to-date picture of the worksite, BIM could have helped prevent incidents by making hazards more visible and responses more coordinated.

This historical reflection underscores the value of integrating digital tools into safety management, not to replace human judgment, but to support it in creating safer, more connected work environments.

## 6.4 FAULT TREE ANALYSIS (FTA)

Building on the insights from the Bow-Tie analysis, this section uses a Fault Tree Analysis (FTA) to examine in greater detail how a dropped load during lifting operations could lead to serious injury or fatality. The FTA helps us trace the specific, often everyday, failures that, when combined, can result in a major incident. It moves beyond general risk categories to identify precise points where safety may break down, especially in a complex SIMOPS environment like the Great Belt Bridge.

The analysis starts from a simple but critical reality: for a person to be harmed by a falling load, two things must happen together:

1. The load must drop.
2. A worker must be in the hazard zone at that same moment.

This “AND” relationship sits at the top of the fault tree and reveals a fundamental truth about SIMOPS incidents: they are rarely caused by one error alone, but by the unfortunate alignment of multiple smaller failures.

### Why a Load Might Drop

The left branch of the fault tree explores the various reasons a load could become unstable and fall. These causes are connected by an “OR” gate, meaning that *any one* of them could be enough to cause the drop:

- Technical failures: Malfunction of crane components, brake failure, or structural weakness in lifting gear.
- Rigging or setup errors: Incorrect sling selection, improper load attachment, or unbalanced rigging.
- Environmental factors: Sudden wind gusts, wave-induced vessel movement, or poor visibility due to fog or rain.
- Planning or operational issues: Inadequate lift plan, miscommunication of load weight or dimensions, or pressure to work outside safe weather windows.

Each of these represents a point where procedures, checks, or conditions could fall short, sometimes due to oversight, sometimes due to unforeseen circumstances.

### Why a Worker Might Be in the Hazard Zone

The right branch examines why someone might be in harm’s way at the wrong time. These causes are also linked by an “OR” gate, any single gap in safety could place a person at risk:

- Inadequate physical controls: Missing or unclear barricades, unmarked exclusion zones, or removed signage.
- Planning and organizational failures: Outdated work schedules, uncoordinated task sequencing, or permit systems that don’t reflect real-time site status.
- Communication breakdowns: Radio failures, unclear instructions, or lack of situational updates between teams working at different levels or areas.
- Human and situational factors: Distraction, fatigue, taking a shortcut, or simply not being aware that a lift is happening nearby.

This side of the tree highlights how much safety depends on shared awareness and clear communication, elements that are challenging to maintain in a large, multi-contractor project.

#### Synthesizing the Fault Tree

Figure 5 illustrates the complete Fault Tree Analysis for a dropped load incident on the Great Belt Bridge.

