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Review

The efficacy of industrial safety science constructs for addressing serious injuries & fatalities (SIFs)

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A B S T R A C T

Neither a formal scientific literature review or research study this opinion piece examines safety science constructs applied to industrial safety in the UK over the past three decades to learn what may be useful to reduce serious injuries & fatalities (SIFs) and address other safety challenges arising from the 4th Industrial revolution. The key questions asked were: [1] what impact has safety science had on industrial injury statistics; [2] what is the quality of the science behind those with a demonstrably positive effect, and [3] where does safety science go next as we head deeper into the 21st century?

Data driven results show the rate of decline in the UKs serious injuries & fatalities (SIFs) in the past 32 years has been negligible ($r^2 = 0.002$), whereas temporary disabilities ($r^2 = 0.90$) declined by around 66 percent. This result suggests safety science has not, and is not (in its current form), impacting the numbers killed or maimed at work in the UK at least, with other countries showing similar patterns in their injury experience.

Examining the influence of a range of safety science constructs, legislative changes, and voluntary initiatives on injury reduction during this period, it is notable that only the safety culture and corporate social responsibility (CSR) constructs exerted clear impacts. An exploration of the science underpinning the safety culture and CSR constructs possibly provides insight that safety scientists and practitioners may find useful as safety science faces the future.

1. Introduction

This manuscript is neither a scientific literature review nor a research study: it is an opinion piece resulting from an invitation to opine on the future of safety science. A challenging task that is akin to gazing into a crystal ball, it makes sense to know, and learn from, the past to provide a baseline: i.e. what does previous safety science tell us about addressing industrial/occupational safety in the future? For example, as well as still addressing issues from the 2nd & 3rd industrial revolutions, the world is currently racing towards the 4th industrial revolution comprising of rapidly changing technologies, artificial intelligence, digitalisation, robotics, and networking of machines, compounded by the increasing complexity of organisational structures and processes (Maynard, 2015; Schwab, 2017). This manuscript takes a helicopter view of industrial safety and safety science in the UK over the past 30 years or so, to ascertain if any lessons can be learned, that usefully could be applied in the future.

A pertinent issue refers to the scope and boundaries of safety science. The existence of safety *per se* as an object of scientific investigation in the conventional sense has already been discussed (e.g. Hollnagel, 2014a; Ge et al., 2019), and is not addressed here. With contributions to the domain including industrial/organisational safety, public safety, democracy & government, health care, and so on, the scope of safety science is very wide, with few boundaries. Many working in the field of safety adopt the pragmatic view that the safety science domain simply refers to a depository of applied scientific knowledge, rather than being a science *per se*, the purpose of which (in industrial safety) is to prevent harm to people and assets. This scientific knowledge domain is informed by multi-faceted approaches, theories, models, different scientific disciplines, methodologies, and, hopefully, rigorous scientific evaluation of interventions that can be, and have been, replicated, to support their use in the real-world (e.g. La Coze, 2013). Usefully, this pragmatic perspective lends itself to determining the efficacy of extant safety science initiatives when applied to industrial safety in the real-world. If previously espoused approaches have been validated, and been shown to impact injury rates or other important outcome variables, they could potentially be adapted to cater for emerging Industry 4.0 issues. The key questions are [1] what impact have these espoused approaches had on injury statistics; [2] what is the quality of the science behind those with a demonstrably positive effect, and [3] where do we go next as we head deeper into the 21st century?

2. Industrial safety data in the UK over the past three decades

Traditionally, the effectiveness of most safety initiatives is monitored via lagging ‘after the event’ measurements such as the number or rate of accident and injury incidents (Lingard et al., 2013). To examine the impact of previous safety science initiatives, therefore, requires access to a reasonably robust incident database over a long period of time to determine if there was a reduction, or not, in injuries, when they

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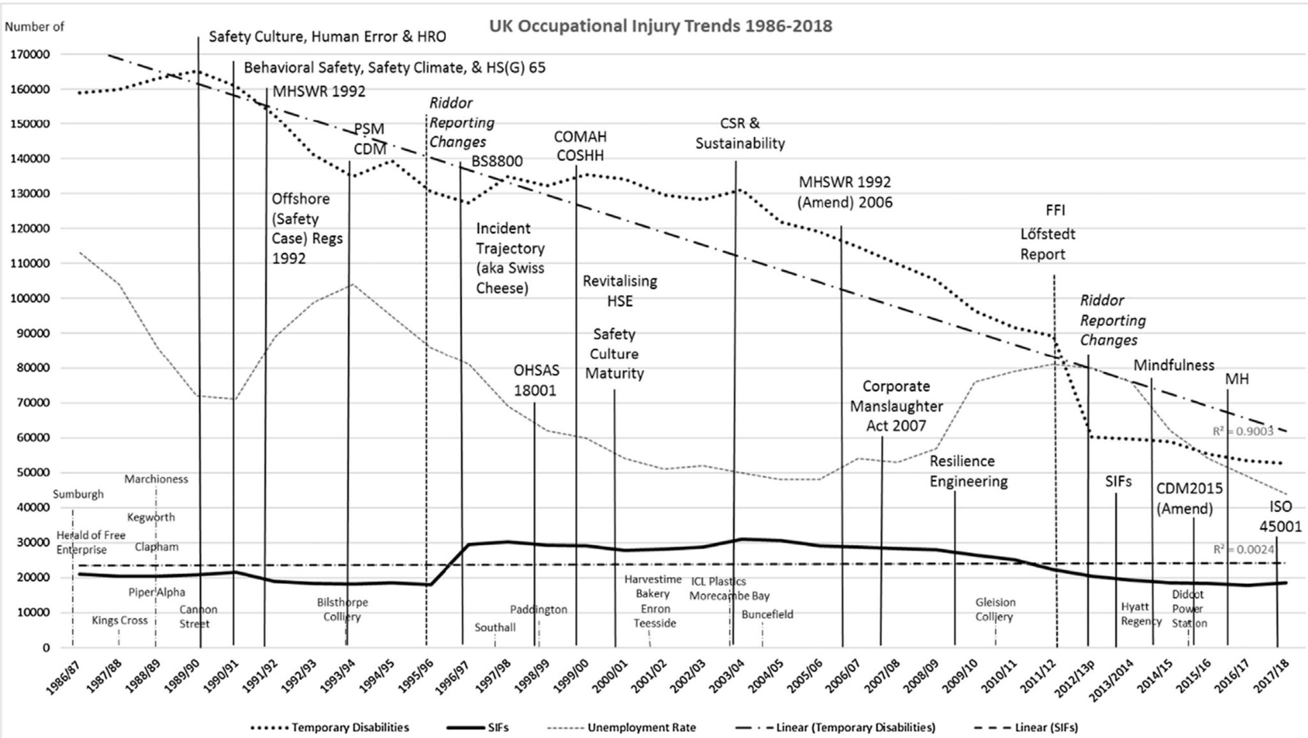

