Constructability, Hazard Identification, and Process Simplification in Early-Stage Oil and Gas Facility Design: A Systematic Review of Engineering Practices and Safety Outcomes

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Abstract

Early-stage design decisions determine how oil and gas facilities are built and how much hazard they contain, yet the engineering practices that address these questions have developed in separate research communities. This systematic review examines three practice domains in early-stage facility design: constructability, hazard identification, and process simplification through inherently safer design. Following PRISMA 2020 guidance, records were identified through publisher platforms, scholarly search and backward citation chaining, and 301 peer-reviewed journal and conference articles published between 1978 and 2021 were included and coded by domain, sector, method and attention to safety outcomes. The evidence base is broadly evenly divided among the three domains but uneven in sector and method. Only 42 included studies address oil and gas facilities directly; constructability evidence comes almost entirely from building and industrial construction, and hazard identification and inherent safety evidence from chemical processing. Conceptual and methodological contributions dominate, computational methods are concentrated in hazard identification, and only 49 studies relate practices to measured accident, incident or performance outcomes. The review finds consistent evidence that design contributes to a large share of process and construction accidents, but weak evidence on the safety return of specific early-stage practices. An integration framework and a research agenda are proposed to connect the three domains through shared design data and outcome-linked evaluation.

Keywords: constructability; hazard identification; HAZOP; inherently safer design; process simplification; oil and gas facility design; systematic review

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1. Introduction

The safety performance of an oil and gas facility is shaped long before construction begins. Once the process scheme, equipment arrangement, inventories and construction strategy are fixed in front-end engineering, the hazards that operators will later manage are largely determined (Kletz & Amyotte, 2010), and investigations such as that of Piper Alpha (Paté-Cornell, 1993) have traced losses to such decisions. Design deficiencies contribute to many chemical process incidents (Kidam & Hurme, 2012; Kinnersley & Roelen, 2007) and construction fatalities (Behm, 2005), as root-cause analysis of major incidents shows (Okwesa et al., 2021).

Three groups of practice address these decisions. Constructability integrates construction knowledge into design (Construction Industry Institute, 1986; Kifokeris & Xenidis, 2017); hazard identification, through HAZID, HAZOP, What-If analysis and failure modes and effects analysis (FMEA), seeks the ways a design can fail (Dunjó et al., 2010); and process simplification, through inherently safer design, removes hazards at source (Kletz, 1978; Kletz & Amyotte, 2010). The three have developed in separate communities (Kifokeris & Xenidis, 2017; Single et al., 2019; Srinivasan & Natarajan, 2012).

The separation matters because the practices act on the same decisions: a modularization choice that eases construction can increase explosion consequences, and a late HAZOP can find problems that earlier simplification would have prevented (O'Connor et al., 2014; Tanabe & Miyake, 2013). Megaproject overruns are linked to weak front-end definition (Jergeas, 2008; Olaniran et al., 2015), and choices made at this stage carry commercial risks, as supply chain (Agbabiaka et al., 2019), procurement (Okonkwo et al., 2018) and infrastructure delivery (Nwafor et al., 2019) frameworks show.

This review asks: (1) what is the size and composition of the evidence base, and how much concerns oil and gas directly; (2) what methods have been used; (3) what the evidence shows about safety outcomes; and (4) what gaps prevent integration. It follows PRISMA 2020 (Page et al., 2021a, 2021b) and engineering review guidelines (Kitchenham & Charters, 2007; Kitchenham et al., 2009).

2. Background and Conceptual Framework

The review draws on systems views of safety (Leveson, 2011; Leveson & Stephanopoulos, 2014), on frameworks of human error causation in high-risk construction and industrial work (Obriki & Arumosoye, 2020), and on the life-cycle view that the opportunity to reduce hazards declines as design progresses (Hurme & Rahman, 2005).

2.1 Early-stage design in the oil and gas facility life cycle

Early-stage design runs from concept selection through front-end engineering, when the process scheme, equipment, layout and construction strategy are fixed (Jergeas, 2008; O'Connor et al., 2015). Oil and gas facilities combine remoteness, space constraints, high-pressure hydrocarbon inventories and modular fabrication (Cigolini & Castellano, 2002; Standards Norway, 2008). Frameworks for operational integrity in high-risk drilling (Nwangwu et al., 2018) and risk-based engineering of gas infrastructure (Asibor & Isong, 2019) show how design choices carry into operation (Animah & Shafiee, 2019).

2.2 Three practice domains

Constructability is the optimum use of construction knowledge in planning, engineering, procurement and field operations (Construction Industry Institute, 1986), and now includes modularization (Tatum et al., 1987), design for manufacture and assembly (Boothroyd, 1994) and early contractor involvement (Song et al., 2009). Hazard identification centres on HAZOP (Dunjó et al., 2010; IEC, 2016), supported by HAZID, SWIFT and layer of protection analysis (Card et al., 2012; Paltrinieri et al., 2013). Process simplification covers the simplification, minimization, substitution and moderation principles of inherently safer design, with process intensification as a means to them (Etchells, 2005; Hendershot, 1997; Kletz, 1996; Stankiewicz & Moulijn, 2000).