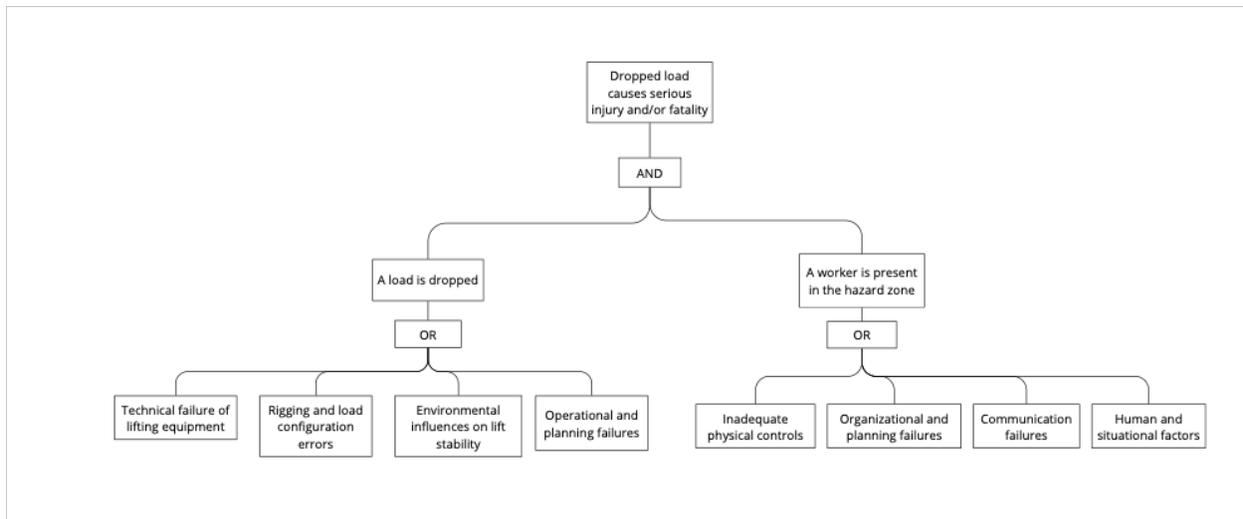


Figure 6 – Fault Tree Analysis for dropped load incident under SIMOPS conditions (developed by the author).

The fault tree analysis shown in figure 6, visually reinforces what the earlier HAZID and Bow-Tie analyses suggested: serious incidents arise from the combination of technical, environmental, organizational, and human factors. A single rigging error might not cause harm if no one is below. A worker in a hazardous zone might not be hurt if the lift proceeds safely. But when these conditions coincide, often due to fragmented information or delayed awareness, the risk of tragedy increases significantly.

## Reflection: The Role of Digital Tools in Disrupting Failure Chains

Looking back, it is clear that many of the failures mapped in this FTA stemmed from a lack of real-time, integrated information. Teams worked with different understandings of the plan, zones were static in a dynamic environment, and changes were communicated slowly.

A BIM-based safety system could help break these failure chains by:

- Providing a shared visual plan that shows lifts, zones, and schedules in one updated view.
- Enabling real-time alerts if environmental conditions change or if someone enters a restricted area.
- Linking permits and procedures directly to the digital model, so conflicts are flagged before work begins.
- Creating a digital record of decisions and changes, improving traceability and accountability.

In essence, the FTA shows us that preventing a serious SIMOPS incident means preventing multiple small problems from lining up. BIM offers a way to do that, not by adding more rules, but by giving everyone on site the clear, current information they need to make safer choices together. This historical reflection helps us appreciate how digital tools can support human judgment and coordination, making complex projects not only more efficient but fundamentally safer for the people who build them.

## 6.5 OVERALL FINDINGS FROM THE SIMOPS RISK ANALYSIS

The combined insights from the HAZID, Bow-Tie, and Fault Tree analyses reveal a consistent and important pattern: the most serious risks during the construction of the Great Belt Bridge did not come from any single source, but from the interaction of technical, environmental, and organizational factors. Activities were deeply interdependent, and even small changes in schedule, weather, or daily workflow could create unexpected and hazardous overlaps between teams and tasks.

The Bow-Tie analysis helped map out the pathways that could lead to a critical event, such as a dropped load, and highlighted the preventive barriers in place to stop it. It showed that safety relied heavily on procedures, communication, and physical controls, all of which required constant human vigilance and coordination.

The Fault Tree Analysis (FTA) took this a step further by illustrating how multiple smaller failures, a technical glitch, a communication gap, an outdated plan, could align at the same time to cause harm. It confirmed that serious incidents are rarely the result of one mistake, but rather the unfortunate coming together of several weaknesses across different parts of the project.

Together, these methods show that SIMOPS risks grow when information is fragmented, awareness is delayed, and teams operate without a shared, real-time understanding of the worksite. In a project as large and complex as the Great Belt Bridge, these challenges were magnified by the scale, the marine environment, and the number of contractors working side by side.

Although the Great Belt Bridge was built before digital tools like BIM were available, the vulnerabilities identified, unclear work zones, coordination breakdowns, and a lack of real-time situational awareness, remain relevant in today's construction industry. This historical analysis is not just about looking back; it's about understanding what still needs to be improved in how we manage safety in complex, multi-team environments.

These findings prepare the ground for the next important question: Could a BIM-supported safety framework have made a difference? By providing integrated visual planning, real-time data, and automated alerts, BIM offers a way to address the very gaps in awareness and coordination that were identified in this case. The following sections will explore this possibility in detail, comparing past challenges with modern digital solutions to build a clearer picture of how safety can be strengthened in future bridge projects.

## 7. RESULTS AND DISCUSSION

This chapter presents and discusses the findings from the analysis of the Pelješac Bridge and Great Belt Bridge construction projects. The aim is to assess how the identified SIMOPS risks, safety practices, and coordination challenges inform the development of a BIM-based safety framework, as outlined in the initial research problem. By comparing a contemporary project (Pelješac) with a historical one (Great Belt), this discussion provides a comprehensive perspective on both enduring challenges and emerging opportunities in bridge construction safety.