Fig. 1. U.K. Occupational Injury Trends 1986–2018, Safety Initiatives, Unemployment Rate, and notable disasters.

were introduced. The United Kingdom's Health & Safety Executive (HSE) offers such data via its RIDDOR database. The "Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDOR) 1995, put duties on employers, the self-employed and people in control of work premises (the Responsible Person) to report certain serious workplace accidents, occupational diseases and specified dangerous occurrences (near-misses) to the British Health & Safety Executive.

To provide data-driven insights to the crystal-ball gazing, the entire range of reported RIDDOR data from 1974 to 2018 were obtained from the British HSE website (i.e. ridhist.exe). HSE notations to the data indicated compulsory reporting was not a requirement from 1974 (When the Health and Safety at Work etc Act 1974 was introduced) to 1980, thus 1974–1980 data is likely contaminated by under-reporting (e.g. Clarke and Robertson, 2008). Similarly, from 1980 to 1986 mandatory reporting applied to a limited number of incident types only, with an annual date range from January to December. This changed in 1986 when the range of mandatory reporting of incident types was expanded with the year running from April to March. This has remained relatively constant since. As such, the reported RIDDOR incident data shown in Fig. 1 are from 1986 to 2018 and show the UKs reported major and minor injury trends for the past 32 years or so. The major injury data is the sum of the number of fatalities and major specified injuries. The minor injury data reflect reports of the number of injuries requiring 3 or 7 days off work (the HSE replaced the former with the latter in 2012). The *number of injuries* is used instead of Injury Rates, due to different sources of employment data pre and post 2004/5, meaning the Injury Rates after this date are not directly comparable with the Injury Rates prior to this date. The RIDDOR data also excludes restricted work cases, first-aid cases, industrial diseases, road traffic, maritime, deep-sea fishing, air transport, and military injuries.

In this paper, fatalities, and major specified injuries (RIDDOR, 1995) are referred to as Serious Injuries & Fatalities (SIFs). The over 3-day or over 7-day minor injuries are referred to as Temporary Disabilities. There are two common severity levels attached to SIFs (Massachusetts Department of Public Health, 2005, 2007), currently in use in various workplaces focused on trying to control SIFs. Presented in Table 1, ranging from most serious to least, these are: Life-Threatening, and Life-Altering cases. Temporary Disabilities, Restricted Work, and First-Aid cases, generally, are not treated as SIFs (unless circumstances decree otherwise), but there are valid arguments for including Temporary Disabilities as SIFs if they incur a lost-time away from work injury of greater than 30 days.

2.1. Safety initiatives introduced into the UK workplace from 1986 to 2018

During the period 1986–2018 various safety science, legislative, and voluntary initiatives were introduced or implemented in the UK.

The safety science initiatives include Safety Culture (inc. safety climate, behavioural safety, safety management systems, safety culture maturity), Human Error (HE), High Reliability Organisations (HRO), Process Safety Management (PSM), Incident Causation Theory, Resilience Engineering (RE), Safety Mindfulness (SM), and Mental Health (MH).

Legislative initiatives include the Management of Health & Safety at Work Regulations (MHSWR), 1992; the Offshore (Safety Case) Regulations 1992; the Construction, Design & Management Regulations (CDM), 1994; RIDDOR Amendments, 1996; The Control of Major Accident Hazards (COMAH) Regulations 1999; the Control of Substances Hazardous to Health Regulations (COSHH) 1999; and the Corporate Manslaughter and Corporate Homicide Act 2007. Various amendments to some of these regulations were also introduced. Revitalising HSE was primarily an internal HSE initiative to make the regulator more effective by partnering with other stakeholders.

Voluntary initiatives, sponsored by professional safety bodies (e.g. Institution of Safety & Health – IOSH) and consultants include the adoption of British Standard BS8800, a guide to occupational health and safety management systems based on the British HSE's HS(G) 65 (1991) Health & Safety management guidance document. Both HS(G) 65 and BS8800 provide a framework to identify, control and decrease workplace health and safety risks. BS8800 later morphed into OSHA(S) 18001, to provide a recognised international standard for the implementation of a health & safety management system, which again

Table 1
SIF Severity Scale.

SIF	Severity Level	Actual Severity	Event Type	Potential Outcomes
Yes	5	Critical	Life-Threatening	Uncertain survival - Injury or illness which could lead to the death of the affected individual.
Yes	4	Severe	Life-Altering	Probable survival - Permanent or long-term impairment or loss of use of an internal organ, body function, or body part.
Yes / No	3	Serious	Temporary Disability	Serious Injury - Traumatic injury causing limited or no use of fingers, hands, or other extremities.
No	2	Moderate	Restricted Work	Moderately severe injury - Lacerations, dislocations, strains, burns, soft tissue injuries, limited use of hand or fingers.
No	1	Mild	First-Aid with immediate return to work	Mildly severe injury - splinters, foreign body in eye, eye burns, or scratches.

morphed into ISO 45001 an international standard agreed by most nations in 2017/18. Corporate Social Responsibility (CSR) is a form of voluntary corporate self-regulation, that is primarily concerned with adhering to high ethical standards to reduce business and legal risk by taking responsibility for corporate actions.