2.3 Linking early-stage practices to safety outcomes

Constructability and design for construction safety act mainly on hazards to construction workers, such as work at height and heavy lifts (Gambatese et al., 2005; Hinze & Wiegand, 1992; Obogo et al., 2020b). Hazard identification acts on the completeness with which hazards are recognized, and depends on team competence (Baybutt, 2003, 2015b). Process simplification acts on the magnitude of hazards themselves (Kletz, 1978, 2003). Measuring these effects requires outcome indicators, which remain contested (Hopkins, 2009; Swuste et al., 2016); near-miss data offer a complementary source (Arumosoye & Obriki, 2019).

3. Methods

The review followed the PRISMA 2020 statement and its elaboration (Page et al., 2021a, 2021b), which update the original statement (Moher et al., 2009), and the search extension PRISMA-S (Rethlefsen et al., 2021). Planning drew on systematic review guidelines (Kitchenham & Charters, 2007; Petticrew & Roberts, 2005), and searching was complemented by snowballing (Wohlin, 2014). Systematic reviews of hazard identification in urban construction (Obogo et al., 2019c), near-miss data in industrial safety management (Arumosoye & Obriki, 2019) and contractual resilience in energy supply chains (Uchechi et al., 2020) provided precedents.

3.1 Review questions and protocol

A protocol specifying the questions, domains, search sources, eligibility criteria and coding frame was prepared before searching (Kitchenham & Charters, 2007). The population was early-stage design of oil and gas, petrochemical, chemical process and industrial construction facilities; the interventions were the three practice domains; and the outcomes were safety performance and intermediate safety measures (Page et al., 2021a). Chemical process and construction studies were included because they hold most of the methodology applied to oil and gas (Kifokeris & Xenidis, 2017; Srinivasan & Natarajan, 2012).

3.2 Search strategy

The search was conducted in September 2021 and covered all years to that date. Records were identified through publisher platforms and scholarly search using the terms in Table 1, and through backward citation chaining (Rethlefsen et al., 2021; Wohlin, 2014). Searches were run separately for each domain and sub-topic so that smaller topics were not crowded out (Donthu et al., 2021), and each record was retained only after its bibliographic details had been verified (Page et al., 2021b).

Table 1. Search concepts used for each practice domain.

Domain	Practice terms	Context terms
Constructability and construction-stage design	constructability; constructability review; modularization; modular construction; prefabrication; preassembly; design for manufacture and assembly; early contractor involvement; interface management; design for construction safety; prevention through design	industrial project; process plant; oil and gas; megaproject; capital project; EPC
Hazard identification and safety outcomes	HAZID; HAZOP; What-If; SWIFT; FMEA; layer of protection analysis; process hazard analysis; automated or computer-aided HAZOP; accident causation; design error; incident database; process safety indicator	offshore; oil and gas; LNG; petrochemical; chemical process; early design
Process simplification and inherent safety	inherently safer design; inherent safety index; minimization; substitution; moderation; simplification; process intensification; unmanned or minimum facilities platform	conceptual design; preliminary design; offshore; oil and gas; process route selection

3.3 Eligibility criteria

Table 2 summarizes the eligibility criteria. Eligible studies were peer-reviewed articles that developed, applied, evaluated or reviewed a relevant early-stage practice, or analysed the contribution of design to accidents, in the included sectors (Dunjó et al., 2010; Kifokeris &

Xenidis, 2017). Books, standards, guidance, reports and methodology references were excluded from the synthesis but retained as context (Shea et al., 2017).

Table 2. Eligibility criteria.

Criterion	Included	Excluded from synthesis
Publication type	Peer-reviewed journal articles and conference papers	Books, standards, regulatory guidance and institutional reports (retained as context)
Topic	Constructability, hazard identification or process simplification relevant to early-stage design; design contribution to accidents and safety outcomes	Operational-phase practices with no design implication
Sector	Oil and gas, petrochemical, chemical process, industrial and building construction	Sectors without transferable design practice
Date	All years to September 2021	None
Verification	Bibliographic details confirmed	Records whose details could not be confirmed
Method references	Not applicable	Systematic review and bibliometric methodology references

3.4 Screening and selection

Figure 1 shows the flow of records. The searches and citation chaining identified 349 records; two duplicates were removed, leaving 347 records that were screened. Of these, 16 were review methodology references and 30 were books, standards or reports; these 46 records were excluded from the synthesis but are cited where they inform interpretation. The remaining 301 peer-reviewed articles were assessed for eligibility and all were included, because each record had been screened for topical relevance before it was recorded (Wohlin, 2014).