### 7.1 SIMOPS RISKS IN BRIDGE CONSTRUCTION

The examination of both bridge projects confirms that risks arising from simultaneous operations are not exceptional events, but inherent and recurring features of large-scale bridge construction. Despite differences in location, construction methods, and available technology, a consistent pattern emerges: incidents and near-misses typically result from the interaction of tasks, not from the tasks themselves.

In the Pelješac Bridge project, the highest risks occurred during heavy lifting, especially when installing large deck segments alongside rebar placement, welding, or work on temporary platforms. These overlapping activities created hazardous interactions both horizontally (between adjacent teams) and

vertically (where work above endangered those below). Marine logistics added further complexity, with supply vessels regularly navigating beneath active lifting zones. Analyses such as Bow-Tie and FTA illustrated how minor schedule adjustments, sudden wind changes, or vaguely defined work areas could rapidly escalate into high-risk SIMOPS situations.

A similar trend was evident in the Great Belt Bridge project. Although constructed before the widespread adoption of BIM and real-time digital tools, historical records reveal significant challenges in coordinating concurrent lifts, work at height, and deck assembly across multiple contractors. Coordination difficulties often arose not from a lack of risk awareness, but from reliance on experience, static drawings, and verbal communication, methods that struggle to keep pace with dynamic site conditions.

Together, these cases underscore that SIMOPS risks frequently emerge when interdependent tasks overlap in time and space, and when the information needed to coordinate them is not shared clearly, quickly, or visually. This highlights a pressing need for digital tools that can foster a real-time, shared understanding of ongoing operations among all site personnel.

## 7.2 BIM PARAMETERS ESSENTIAL FOR SAFETY

The findings indicate that an effective BIM-based safety framework must be built upon specific data parameters to adequately represent the complexities of SIMOPS scenarios. Key parameters include:

- Clearly defined spatial work zones and exclusion areas.
- Accurate equipment geometry and operational limits (e.g., crane working radii).
- Detailed vertical activity mapping to manage multi-level work.
- 4D scheduling data that integrates time with 3D geometry to visualize task overlaps.

In the Pelješac Bridge case, several hazardous situations resulted from insufficient real-time data. For example, workers were sometimes unaware that a lift had commenced, or teams adjusted formwork while concrete was still curing. These issues stemmed not from a lack of skill, but from gaps in communication and coordination, where teams relied on assumptions or outdated schedules in the absence of a centralized, live information source.

The Great Belt Bridge analysis reinforces this conclusion. Although tasks were carefully planned, the lack of an integrated digital model meant that teams depended on static documents, printed drawings and daily

briefings, that quickly became obsolete as conditions changed. This disconnect between plan and reality made it difficult to maintain situational awareness, increasing the likelihood of unintended SIMOPS conflicts.

### 7.3 COMMUNICATING REAL-TIME RISKS THROUGH HUMAN-CENTERED BIM TOOLS

Both case studies demonstrate that safety information must be communicated in ways that are intuitive, actionable, and accessible to all workers. Traditional methods, such as verbal briefings, radio updates, and 2D diagrams, are often inadequate in complex SIMOPS environments, where task locations and timings can change rapidly. When communication is unclear or delayed, situational awareness diminishes, raising the risk of hazardous overlaps.

On the Pelješac Bridge, this was evident when workers inadvertently entered crane exclusion zones or worked below active lifts. While supervisors understood the risks, this knowledge was not always conveyed to on-site personnel in a timely or easily understandable manner. A user-friendly digital platform, featuring color-coded hazard zones, real-time notifications, simplified 4D visuals, and mobile access, could have significantly improved workers' ability to recognize and avoid dangers. The Great Belt Bridge experience further supports this need. Without digital visualization tools, workers relied on memory, assumptions, and fragmented information, factors that increased the potential for error and unsafe decisions.

These examples emphasize the importance of human-centered design in BIM safety tools. When risk information is presented visually, consistently, and in real time, workers are better equipped to make informed choices in evolving environments. This approach not only enhances safety but also empowers personnel by making complex information more relatable and easier to act upon.