By and large, both legislative and voluntary certification initiatives promoted the identification, appraisal, assessment, and control of workplace risks, within a Plan, Do, Check, Act (PDCA) cycle (e.g. Deming, 1986).

2.2. The impact of safety science initiatives on industrial safety in the UK from 1986 to 2018

The UK injury trends in Fig. 1 were overlaid with [1] occurrences of major UK disasters from 1986 to 2018; [2] safety science, legislative, and voluntary initiatives introduced into UK workplaces from 1989/90; and [3] the UK unemployment rate from 1986 to 2018 (downloaded from the UK's Office of National Statistics). As such Fig. 1 provides a global view of industrial safety over the past three decades, and provides insights about the effectiveness of the various safety initiatives impact on injuries. For example, there is a clear, consistent downward trend ($r^2 = 0.90$) in temporary disabilities since 1989/90, resulting in a 66 percent reduction to date. Conversely, the number of SIFs remained static ($r^2 = 0.002$) with an annual average of 24,000 cases. This is surprising, and suggests that the various safety initiatives introduced into the UK during the 1986–2018 period exerted their intended effects on temporary disabilities, rather than SIFs.

Fig. 1 also appears to show two seminal moments exerting a clear influence on incident reduction in the UK. The first was the introduction of the safety culture construct in 1990 (INSAG, 1986; Fennel, 1988; Cullen, 1990; IAEA, 1991; CBI, 1991); the second was the introduction of the Corporate Social Responsibility (CSR) agenda in 2004 (HSE, 2004). In both instances, there were clear downward trends in SIFs and temporary disabilities after their introduction, albeit of different magnitudes. A perusal of Fig. 1 also supports the view that very little else exerted a clear impact, albeit other initiatives (e.g. MHSWR, 1992, OSHA(S) 18001, etc.) undoubtedly influenced and reinforced the effects of both safety culture and CSR.

Nonetheless, three confounding factors may explain some of the variation. The first is changes to the reporting of RIDDOR incidents. In 1996, the British HSE required RIDDOR to apply to a single set of reporting requirements to all work activities in Great Britain and in the offshore oil and gas industry: the standard was injuries greater than 3 days off-work. The HSE simultaneously reassigned its responsibility for railway safety and incidents to the Office of Rail Regulation (ORR). It is notable that the changes to RIDDOR halted the previous six-year injury reduction trend, and led to a 9-year plateau in both temporary disabilities and SIFs. The 2012 change, 18 years later, led to reporting of incidents over 7-day lost-time only, which in turn led to a dramatic 29,000 drop in the numbers of temporary disabilities reported over the next 12 months. Unfortunately, companies misclassified and downplayed the severity of 25 percent of the temporary disabilities (HSE, 2015) instead of reporting them as SIFs. Thus, the purported declines in both types of injury since 2012 may not be quite as robust as portrayed.

The second factor is the UKs Unemployment Rate (ER), which is positively associated with the temporary disabilities ($R = 0.41$, $p = < 0.05$), and negatively correlated with SIFs ($R = -0.52$, $p = < 0.01$). It appears, temporary disabilities rise and fall in tandem with the UKs unemployment rate by about 17 percent, while the influence on SIFs is the opposite: SIFs decrease when ER rises, and rise when the ER falls, by around 27 percent. This accords with other work establishing links between economic cycles and injury rates (e.g. Davies et al., 2009; Asfaw et al., 2011; Fernández-Muñiz et al., 2018). However, given the two RIDDOR reporting changes, the true relationship between ER and the UKs injuries is unknown.

The third potential confound is that temporary disabilities occur more often than SIFs, meaning the different rates of decline are simply reflecting a base rate issue: i.e. there is a lower *a-priori* probability of a SIF than a temporary disability. Although a low base rate remains a possibility, the issue is not clear-cut: given the relatively constant ratios espoused by advocates of Heinrich's incident triangle (Heinrich, 1931) between minor and serious injuries, which asserts both types of injury should decline at the same rate. Heinrich's accident triangle (*sic.*) has dominated the thinking of the safety profession for almost 90 years. He essentially argued that a ratio of lower to higher severity incidents exists in the form of a "safety-triangle" (i.e. high severity incidents are often preceded by a larger number of less severe incidents and near misses). Heinrich theorized that for every 1 major injury or fatality, there were 29 minor injuries and 300 non-injury incidents. Recent SIF research shows that Heinrich was descriptively correct in his assertion of there being more lesser than serious events (e.g. Marshall et al., 2018), but the Ratio's vary and are not constant (Manuele, 2011; Martin and Black, 2015). The UKs experience exhibited in Fig. 1 also demonstrates the variation in Ratio's, as the SIFs to temporary disability ratio increased from 0.13 in 1986/7 to 0.35 in 2017/18 resulting from the static ($r^2 = 0.002$) SIF trend line. Similar injury trends are observed in other countries, for example the USA (Manuele, 2008; Martin and Spigener, 2018; BLS, 2019). Such trends indicate the relatively low base rate does not account for the varying rates of decline. Heinrich also asserted that similar causes underlie both high and low severity events, and there is a predictive relationship between the two (e.g. Marshall et al., 2018). However, a growing body of evidence casts doubt on the notion of similar causes underlying high and low severity events (e.g. Gallivan et al., 2008; Nascimento et al., 2013; Lööw and Nygren, 2019; Shafique and Rafiq, 2019).