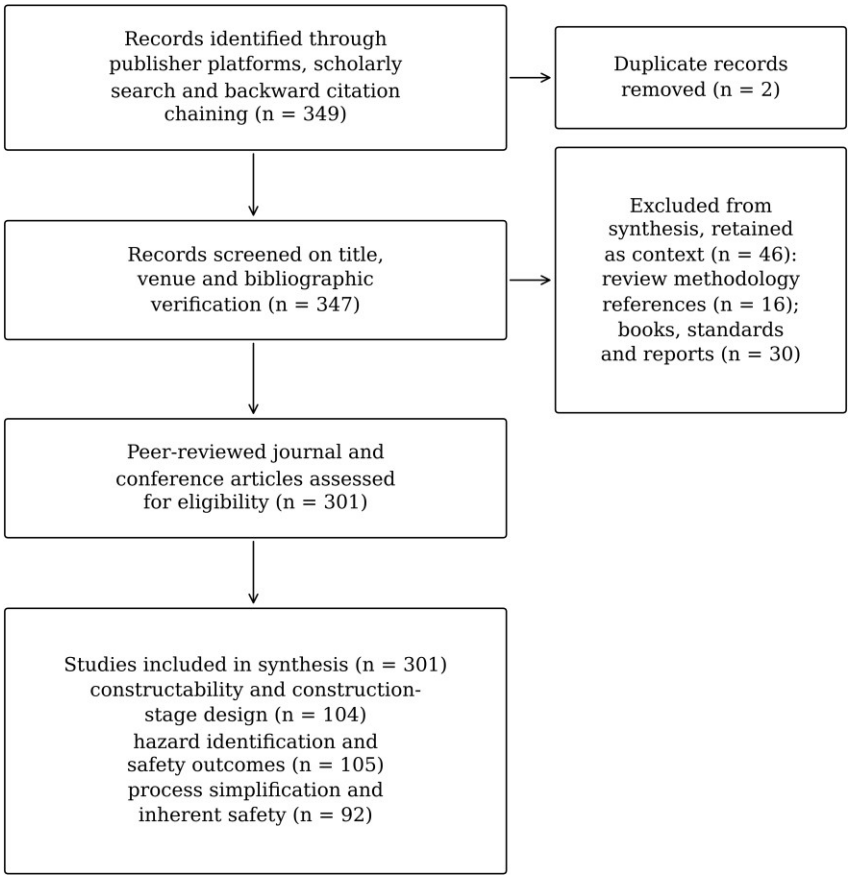


Figure 1. PRISMA 2020 flow diagram of record identification, screening and inclusion.

3.5 Data extraction and coding

Each study was coded on five variables: practice domain; sector (oil and gas, chemical and process, or construction and projects); research method (conceptual or methodological, empirical or case-based, computational and knowledge-based, index or metric development, or review); publication period (four bands); and whether it related a practice to an accident, incident, injury or performance outcome. Coding applied keyword rules to titles, topic labels and venues, as in bibliometric mapping (van Eck & Waltman, 2010), after checking the frame against a sample of records.

3.6 Quality appraisal and synthesis

Because the studies are methodologically heterogeneous, no single appraisal instrument was appropriate; AMSTAR 2 and the Mixed Methods Appraisal Tool (Hong et al., 2018; Shea et al., 2017) informed the narrative synthesis rather than a scored exclusion. Synthesis combined descriptive analysis of the coded variables with thematic synthesis within each domain (Petticrew & Roberts, 2005).

4. Results

Sections 4.1 and 4.2 describe the 301 included studies, Sections 4.3 to 4.5 synthesize each domain and Section 4.6 brings together the outcome evidence.

4.1 Characteristics of the evidence base

The 301 included studies comprise 288 journal articles and 13 conference papers published between 1978 and 2021: 104 address constructability and construction-stage design, 105 hazard identification and safety outcomes, and 92 process simplification and inherent safety. Table 3 and Figure 2 show their distribution by period. Process simplification research peaked in the 2000s with inherent safety indices (Khan & Amyotte, 2005; Leong & Shariff, 2008), while constructability and hazard identification grew most in the 2010s through modularization (O'Connor et al., 2014) and computational HAZOP (Single et al., 2019). The 45 studies from 2020 and 2021 include machine learning and natural language processing of HAZOP and incident reports (Feng et al., 2021; Kurian et al., 2020).

Table 3. Included studies by practice domain and publication period.