### 7.4 INTEGRATING BIM INTO EXISTING SAFETY PROCEDURES

The findings from both projects reveal significant limitations in conventional safety practices when applied to complex SIMOPS contexts. Essential systems such as Permit-to-Work (PTW), toolbox talks, and daily planning meetings are fundamental to construction safety, yet they often operate in isolation from real-time site conditions. As a result, they may not accurately reflect the fluid and interactive nature of ongoing operations.

For instance, PTW approvals were sometimes based on outdated schedules, leading to permits that did not match actual site activities. Toolbox talks often relied on verbal descriptions of hazards, which can be difficult to visualize in dynamic, three-dimensional settings. Daily coordination meetings frequently lacked

accurate, up-to-date information on the locations of equipment, teams, and concurrent tasks, limiting their effectiveness in preventing hazardous overlaps.

Integrating BIM into these established safety practices offers a powerful way to enhance their relevance and impact:

- A BIM-supported PTW system could automatically cross-reference permit requests with live 4D models to identify and prevent SIMOPS conflicts before approval.
- Toolbox talks could use visualizations or animations extracted directly from the BIM model to help workers clearly understand the day's hazards in their spatial context.
- Daily meetings could be conducted with an updated 4D timeline, ensuring that supervisors and teams share a common, accurate understanding of planned operations.

Furthermore, BIM enables continuous, precise documentation of safety-related updates, supporting regulatory compliance and improving traceability during audits or incident investigations. By linking traditional safety protocols to real-time digital data, BIM transforms them from static administrative tasks into dynamic, data-informed safety strategies that actively contribute to risk reduction.

## 8. CONCLUSION

This study has systematically investigated the development and potential of a BIM-based safety framework for managing simultaneous operations (SIMOPS) in bridge construction projects. Through in-depth analysis of two landmark case studies, the contemporary Pelješac Bridge and the historical Great Belt Bridge, this research has identified persistent safety challenges, evaluated the limitations of traditional safety systems, and demonstrated how digital integration can transform safety management from a reactive, document-driven process into a proactive, coordination-centered practice.

The findings reveal a consistent and critical insight: safety in SIMOPS is not merely a matter of compliance or equipment, but fundamentally a challenge of awareness, communication, and coordinated decision-making. Incidents in complex bridge projects rarely result from a single technical failure. Instead, they emerge from the convergence of organizational gaps, such as outdated schedules, unclear work zones, fragmented communication, and a lack of real-time situational awareness. Traditional safety tools, including paper-based permits, static 2D drawings, and verbal briefings, are poorly suited to the dynamic, multi-team environments where tasks overlap continuously in both time and space.

The proposed BIM-based safety framework directly addresses these systemic weaknesses by creating a shared digital environment where design intent, construction sequencing, safety controls, and live site data converge. Key outcomes from this research demonstrate that:

- BIM enables proactive risk visualization and planning. Through 4D simulations, dynamic hazard zoning, and automated clash detection, teams can foresee and mitigate spatial and temporal conflicts long before they reach the construction site.
- Digital integration strengthens established safety protocols. By embedding Permit-to-Work (PTW) systems, toolbox talks, and daily coordination meetings within the BIM environment, safety procedures become context-aware, adaptive, and intrinsically linked to real-time site conditions.
- Human-centered design ensures clarity and usability. Intuitive, role-specific interfaces, featuring color-coded zones, real-time alerts, and simplified visualizations, help workers and supervisors maintain situational awareness without cognitive overload, making complex safety information accessible and actionable.
- Regulatory alignment and traceability are enhanced. The framework supports and extends compliance with key standards such as ISO 45001, ISO 31000, ISO 19650, and EU Directive 92/57/EEC by ensuring consistent documentation, audit readiness, and a verifiable digital thread from planning to execution.

Importantly, this research also acknowledges practical limitations and implementation challenges. The framework focuses primarily on the construction phase, and its real-world adoption will require addressing issues of system interoperability, workforce digital literacy, organizational change management, and the cultural shift toward data-driven safety. These are not merely technical hurdles; they reflect the human and institutional dimensions of digital transformation in construction.

Looking forward, this study provides a compelling evidence-based case for repositioning BIM not only as a design and engineering tool but as a central platform for safety collaboration and risk governance. Future work should focus on:

- Pilot implementations to validate the framework under real project conditions.
- Integration of emerging technologies such as IoT sensors, wearable devices, and AI-driven predictive analytics to enhance real-time monitoring and proactive alerting.