Taking all these factors into account, and applying the principles of Occam's Razor, the simplest explanation for the UKs experience in the decline of its workplace injuries is that the impact of the various safety initiatives has primarily been on temporary disabilities, rather than SIFs. It is likely this is also the case for other countries showing similar patterns in their data.

3. Examining the quality of the science supporting the safety culture construct

Fig. 1 showed that the safety culture construct appeared to provide an impetus to the decline in the UKs injury trends from 1990/91. From 1986 to 1990 there were eight major safety disasters influencing the way occupational/industrial safety was subsequently viewed and managed in the UK. For example, the legacy of the 1988 Piper Alpha disaster highlighted the importance of safe management practices, behavioural responses, and work safety climates (Reason, 1990, 1995), while fundamentally changing process safety approaches in the UK Oil & Gas industry (Crawley, 1999). Almost simultaneously, the aftermath of the Chernobyl nuclear disaster promoted the safety culture construct (INSAG, 1986; IAEA, 1991). This was perfect timing for British Industry as it desperately sought solutions to stop the major disasters and the associated serious injuries & fatalities. Le Coze (2019) highlights the managerial context during the 1980 and 1990's was characterised by patterns of greater interactions between academics, publishers, consultants, regulators and industries, that promoted and led to the adoption of various safety initiatives such as safety culture.

For almost three decades, safety culture has been highly promoted, advocated and debated, but remains a contentious notion (Le Coze, 2019). The term "safety culture" is a *social construct* referring to, and used to, encapsulate, and explain organisational safety failings (IAEA, 1991). Its *purpose* is to improve occupational safety in organisations, by preventing low-frequency, high-severity catastrophic events such as Chernobyl and the Piper Alpha, as well as high-frequency, lower-impact events resulting in personal injuries. A construct is defined as "an idea, theory or intellectual creation containing various conceptual elements (i.e. abstract ideas) typically considered to be subjective and not based on empirical evidence. According to Reichers and Schneider (1990), the evolution of any construct is thought to proceed through three overlapping stages: [1] *introduction and elaboration* which is characterised by attempts to sell the ideas and legitimise the new construct; [2] *evaluation and augmentation* is where critical reviews and early literature on the construct identifying the construct's parameters, first appear; and, [3] *consolidation and accommodation* is where controversies wane, and what has become known, is treated as fact or generally agreed upon phenomenon, that forms the basis for shared assumptions about the constructs reality. The author makes use of Reichers and Schneider's three-step process as a framework to structure the evaluation of the science underpinning the safety culture construct and any impacts on injury reduction.

3.1. Introduction and elaboration

The International Atomic Energy Agency (IAEA, 1991) defined safety culture as "*that assembly of characteristics and attitudes in organisations and individuals which establishes that, as an overriding priority, [nuclear power] safety issues receive attention warranted by their significance*", which lends itself to a functionalist approach toward safety culture (e.g. Reason, 1997). Many influential scholars ignored the IAEA's definition and developed their own. With more than 50 definitions of the safety culture construct (Vu and De Cier, 2014) both industry and academe are now confused about the scale and scope of the safety culture construct, and what it means in practice, as foreseen by Hale (2000). The most ubiquitous definition in the UK is from the British Health and Safety Commission (1993) "*…the product of individual and group values, attitudes, competencies, and patterns of behaviour that determine the commitment to, and the style and proficiency of, an organisation's health & safety programmes. Organisations with a positive safety culture are characterised by communications founded on mutual trust, by shared perceptions of the importance of safety, and by confidence in the efficacy of preventative measures*". Given its emphasis on psychological features (i.e. values, attitudes, commitment, trust, perceptions, and confidence), the HSC's definition tends to reflect the interpretive approach to safety culture (e.g. Waring, 1996).

The dichotomy between interpretive and functionalist approaches toward safety culture is at the root of many definitional disagreements over the past 32 years. Interpretative approaches, favoured by social scientists (anthropologists, sociologists, etc.), view the organisation as the culture, where the 'cultural' reality is based on its social construction by the organisation's membership. The emphasis of this approach is to gain an in-depth understanding of the prevailing cultural influences on people's behaviour. Profoundly impacting subsequent safety culture research, it is now common to use safety climate measures (e.g. Zohar, 1980) to assess and influence assumptions, values, and attitudes to improve the safety culture (e.g. Guldenmund, 2010). In contrast, managers and HSE practitioners tend to favour a functionalist approach by addressing management system faults, people's safety related behaviour, their risk-perceptions, and decision-making to change the safety culture. This approach is reflected in Behavioural Safety processes (Komaki et al., 1978; Sulzer-Azaroff, 1978), High Reliability Organisations (Perrow, 1984; Roberts, 1990), Human Error approaches (Rasmussen, 1982; Reason, 1990), Management Systems & Standards (e.g. BS 8800; OSHA(S) 18001; ISO 45001); Risk Assessments (U.S. Nuclear Regulatory Commission, 1975), and Root Cause Analysis (Johnson, 1973). Overall, regardless of approach, most definitions of the safety culture construct tend to agree it reflects a proactive stance to improving occupational safety (Lee and Harrison, 2000), and the way people think and/or behave in relation to safety (Cooper, 2000). The issue here, as the science of safety proceeds, is which approach to safety culture genuinely prevents process safety incidents and personal injuries. Le Coze (2019) points out that some sociologists entirely reject the notion of a safety culture preferring to concentrate on organisational culture instead (e.g. Hopkins, 2016), some safety researchers view it as a neutral theoretical object that's simply there as something to be studied (e.g. Guldenmund, 2010), others see it as a useful concept for industry under certain conditions (e.g. Antonsen, 2016), while pragmatics have fully embraced the concept and striven to develop reliable and valid tools, measurement methods, and improvement strategies (e.g. Reason, 1998). Clearly, such debates will rumble on for some time yet, until a substantial body of empirical evidence either confirms or refutes the utility of the construct, and its parameters, in the real world.