Domain	Before 2000	2000 to 2009	2010 to 2019	2020 to 2021	Total
Constructability and construction-stage design	18	18	51	17	104
Hazard identification and safety outcomes	7	25	54	19	105
Process simplification and inherent safety	10	39	34	9	92
Total	35	82	139	45	301

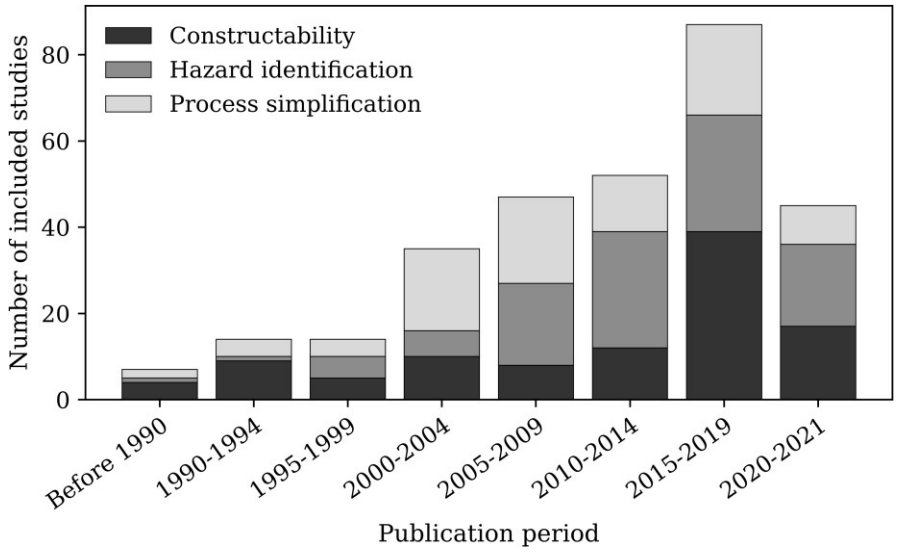


Figure 2. Number of included studies by practice domain and publication period.

The sectoral distribution (Table 4) is strongly uneven: only 42 studies, about 14 percent, address oil and gas facilities directly. Seven constructability studies do so, among them analyses of hydrocarbon megaproject overruns (Olaniran et al., 2015) and supply chain and procurement frameworks (Agbabiaka et al., 2019; Okonkwo et al., 2018); hazard identification and process simplification contribute 21 and 14, the latter mostly from a few offshore inherent safety groups (Crivellari et al., 2021; Khan & Amyotte, 2002). Most knowledge about these practices in oil and gas design is therefore inferred from other sectors.

Table 4. Included studies by practice domain and sector.

Domain	Oil and gas	Chemical and process	Construction and projects	Total
Constructability and construction-stage design	7	5	92	104
Hazard identification and safety outcomes	21	82	2	105
Process simplification and inherent safety	14	77	1	92
Total	42	164	95	301

4.2 Research methods

Table 5 and Figure 3 show the research methods. Conceptual and methodological studies form the largest group in every domain, 140 of 301 studies. Computational and knowledge-based studies cluster in hazard identification (30 studies) (Rahman et al., 2009; Vaidhyanathan & Venkatasubramanian, 1995), index and metric development in process simplification (13 studies) (Edwards & Lawrence, 1993; Kazi et al., 2019), and empirical and case-based work in constructability (Goh & Chua, 2016; Jergeas & Van der Put, 2001); reviews number 43 (Gao et al., 2020; Srinivasan & Natarajan, 2012).

Table 5. Included studies by practice domain and research method.

Domain	Conceptual or methodological	Empirical or case-based	Computational and knowledge-based	Index or metric development	Review	Total
Constructability and construction-stage design	56	20	9	3	16	104
Hazard identification and safety outcomes	40	17	30	6	12	105
Process simplification and inherent safety	44	11	9	13	15	92
Total	140	48	48	22	43	301

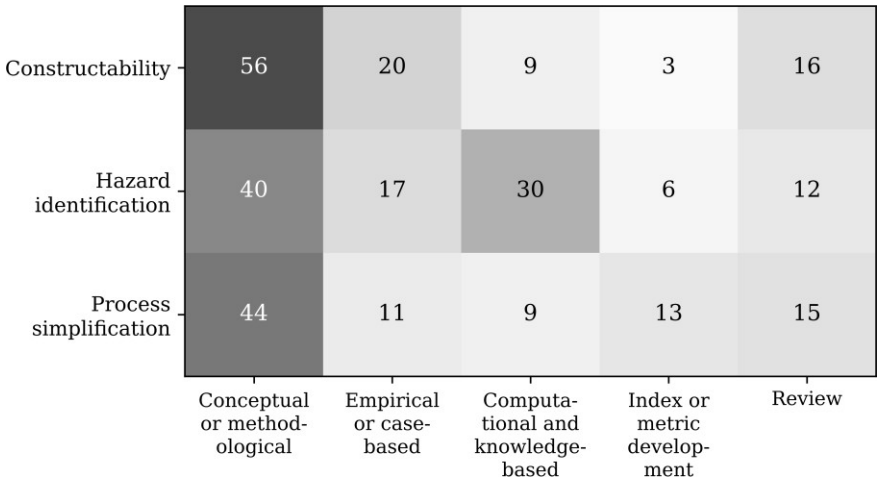


Figure 3. Included studies by practice domain and research method. Cell values are study counts.