- Development of industry-wide guidelines and standards for BIM-enabled safety management, fostering consistency and interoperability across projects and organizations.

In closing, this research affirms that safety in complex bridge construction is ultimately about people working together with clarity and foresight. A BIM-based safety framework does not replace human judgment, it empowers it. By providing a unified, visual, and real-time representation of the worksite, BIM helps teams see what was once invisible, coordinate what was once fragmented, and decide with confidence in high-stakes environments. In doing so, it supports a fundamental shift from reactive compliance to proactive care, building not only stronger bridges, but safer and more resilient construction cultures.

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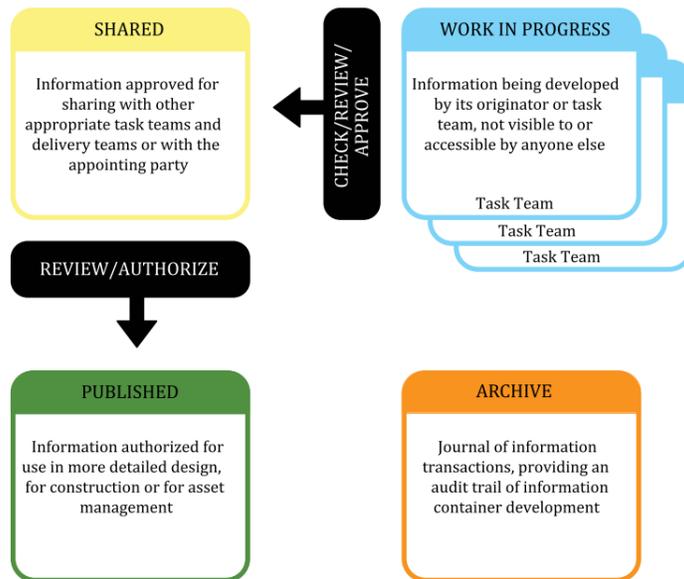
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## 10. ANNEX



Annex 1, DS/EN ISO 19650-1:2018. *Organisering og digitalisering af information om bygge- og anlægsarbejder, herunder BIM – Informationshåndtering med BIM – Del 1: Begreber og principper.* Dansk Standard (DS).

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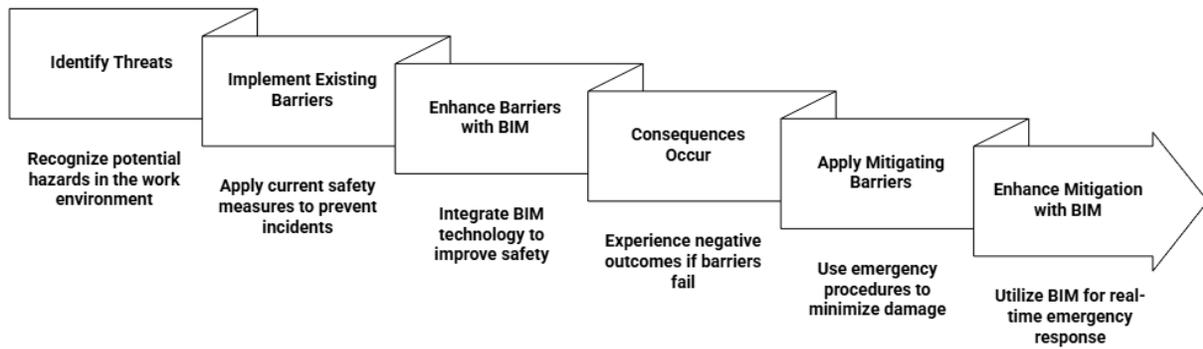


Annex 2 – Visual summary of the Bow-Tie model – developed by the author accordance with ISO 31010