3.2. Evaluation and augmentation

The development of three models of safety culture during the 1986 – 2000 period has guided subsequent theory, research, and practice. Each attempted to provide an actionable framework, and each has been influential in the sense researchers, regulators and industry have made use of them in some empirical and/or practical capacity.

Based on Bandura's (1977) Social Learning Theory, Cooper's (2000) reciprocal model treats safety culture as a sub-culture of an organisation's overall culture, and highlights safety culture is the *product* of multiple goal-directed interactions between people (psychological), jobs (behavioural) and the organisation (situational). The psychological, behavioural, and situational aspects are the inputs to the safety culture construct, with the key transformation process being the organisation's goals, expectations, and managerial practices (i.e. leadership) to create the prevailing safety culture *product* (Cooper and Finley, 2013). Viewed from this perspective, the prevailing organisational [safety] culture is reflected in the dynamic reciprocal relationships between members' perceptions about, and attitudes towards, the operationalisation of organisational [safety] goals; members' day-to-day goal-directed [safety] behaviour; and the presence and quality of the organisation's [safety] systems and sub-systems to support the goal-directed behaviour. Large-scale studies on accident prevention (e.g. Lund and Aarø, 2004) and safety culture (e.g. Cooper, 2008; Fernández-Muñiz et al., 2009; Lefranc et al., 2012; Cooper et al., 2019) provide support for the utility of the reciprocal safety culture model.

Guldenmund's (2000) adoption of Schein's (1992) interpretive three-layered Organizational Culture framework reflecting anthropology and organisational theory, contains three layers: [1] *core basic assumptions* which are unconscious, and unspecified (i.e. invisible): the assumptions or suppositions about safety are not articulated, but are taken for granted as the basis for argument or action; [2] *espoused beliefs and values*: operationalised as relatively explicit and conscious "attitudes" whose target is hardware (safety controls), software (effectiveness of safety arrangements), people (functional groups) and people's safety-related behaviours; and [3] *artefacts*: visible safety objects (e.g. PPE, inspection reports, safety posters, etc.). In this model, 'culture' is a pattern of basic assumptions, invented, discovered, or developed by a group as it learns to cope with its problems of external adaptation and internal integration. To date, some indirect anecdotal evidence provides support for the model in the safety arena (Nielsen, 2014), but no solid empirical evidence has yet been published.

Based on incident analyses, Reason's (1998) model categorically states safety culture is not a unitary construct, as it comprises various interacting elements. He equates safety culture with an 'informed culture', which is dependent in turn upon an effective reporting culture' underpinned by a 'just culture'. Simultaneously, a flexible culture' is required if the organisation is to reconfigure itself in the light of certain kinds of dangers, which in turn will require a 'learning culture'. To some degree these are both objects of, and processes creating, the safety culture product: an informed culture. Empirical evidence provides support for the model (e.g. Collinson, 1999; Saji, 2003; Pluye and Hong, 2014; Cooper et al., 2019).

Simultaneously, the concept of work safety climates (Zohar, 1980), a sub-domain of safety culture, came to the fore. To provide focus to this research literature, Flin et al. (2000) categorised the topics measured into common targets: [1] Management and Supervision; [2] specific safety systems; [3] Risk; [4] Work Pressure; [5] Competence; and [6] Procedures/Rules. A vast amount of safety climate research studies abounds in the safety science literature, but many are somewhat problematic, as discussed below.

3.3. Consolidate and accommodate

Fig. 1 shows the beginning of a 5–6 year decline in both SIFs and temporary disabilities in 1990, the time the Safety Culture, Human Error (HE) and High Reliability Organisations (HRO) constructs were introduced. At this time, Governmental public enquiries into the Kings Cross Fire (Fennell, 1988, p. 127), Clapham Junction (Hidden, 1989, p. 167) and the Piper Alpha disaster (Cullen, 1990, p. 300) emphasised the role of a poor safety culture in these catastrophic tragedies. Subsequently, the safety culture construct was promoted heavily into the British Industrial landscape by the Confederation of British Industry (CBI, 1991), the British Health & Safety Executive (HSE, 1991) and the British Health & Safety Commission (HSC, 1993).

Both HE and HRO are sub-domains of the over-arching safety culture construct: HE and HRO respectively reflect psychological and situational aspects of the construct. HE & HRO both try to address unwanted variability and strive as far as possible to eliminate the root cause, which is often the presence of situational Human Error traps (Reason, 2000), created by, for example, instances of man–machine or man-task misfits (Rasmussen, 1982). In case of systematic or frequent misfits, design error is the likely cause. Occasional misfits typically are due to variability on the part of the system or the person, and are considered as system failures or human errors, respectively.

HE is commonly defined as '*the failure of planned actions to achieve their desired ends* (Reason, 1990), with all people being prone to making errors. Often leading to a minor incident, they can sometimes lead to a catastrophic incident (e.g. Hidden, 1989). As learning from errors is an important way of developing professional competence (Bauer and Mulder, 2007), HE frameworks are often used in incident investigation processes (e.g. Reinach and Viale, 2006). Nonetheless, it appears there are no empirical studies examining the impact of Human Error reduction initiatives on safety performance, although there is anecdotal evidence from industry (e.g. Cannon, 2012). Van Dyck et al. (2005), however, did show an error management culture was associated with a firm's survivability and profitability, by comparing questionnaire responses and independent outcome data. Field research on the Human Error construct is imperative if it is going to play a meaningful role in incident reduction and the science of safety.

Similarly, HRO implementation studies are survey or interview based (e.g. Bourrier, 1996; Bagnara et al., 2010) but do not reveal its impact on safety performance. Rather they tend to focus on implementation difficulties. Currently, there are major gaps about how to transfer HRO principles into organisations, a lack of understanding about HROs due to the absence of a unified definition, and how reliability-seeking organisations can access the potentials of becoming HROs (Enya et al., 2018).