4.3 Constructability and construction-stage design

The 104 constructability studies come mainly from building and industrial construction (Gambatese et al., 2007; Kifokeris & Xenidis, 2017); their relevance to oil and gas lies chiefly in modularization and megaproject research (Cigolini & Castellano, 2002; Olaniran et al., 2015).

4.3.1 Constructability programs and implementation

Foundational research under the Construction Industry Institute set out constructability concepts for engineering, procurement and field operations (Construction Industry Institute, 1986, 1993; O'Connor & Tucker, 1986; O'Connor et al., 1986). Later work developed implementation models (Radtke & Russell, 1993), benchmarking (O'Connor & Miller, 1994) and ways of overcoming barriers (O'Connor & Miller, 1995), and quantified constructability benefits (Jergeas & Van der Put, 2001), which are associated with better project outcomes (Deshpande et al., 2012).

4.3.2 Modularization and prefabrication

Modularization is the practice most relevant to oil and gas facilities. Studies have identified its critical success factors, its trade-offs against stick-built execution (O'Connor et al., 2014, 2015) and the conditions for cost and schedule success (Choi et al., 2016); module yard simulation (Mohamed et al., 2007) and crane path checking for heavy lifts (Lei & Taghaddos, 2013) address execution, and onshore process plant modularization (Cigolini & Castellano, 2002) connects this work to process facilities. Prefabrication research concerns mostly buildings (Gibb, 1999; Yin et al., 2019).

4.3.3 Design for manufacture and assembly

Design for manufacture and assembly originated in product design (Boothroyd, 1994) and has been applied in the water industry (Trinder, 2018), reviewed for construction (Gao et al., 2020) and supported by a big-data design options repository (Gbadamosi et al., 2020), but not yet studied for process modules.

4.3.4 Early contractor involvement and interface management

Early contractor involvement improves schedule and project performance (Meng & Humphreys, 2015; Song et al., 2009), shaped by relational contracts (Malvik et al., 2021). Interface management has received much less attention (Shokri et al., 2014), although contractor safety performance in multi-contract industrial projects (Arumosoye & Obriki, 2020) and liability mitigation in energy service contracts (Ngonadi & Ominyi, 2019) address related governance questions. Given the many interfaces in oil and gas EPC projects, this is a notable gap.

4.3.5 Design for construction safety and prevention through design

Designers influence construction worker safety (Gambatese et al., 2005; Hinze & Wiegand, 1992), and a substantial share of construction fatalities could have been prevented by design changes (Abdelhamid & Everett, 2000; Behm, 2005, 2006). Prevention through design research has examined designers' practice in developing countries and organisational capability (Hardison & Hallowell, 2019; Manu et al., 2018, 2019; Toole & Gambatese, 2008). Work on leadership-driven safety culture (Obogo et al., 2019a), safety risk governance on multi-contractor projects (Obogo et al., 2019b) and management safety walkthroughs (Obriki & Adegbuji, 2019) addresses the construction phase that design hands over to, and building information modelling supports design-stage risk review (Hossain et al., 2018; Jin et al., 2019).

4.3.6 Megaproject performance

Megaprojects show systematic cost overruns (Flyvbjerg et al., 2003), including in oil sands (Jergeas, 2008) and hydrocarbon projects, which have been explained through chaos theory (Olaniran et al., 2015, 2017). Overruns are attributed partly to immature front-end definition, which constructability aims to address, but safety outcomes are not examined.

4.4 Hazard identification and safety outcomes

The 105 hazard identification studies come mostly from chemical process research, but 21 concern oil and gas, the highest share of any domain (Animah & Shafiee, 2019).

4.4.1 HAZOP and process hazard analysis quality

HAZOP is the most studied technique, with reviews of its history and literature (Dunjó et al., 2010; Kletz, 1997) and an application standard (IEC, 2016). Critiques have examined its

limitations (Baybutt, 2015a) and the ability of process hazard analysis to identify accidents, the requirements for improved methods and team competency (Baybutt, 2003, 2014, 2015b), and whether conventional scenario definition remains fit for purpose (Cameron et al., 2017).

4.4.2 Automated and computer-aided hazard identification

Automation is the most computationally intensive strand. Digraph-based models (Vaidhyanathan & Venkatasubramanian, 1995) were followed by expert systems such as TOPHAZOP (Khan & Abbasi, 1997), PHASuite (Zhao et al., 2005) and ExpHAZOP+ (Rahman et al., 2009), ontology-based support (Morbach et al., 2007; Single et al., 2019, 2020b) and natural language processing of completed HAZOP reports (Feng et al., 2021).