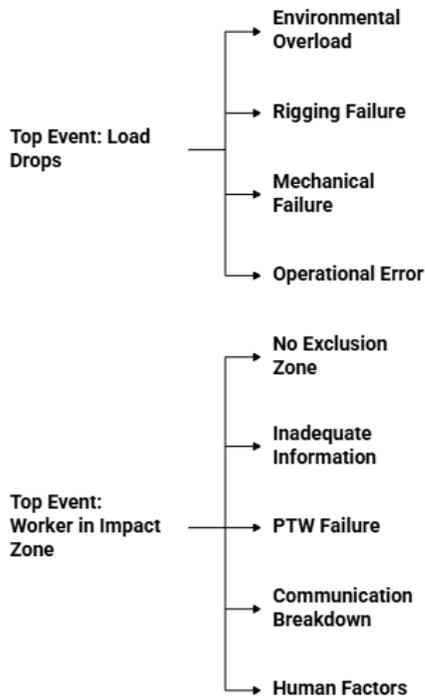
Scenario	Hazard	Causes	Consequences	Existing Controls	BIM Opportunities
<b>Crane lifting + rebar installation</b>	Falling load	Poor coordination, wind gusts, schedule overlap	Fatality, structural damage	Lift plan, radio comms	4D clash detection, real-time alerts
<b>Concrete pouring + formwork adjustment</b>	Formwork collapse	Early removal, timing conflicts	Worker injury, delays	PTW, supervision	BIM-linked curing time data
<b>Work at height + workers below</b>	Falling objects	Tools/material unsecured	Serious injury	Safety nets, PPE	Live hazard zones on tablets
<b>Marine vessel supply + crane ops</b>	Vessel-crane collision	Miscommunication	Equipment damage, drowning	Marine procedures	BIM logistics mapping
<b>Cable installation + deck welding</b>	Fire hazard	Hot works near flammable materials	Burns, fire	PTW	BIM proximity rules

Annex 3 -Hazid for Peljesac bridge – developed by the author

## Bow-Tie Breakdown Sequence



Annex 4 – bow tie sequence - developed by the author



Annex 5 – FTA model – developed by the author

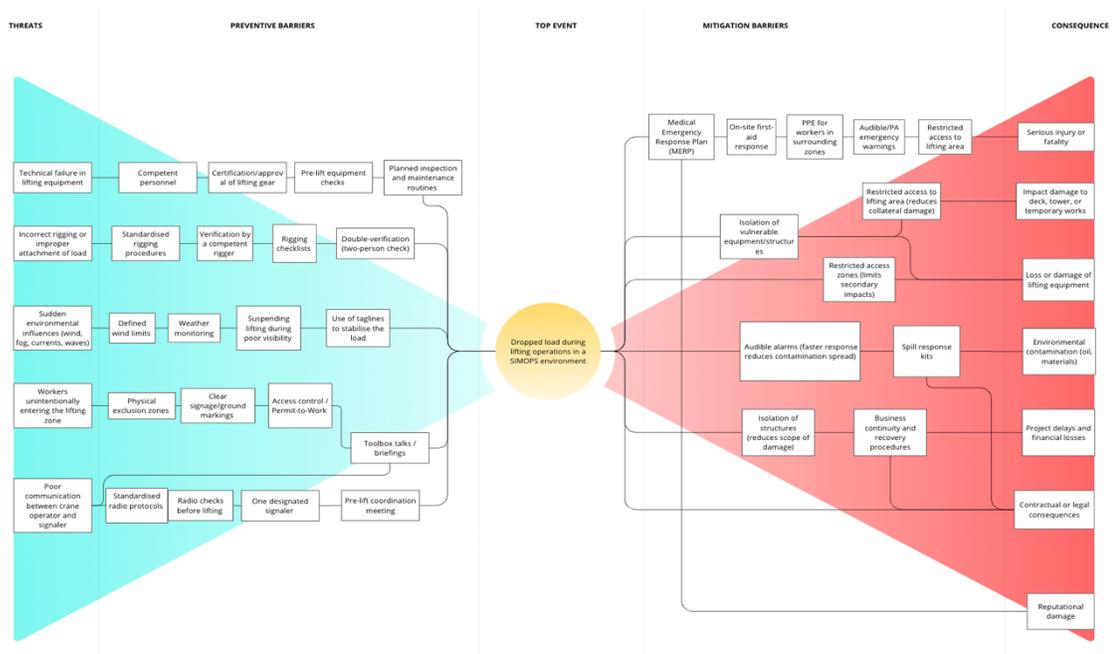
#	Process / SIMOPS Situation	Failure Mode	Effect	S	O	D	RPN	BIM-Based Action / Control
1	Deck segment lifting with simultaneous rebar work	Worker enters crane impact zone	Worker hit by falling load → fatality	10	6	6	360	Visual exclusion zones in BIM, 4D lift simulation, automatic alert when tasks overlap, BIM-linked PTW blocking conflicting work
2	Concrete pouring + formwork adjustment in adjacent segment	Formwork removed too early	Local collapse, worker injury, rework	8	5	5	200	BIM object parameters for curing time, PTW dependence on curing status, 4D sequencing to prevent early removal
3	Work at height above temporary platforms	Tools or materials not secured	Falling objects injuring workers below	8	6	5	240	Highlight vertical SIMOPS in BIM, mark drop zones, alerts when tasks scheduled above occupied platforms, safety briefings supported by 3D views
4	Marine vessel passing under active crane	Poor coordination of timing and route	Collision with crane or dropped load on vessel	7	4	6	168	BIM-based marine traffic corridors, integration of vessel routes into 4D model, dashboard showing “no-go windows” for vessels during lifts
5	Hot works near cable installation	Heat or sparks ignite nearby material	Local fire, burns, cable damage	7	3	6	126	BIM “hot work” zones with proximity rules, automatic clash check between hot-work tasks and sensitive components, BIM-supported PTW for hot works
6	Schedule changes not reflected in safety planning	Updated tasks overlap in same zone	Unexpected SIMOPS, all hazard levels increase	9	5	7	315	Live link between schedule (4D) and safety model, automatic re-check of conflicts after every update, notifications to supervisors