Given the lack of empirical research evidence related to the impact of both HE and HRO on safety performance over the past three decades, and the struggle of many organisations to understand the associated concepts, logic would suggest that the influence of HE and HRO on Britain's minor and serious injuries in the 1990s and beyond was, and is, negligible. Clearly, major opportunities exist to conduct empirical studies in both HE and HRO as the science of safety goes forward. Nonetheless, it appears, with a lack of evidence to the contrary, the impact on the UKs injuries from 1990 was solely related to the introduction of the safety culture construct and its sub-domains, at least until 2004 when CSR was introduced.

3.3.1. Behavioural safety

Behavioural safety is one of the most effective and successful paradigms in the history of the science of safety. It addresses the behavioural aspect of safety culture and grew out of the organizational behaviour management (OBM) literature in the US during the 1970s (Komaki et al., 1978; Sulzer-Azaroff, 1978). Applied OBM studies successfully improved occupational safety (Grindle et al., 2000), quality performance (Welsh et al., 1992), productivity improvement (Jessup and Stahelski, 1999), absenteeism (Orpen, 1978), sales (Fellows and Mawhinney 1997), and patient infection control (Babcock et al., 1992). The introduction of behavioural safety into the UK via the UMIST research group on behalf of the British HSE from 1989 to 1999 in the UK construction industry (Duff et al., 1993, 1994; Marsh et al., 1995, 1998; Robertson et al., 1999) certainly appears to have reinforced the downward trend in the number of SIFs and temporary disabilities from 1992 onwards in the UK. For example, follow-on studies successfully reduced injuries in UK manufacturing (Cooper et al., 1994), paper mills (Cooper, 2006), nuclear facilities (Cox et al., 2004) and hospitals (Cooper et al., 2005). Numerous implementations were conducted in UK industry by consulting companies or by companies themselves, with many case studies reported (e.g. Foster et al., 2008). Reviews of the extant behavioural safety literature show significant and consistent impacts on behavioural change and incident reduction, although this is dependent upon the design of the behavioural safety process (Cooper, 2009), and optimal implementation (e.g. Oswald et al., 2018). However, many research questions remain unanswered to ensure behavioural safety is based on a comprehensive evidence-based footing (Wirth and Sigurdsson, 2008). For example, the impact of extending the focus to process safety issues and management behaviour (Anderson, 2005; Cooper, 2010).

3.3.2. *Safety climate*

Addressing the psychological aspect of safety culture, safety climate (Zohar, 1980) is a term used to describe shared employee perceptions of how safety management is being operationalised in the workplace, at any moment in time (Byrom and Corbridge, 1997). These perceptions provide an indication of the (true) priority of safety (Zohar, 2000) in an organisation compared to other priorities such as production or quality. A safety climate assessment, therefore, is simply a snapshot of the workforce's view about safety at a given time (Flin et al., 2000).

The UMIST research group introduced the concept of safety climate into the UK (Cooper, 1992; Phillips et al., 1993), and seemingly it would appear safety climate has helped buttress the downward trend in UK injuries. However, this is highly debateable, as there is no clear consistent relationship between safety climate and injury outcomes (e.g. Gadd and Collins, 2002; Clarke, 2006) or safety behaviour (Cooper and Phillips, 2004), with previous injury history being a better predictor of safety climate than *vice versa* (Beus et al., 2010). By way of example, a large-scale study (Smith et al., 2006) with a sample of 41,608 respondents across 19 industries, initially showed safety climate was correlated with workers' compensation injury rates, but when adjusted for the hazardous nature of the industry, the association disappeared entirely. Some (e.g. Payne et al., 2009) report safety climate is strongly related to *future* incident rates (typically after a 5-month time lag or so). However, to propose safety climate is predictive of future incident rates (i.e. Zohar, 2003) is to misconstrue or exaggerate its effects. What such relationships truly show is that a safety climate assessment leads to managerial goal-setting (Locke and Latham, 1990) and associated actions to rectify any problems identified: it is these goals and actions that are predictive of future performance, *not* the safety climate *per se*. Dyreborg and Mikkelsen, (2003), for example, showed that without follow-up goals, enterprises with the highest safety climate scores subsequently experienced more accidents than others. Conversely, enterprises with the lowest safety climate scores did not experience accidents in the follow-up period.

After 40 years, safety climate research is still struggling to obtain unequivocal evidence linking safety climate to actual safety performance (Gadd and Collins, 2002; Goodheart and Smith, 2014; Leitão and Greiner, 2015). It is clear much of the inconsistency is due to sub-optimal research. Numerous reviews (e.g. Colla et al., 2005; Flin et al., 2006; Christian, Bradley, Wallace, and Burke, 2009; O'Connor, O'Dea, Kennedy, and Buttrey, 2011; Hessles and Larson, 2016) show most safety climate studies have not even attempted to assess the relationship between safety climate and actual outcomes such as incident rates. Of the 141 studies in the review examples mentioned, only 12 (9%) attempted to establish a relationship between safety climate and actual safety outcome data.

Similarly, most safety climate research contains common method variance (CMV) (Podsakoff et al., 2003). This has resulted in a general inflation across all correlations (Clarke, 2010) from the use of self-report violations, incidents, injuries, & safety behaviour (Gadd and Collins, 2002), where social desirability responding (Paulhaus, 1989), and respondent's poor recollection of past events (Liao et al., 2001) can exert a significant influence on results. Thus, the internal reliability & criterion-related validity of most safety climate instruments reported in the extant literature are suspect. In turn, the extant scientific safety literature relying upon them is tarnished: it is imperative safety scientists account for CMV in their work before even considering publication to protect the integrity of the scientific knowledge base, in the same way that many scientists publishing in psychological and business journals do (e.g. Chang et al., 2010; Conway and Lance, 2010).