4.4.3 HAZID, SWIFT, FMEA and layers of protection

Techniques used earlier than HAZOP are less studied. CCPS guidelines and ISO 17776 define hazard identification for process and offshore design (Center for Chemical Process Safety, 2008; ISO, 2016); DyPASI identifies atypical scenarios (Paltrinieri et al., 2013) and SWIFT offers an alternative to FMEA (Card et al., 2012). Layer of protection analysis (Center for Chemical Process Safety, 2001) has been reviewed for the oil and gas industry (Markowski, 2012).

4.4.4 Accident causation and design error

The accident causation literature consistently finds that design contributes substantially to accidents (Kidam & Hurme, 2012; Kinnersley & Roelen, 2007; Taylor, 2007), and the BP Texas City investigation highlighted siting and design issues alongside organizational failures (U.S. Chemical Safety and Hazard Investigation Board, 2007). Studies of maintenance as an accident contributor (Okoh & Haugen, 2013), incident prevention in maintenance engineering (Obogo et al., 2021b), human factors in oil and gas accidents (Nwankwo et al., 2021; Theophilus et al., 2017) and tight coupling (Perrow, 1984) add organizational perspectives, and offshore blowouts have been modelled as barrier failures (Xue et al., 2013).

4.4.5 Incident databases and learning from accidents

Analyses of European major accidents (Nivolianitou et al., 2006), energy accidents over a century (Sovacool, 2008), Chemical Safety Board investigations (Park et al., 2021) and offshore incidents in ice-prone seas (Necci et al., 2019) establish patterns of causes. Root-cause analysis (Okwesa et al., 2021), near-miss reporting (Obogo et al., 2021a) and near-miss data use (Arumosoye & Obriki, 2019) supplement major accident records, and machine learning and ontology methods now support analysis of incident narratives (Kurian et al., 2020; Sattari et al., 2021; Single et al., 2020a).

4.4.6 Process safety indicators and outcome measurement

Linking practices to outcomes requires indicators. Regulatory guidance and early debate framed the field (Health and Safety Executive, 2006; Hopkins, 2009), and reviews have questioned the solidity of the concept (Swuste et al., 2016, 2019). Dynamic risk methods (Khakzad et al., 2013a) could support outcome-oriented evaluation but are rarely applied to early-stage practices, and QHSE audit systems (Obogo et al., 2020a) and organizational learning maturity models (Arumosoye & Obriki, 2021) track performance without attributing it to design.

4.4.7 Offshore risk and safety barriers

Offshore studies apply Bayesian and barrier-based methods to drilling risk (Khakzad et al., 2013b). They treat the design as given, but define the scenarios early-stage hazard identification must anticipate (ISO, 2016; Standards Norway, 2008).

4.5 Process simplification and inherent safety

The 92 process simplification studies form the oldest domain, originating in the late 1970s, with a long tradition of index development (Edwards & Lawrence, 1993; Kletz, 1978; Roy et al., 2016); fourteen address oil and gas (Crivellari et al., 2021; Khan & Amyotte, 2002; Metcalf, 1993).

4.5.1 Principles and their development

Inherent safety was introduced with the argument that what you do not have cannot leak (Kletz, 1978), and its principles were developed further (Hendershot, 1997; Kletz, 1996, 2003; Kletz & Amyotte, 2010) and codified in CCPS life-cycle guidelines (Bollinger et al., 1996; Center for Chemical Process Safety, 2019). Reviews describe progress to date (Gao et al., 2021a; Srinivasan & Natarajan, 2012).

4.5.2 Inherent safety indices and metrics

Quantifying inherent safety has been the most active line of research, from the Prototype Index of Inherent Safety (Edwards & Lawrence, 1993) and the Inherent Safety Index (Heikkilä et al., 1996) to the Integrated Inherent Safety Index (Khan & Amyotte, 2005), the Inherent Safety Index Module (Leong & Shariff, 2008), consequence-based approaches (Tugnoli et al., 2007) and recent dynamic metrics (Gao et al., 2021b; Kazi et al., 2019). Different indices can rank the same alternatives differently (Abedi & Shahriari, 2005; Jafari et al., 2018; Rahman et al., 2005; Roy et al., 2016), and integrated approaches add sustainability and reliability (Ade et al., 2018; Moreno-Sader et al., 2019).

4.5.3 Inherent safety at the conceptual and preliminary design stage

Inherent safety has been applied when design information is limited, through early safety, health and environmental assessment (Koller et al., 2000), life-cycle implementation (Hurme & Rahman, 2005) and conceptual-stage approaches (Athar et al., 2019; Park et al., 2020).