Annex 6 – FMEA – developed by the author

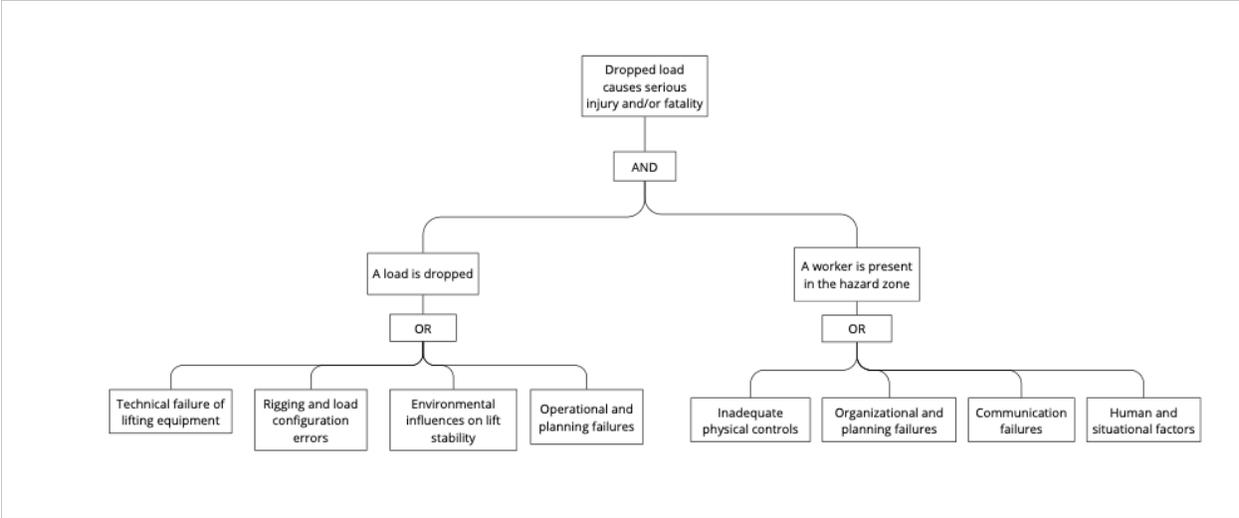
<b>Hazard</b>	<b>Causes</b>	<b>Potential Consequences</b>	<b>Existing Controls</b>	<b>SIMOPS Relevance</b>	<b>BIM Opportunities</b>
<b>1. Dropped load during lifting operations</b>	<ul style="list-style-type: none"> <li>• Sudden wind gusts</li> <li>• Rigging failure (worn wires, incorrect assembly)</li> <li>• Crane mechanical issues</li> <li>• Miscommunication</li> <li>• Workers entering lifting zone</li> </ul>	<ul style="list-style-type: none"> <li>• Fatality or severe injury</li> <li>• Damage to deck, pylons, temporary works</li> <li>• Impact on vessels below</li> <li>• Environmental spill</li> <li>• Delays, cost overruns, legal impact</li> </ul>	<ul style="list-style-type: none"> <li>• Manual rigging inspection</li> <li>• Wind limits for lifting</li> <li>• Permit-to-Work</li> <li>• Exclusion zones</li> <li>• Radio communication procedures</li> </ul>	Lifting occurred directly above and near deck works, platforms, and marine logistics: high potential for overlap	<ul style="list-style-type: none"> <li>• 4D lifting simulation</li> <li>• Real time zone monitoring</li> <li>• Automatic alerts for workers entering zones</li> <li>• Integrated weather data</li> <li>• Digital PTW</li> </ul>
<b>2. Falling objects during vertical SIMOPS</b>	<ul style="list-style-type: none"> <li>• Work at multiple heights</li> <li>• Poor tool securing</li> <li>• Cranes moving above active platforms</li> <li>• Limited visibility between teams</li> </ul>	<ul style="list-style-type: none"> <li>• Injuries / fatality</li> <li>• Damage to structures or platforms</li> <li>• Work stop</li> </ul>	<ul style="list-style-type: none"> <li>• PPE (helmets)</li> <li>• Tool lanyards</li> <li>• Physical barriers</li> <li>• Level separation when possible</li> </ul>	Pylon crews worked directly above deck teams: vertical interaction risk	<ul style="list-style-type: none"> <li>• 3D vertical zone mapping</li> <li>• Real time worker location tracking</li> <li>• Alerts when stacked work zones overlap</li> </ul>
<b>3. Vessel crane interaction (maritime SIMOPS)</b>	<ul style="list-style-type: none"> <li>• Strong currents and waves</li> <li>• Fog and low visibility</li> <li>• Miscommunication between vessels and crane operators</li> </ul>	<ul style="list-style-type: none"> <li>• Collision with structure or crane</li> <li>• Dropped load onto vessel</li> <li>• Crew injury</li> <li>• Environmental contamination</li> </ul>	<ul style="list-style-type: none"> <li>• Marine radio protocols</li> <li>• Marked navigation channels</li> <li>• Marine coordination team</li> </ul>	Vessel routes passed under crane lifting zones: horizontal SIMOPS overlap	<ul style="list-style-type: none"> <li>• AIS vessel tracking integrated with BIM</li> <li>• Automated entry into zone alarms</li> </ul>