Without a doubt safety climate surveys can be useful diagnostic tools as they can help to reveal significant safety issues. Goals can then be set and actions taken to address the issues identified. However, it is very clear the science involved in the safety climate domain requires considerable improvement. In my view, studies not attempting to validate their measures against actual outcome criteria, and/or contain contaminated self-report measures should not receive the reward of publication. Researchers and their supervisors carry the responsibility to not submit them, while journal reviewers and editors have the responsibility to reject them. Some may find this view controversial, but it is proposed simply in an effort to improve and protect the science base.

3.3.3. *Safety management systems*

Safety management systems (SMS) address the situational aspect of safety culture. They proactively integrate organisational mechanisms designed to control health & safety risks, ongoing and future health & safety performance, and compliance to legislation (Cooper, 1998). Considered a systematic and comprehensive process that brings together operations, technical services, financial management, and human resource management, an SMS reflects Deming's (1986) Plan, Do, Check, Act (PDCA) cycle. As such they lead to focused goals and actions, in the expectation they reduce incidents (Paas et al., 2015). There are two types of SMS: mandated (i.e. legislated) and voluntary (i.e. BS 8800; OSHA(S) 18001; ISO 45001).

3.3.3.1. Mandatory SMS. Under-pinned by the UKs Health & Safety at Work Act 1974, the *Management of the Health & Safety at Work Regulations (MHSWR) 1992* primarily required Risk Assessments (e.g. White, 1995) on a facility's work activity where five or more people are employed. Risk Assessments should help to reduce the number of workplace injuries, but there is no published empirical evidence to show this is true: again, providing an area of opportunity as the science of safety goes forward. Fig. 1 also shows no discernible effects of MHSWR on the number of UK injuries, although it did provide a framework for action going forward. Unfortunately, the impact of introducing HSE legislation affecting safety performance (i.e. MHSWR, PSM, CDM, COMAH; COSHH) over the past 30 years has had no scientific evaluation. One study (Robson et al., 1999) evaluating the impact of introducing a national Occupational Health & Safety Management System (OHSMS) in Norway in 1992, concluded the evidence was insufficient to make recommendations, either in favour of, or against, OHSMSs. Other research (e.g. Tzannatos and Kokotos, 2009) comparing the pre-post introduction of the International

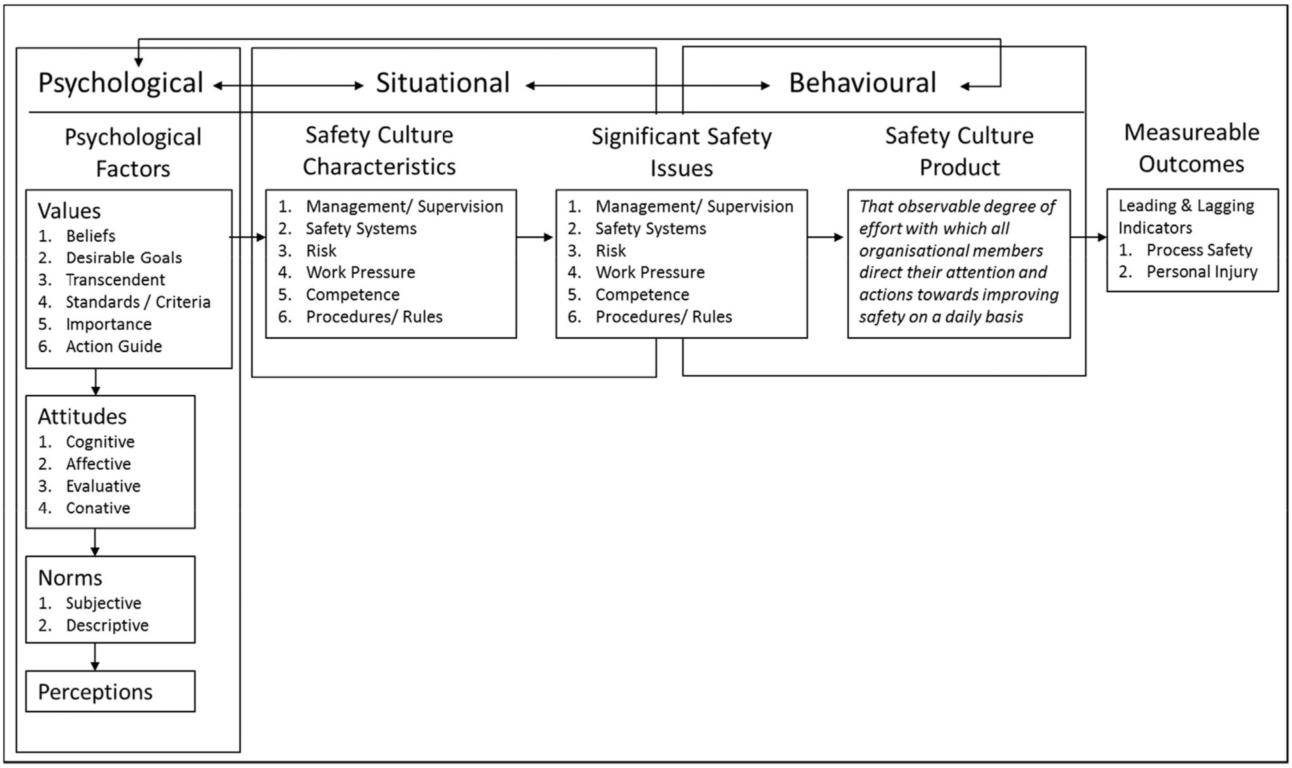

Fig. 2. Cooper's (2016) revised reciprocal model of safety culture.