4.5.4 Process intensification and safety

Process intensification offers simplification through smaller, integrated equipment (Stankiewicz & Moulijn, 2000), but its safety implications are mixed (Baldissone et al., 2014; Etchells, 2005), and safety must be built into the synthesis of intensified systems (Tian & Pistikopoulos, 2018).

4.5.5 Inherent safety in oil and gas and offshore facilities

The oil and gas evidence is concentrated in a few groups, which have reviewed inherent safety offshore (Khan & Amyotte, 2002) and developed indices for early design of offshore facilities (Crivellari et al., 2021). Other studies address maintenance-related major accident prevention offshore (Okoh & Haugen, 2014), inherently safer design as a route to world-class performance (Nair et al., 2019) and modularized LNG plants (Tanabe & Miyake, 2013). Minimum facilities concepts for unmanned platforms are the most direct application of simplification offshore (Metcalf, 1993; Pat-El et al., 2016).

4.5.6 Implementation barriers

Implementation remains limited. Industry risk aversion (Edwards, 2005) and the challenges of new and existing facilities (Mannan et al., 2003) constrain adoption, which depends on organizational conditions (Ashford & Zwetsloot, 2000). Inherent safety can be built into incident investigation (Goraya et al., 2004) and is extending to bioprocessing (Ade et al., 2019), yet barriers have persisted for three decades (Gao et al., 2021a; Srinivasan & Natarajan, 2012).

4.6 Evidence linking early-stage practices to safety outcomes

Only 49 of the 301 studies relate a practice to an accident, incident, injury or performance outcome: 17 in constructability, 27 in hazard identification and five in process simplification (Table 6). The strongest evidence is retrospective: design contributes to a large share of accidents in process operations and construction (Behm, 2005; Kidam & Hurme, 2012; Kinnersley & Roelen, 2007). Evidence that specific practices reduce accidents is much weaker: constructability is linked to cost and schedule rather than safety (Jergeas & Van der Put, 2001; Song et al., 2009), hazard identification studies examine completeness rather than incidents prevented (Baybutt, 2003; Cameron et al., 2017), and inherent safety indices measure hazard potential rather than observed accident rates (Leong & Shariff, 2008; Rahman et al., 2005).

Table 6. Types of evidence linking early-stage practices to safety outcomes.

Evidence type	Principal finding	Strength	Representative studies
Retrospective analysis of construction fatalities	A substantial share of construction fatalities could have been prevented by design changes	Moderate; based on investigation records	(Abdelhamid & Everett, 2000; Behm, 2005, 2006)
Retrospective analysis of process accidents	Design error and design deficiencies contribute to many process accidents	Moderate; based on incident databases	(Kidam & Hurme, 2012; Kinnersley & Roelen, 2007; Park et al., 2021; Taylor, 2007)
Incident database analysis	Recurring causes and consequences in chemical, energy and offshore accidents	Moderate for patterns; weak for design attribution	(Necci et al., 2019; Nivolianitou et al., 2006; Sovacool, 2008)
Constructability and project performance	Constructability and early involvement improve cost and schedule	Moderate for cost and schedule; absent for safety	(Deshpande et al., 2012; Jergeas & Van der Put, 2001; Song et al., 2009)
Completeness of hazard identification	Conventional analyses miss scenarios and safeguards	Weak to moderate; few comparative studies	(Baybutt, 2003, 2014; Cameron et al., 2017)
Inherent safety indices	Indices discriminate between alternatives but rank them inconsistently	Indirect; no link to observed accident rates	(Abedi & Shahriari, 2005; Rahman et al., 2005; Roy et al., 2016)
Inherent safety in incident investigation	Many investigated incidents had inherent safety solutions available	Moderate; retrospective	(Goraya et al., 2004; Park et al., 2021)

5. Discussion

The systems view of safety (Leveson, 2011; Perrow, 1984) and the life-cycle perspective of inherent safety (Hurme & Rahman, 2005) both imply that practices acting on the same decisions should be coordinated rather than applied in isolation (Hale et al., 2007).

5.1 Principal findings

Four findings stand out. First, the three domains have comparably sized literatures but draw on different sectors, and only about 14 percent of studies concern oil and gas directly, so practice in the sector rests largely on transferred evidence (Khan & Amyotte, 2002; Kifokeris & Xenidis, 2017). Second, methods differ by domain: automation in hazard identification (Single et al., 2019), indices in process simplification (Jafari et al., 2018) and surveys in constructability (Goh & Chua, 2016), which makes findings hard to combine.

Third, evidence that specific early-stage practices improve safety is weak: design contributes to many accidents (Behm, 2005; Kidam & Hurme, 2012), but few studies show that a given

practice has reduced them (Hopkins, 2009; Swuste et al., 2016). Fourth, implementation barriers have persisted in inherent safety (Edwards, 2005; Mannan et al., 2003) and prevention through design (Hardison & Hallowell, 2019; Toole & Gambatese, 2008), and they are organizational and contractual as much as technical (Ashford & Zwetsloot, 2000; Manu et al., 2018). Models for institutionalizing life-preserving safety practices (Obriki & Arumosoye, 2021) and for organizational learning in safety performance (Arumosoye & Obriki, 2021) point to the same levers.