					<ul style="list-style-type: none"> <li>• Weather and current prediction overlays</li> </ul>
<b>4. Spatial and temporal conflicts during heavy assembly</b>	<ul style="list-style-type: none"> <li>• Multiple teams working close together</li> <li>• Outdated schedule information</li> <li>• Manual coordination delays</li> <li>• Unexpected workflow changes</li> </ul>	<ul style="list-style-type: none"> <li>• Workers entering unsafe zones</li> <li>• Equipment collisions</li> <li>• Rework and delays</li> </ul>	<ul style="list-style-type: none"> <li>• Paper drawings</li> <li>• Toolbox talks</li> <li>• Supervisor coordination</li> </ul>	Assembly tasks overlapped with welding, bolt tensioning, lifting: time and space conflicts	<ul style="list-style-type: none"> <li>• 4D sequencing</li> <li>• Automatic conflict detection</li> <li>• Shared real-time schedule updates</li> </ul>
<b>5. Weather related operational instability</b>	<ul style="list-style-type: none"> <li>• Strong or shifting winds</li> <li>• Fog</li> <li>• Ice on platforms</li> <li>• Strong currents affecting vessels</li> </ul>	<ul style="list-style-type: none"> <li>• Swinging loads</li> <li>• Slip/fall accidents</li> <li>• Vessel instability</li> <li>• Emergency shutdowns</li> </ul>	<ul style="list-style-type: none"> <li>• Manual weather checks</li> <li>• Wind limits for cranes</li> <li>• Work stop procedures</li> </ul>	Weather affected all parallel work zones: unpredictable SIMOPS risk	<ul style="list-style-type: none"> <li>• Real-time weather integration</li> <li>• Automated stop-work alerts</li> <li>• Predictive modelling for planning</li> </ul>

Annex 7 - HAZID for Great Belt Bridge SIMOPS Hazards - developed by the author



Annex 8 - Bow-Tie model for dropped load during lifting operations - Developed by the author based on ISO 31010.



Annex 9 – Fault Tree Analysis for dropped load incident under SIMOPS conditions - developed by the author.