5.2 Toward integration of the three domains

Integration requires three elements. The first is shared design data: hazard identification automation relies on process ontologies (Morbach et al., 2007; Single et al., 2020b), inherent safety indices on equipment and inventory data (Kazi et al., 2019; Leong & Shariff, 2008), and constructability analysis on building information models (Hossain et al., 2018; Yin et al., 2019). Aligned representations would let one early-stage model support all three reviews and expose trade-offs as they arise (Gbadamosi et al., 2020; Jin et al., 2019), and multi-attribute assessments show this is feasible (Ade et al., 2018; Crivellari et al., 2021; Moreno-Sader et al., 2019).

The second is a common decision point. Constructability, HAZID and inherent safety reviews are often held at different stages with different participants (Baybutt, 2012; O'Connor & Miller, 1994), whereas evidence on contractor involvement and team competence favours joint review at concept selection (Baybutt, 2015b; Song et al., 2009). The third is outcome-linked evaluation: without indicators connecting early decisions to accidents and injuries, practices cannot be compared (Health and Safety Executive, 2006; Swuste et al., 2019). Machine learning analysis of incidents (Kurian et al., 2020; Single et al., 2020a) and data-driven occupational safety risk control in energy infrastructure projects (Obriki & Arumosoye, 2018) show how this could be done.

5.3 Research agenda

Table 7 summarizes the research agenda. The highest priority is oil and gas specific evidence, particularly on how module design affects congestion and explosion consequences (O'Connor et al., 2014; Tanabe & Miyake, 2013). Others are comparison of hazard identification methods against actual scenarios (Cameron et al., 2017), calibration of inherent safety indices against accident data (Abedi & Shahriari, 2005) and study of interfaces in EPC projects (Malvik et al., 2021; Shokri et al., 2014).

Table 7. Research agenda arising from the review.

Gap	Research need	Suggested approach
Limited oil and gas specific evidence	Studies of constructability, modularization and inherent safety	Multi-project case studies and operator-contractor data sharing

Gap	Research need	Suggested approach
	on hydrocarbon facilities	
Weak outcome evidence	Link early-stage practices to accidents, incidents and construction injuries	Longitudinal studies using incident databases and leading indicators
Inconsistent inherent safety indices	Calibrate indices against observed outcomes	Retrospective analysis of facilities with known incident histories
Uncompared hazard identification methods	Compare completeness of HAZID, HAZOP, SWIFT and automated tools	Controlled comparison on common design cases
Separate design representations	Shared design data for constructability, hazard identification and inherent safety	Ontology alignment and building information modelling integration
Neglected interface management	Safety effects of contractual and discipline interfaces	Analysis of incidents at interfaces in EPC projects
Persistent implementation barriers	Organizational and contractual enablers of early-stage practice	Comparative studies across operators and regulatory regimes

Methodological work is also needed on the reliability of machine learning in safety-critical design (Sattari et al., 2021), the operability of intensified processes (Baldissone et al., 2014) and the adaptation of prevention through design and design for manufacture and assembly to hydrocarbon process modules (Gao et al., 2020; Hardison & Hallowell, 2019). Layout indexing could test the integration of inherent safety with constructability directly (Tugnoli et al., 2008), and heat stress risk in extreme environments (Adegbuji & Obriki, 2018) likewise depends on layout decisions fixed early.

5.4 Limitations

The review has limitations. Searching relied on publisher platforms, scholarly search and citation chaining rather than fixed databases and may have missed poorly indexed studies (Rethlefsen et al., 2021; Wohlin, 2014); retaining only verified records may exclude grey literature. Keyword coding of bibliographic records is less precise than full-text extraction (van Eck & Waltman, 2010), and formal quality scoring was not performed. Conclusions about oil and gas depend on the uncertain transferability of evidence from other sectors (Khan & Amyotte, 2002).

6. Conclusion

This review of 301 peer-reviewed studies published between 1978 and 2021 found an evidence base on constructability, hazard identification and process simplification that is evenly divided among the domains but uneven in sector and method, with only about one in seven studies addressing oil and gas facilities directly.

Design contributes to a large share of construction and process accidents, but evidence that particular practices reduce accidents is weak because few studies link practices to measured outcomes, and implementation barriers are organizational as well as technical.

Three priorities follow: oil and gas specific evidence, particularly on modularization and hazard consequences; shared design data and a common decision point at concept selection; and outcome-linked evaluation using incident databases and leading indicators. Addressing them would make early-stage design the most effective point at which to make oil and gas facilities both buildable and safe.

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