Maritime Organisation's (IMO) Code regulating safety at sea from 1993 to 2006, demonstrated adverse incidents had reduced post-introduction. Thus, it appears that introducing an SMS at national or global levels might exert a positive impact on injury reduction, but empirical evidence confirming this would be very useful.

3.3.3.2. Voluntary SMS. Examining the extant literature exploring the impact of an SMS on individual company outcomes, shows a formal SMS tends to improve safety performance. A process safety example, Chevron's (2012) Operational Excellence Management System (OEMS) outcome data from 2004 to 2011 shows reductions in their Total Recordable Incident Rates (TRIR), spills, emission rates, and refinery effluent exceedances. Companies certified to international standards (i.e. OSHA(S) 18001) also tend to demonstrate that improvements follow: they help to improve safety conditions at the workplace, which, in turn, significantly reduce injury rates (Chang and Liang, 2009; Yoon et al., 2013), improves productivity (Abad et al., 2013), and competitiveness and financial performance (Fernández-Muñiz et al., 2009). In sum, changing and optimising the situation by introducing a formal SMS that codifies and guides people's behaviour does appear to help significantly reduce the conditions for a process safety disaster and personal injuries, but they may take a considerable time to exert an influence. Again, systematic research in this area would be valuable, particularly with the current promotion of ISO 45001 to the world-wide safety profession providing a timely opportunity for evaluation.

3.3.3.3. SMS implementation. Regardless of whether the nature of an SMS is legislative or voluntarily, a key element of ensuring its effectiveness at reducing incidents appears to be the auditing & review process (Shannon et al., 1997; Mearns et al., 2003). This becomes very apparent when we consider a series of independent studies identifying the causal factors of process safety incidents (e.g. Collins and Keely, 2003). These show managerial behaviours, or their lack of, cause 80 percent of Loss of Primary containment incidents (LOPC's). They also show 80 percent of process safety disasters occur during routine operations (64%) and maintenance (16%). Categorised by Flin et al.'s, (2000) common safety culture elements, Cooper (2016) showed these causal factors were related to [1] failures in leadership; [2] ignoring lessons learned; [3] Poor risk appraisal, risk assessment; and risk controls; [4] the safety-productivity conflict; [5] a lack of knowledge, skills, & abilities; and, [6] poor quality procedures, or an absence of procedures /rules/standards. The same or similar managerial behaviours were related to the occurrence of SIFs. Thus, regular monitoring and reviewing of the managerial performance of those responsible for using the various aspects of the SMS is vital (Hurst et al., 1996; Hass and Yorio, 2016). Further research examining this could help stop SIFs, and would benefit the science of safety, as it could help to define the parameters and conditions optimising the functioning of an SMS.

3.3.4. Safety culture integration

It is notable the psychological aspects of safety culture have no definitive empirical links to safety performance either because there is no research available (e.g. human error), or because attempts to do so are rare (i.e. safety climate). However, safety climate may exert an effect on safety performance due to employee participation, and engagement in follow-up actions, but we do not know. The science behind behavioural safety is well-established and shows demonstrable impacts on personal injuries in a variety of settings around the globe: where the workforce target specific behaviours, *and* receive feedback on progress, injuries reduce. Similarly, changing the situational aspects by introducing organisational safety management systems to provide structure, helps to reduce injuries. Each of these three approaches to occupational/industrial safety, comprise an essential element of the safety culture construct.

Linking the safety culture construct *per se* to actual safety performance, has also been problematic for various reasons (e.g. Wiegmann et al., 2004; Cole et al., 2013), not least because it is rarely linked to established safety models (Gilbert et al., 2018), and safety climate is commonly used as a proxy for safety culture (e.g. Flin, 2007). Based on earlier safety climate work (Flin et al., 2000), the results of public inquiries into process safety disasters (Cooper and Finley, 2013), and process safety research (e.g. Collins and Keely, 2003; Christou and Konstantinidou, 2012; IAEA, 2014; Wood et al., 2013; Gyenes and Wood, 2014; Wood and Gyenes, 2015), Cooper (2016) clearly identified the universally applicable targets of safety culture (i.e. the characteristics and significant safety issues associated with each) to address both process safety issues and SIFs, which led to a revision of the (2000) reciprocal safety culture model (see Fig. 2). Recent work confirmed its criterion-related validity (Cooper et al., 2019), by unequivocally linking each of the model's safety culture characteristics to a variety of personal injury statistics, including actual and potential SIFs. However, the study awaits replication in a variety of settings as scientific endeavours on the safety culture construct proceed.

3.3.5. Safety culture maturity

Showing no discernible impact on the UKs injuries when introduced into the UK (Fleming, 2001), safety culture maturity models (SCMM) involve assessing the completeness of safety processes in organisations at various maturity stages (typically 5). Essentially measuring the progress of safety culture improvement interventions (Goncalves Filho, and Waterson, 2018), the various maturity stages are *de facto* measures of the safety culture *product* (Cooper, 2018a). Defined as "*that observable degree of effort with which all organisational members direct their attention and actions towards improving safety on a daily basis*" (Cooper, 2000), a focus on this product is a viable and practical means of measuring safety culture (e.g. Vogus and Sutcliffe, 2007).

After 18 years, the concept of safety culture maturity is still in the evaluation and augmentation stage. With an absence of a theoretical basis, no published SCMM (e.g. Lawrie, Parker, and Hudson, 2006) has proven empirical links to actual safety performance (Goncalves Filho and Waterson, 2018). The exception is Kyriakidis et al. (2012). Looking at world-wide metro railway safety, and developing their own SCMM, this group obtained small but significant negative correlations between safety culture maturity scores and lesser injuries, but not for serious safety incidents, their precursors, or resulting fatalities. However, removing extreme outliers in the number of fatalities led to a significant correlation. This latter work signals the concept of safety culture maturity has the potential to be a valid predictor of safety culture *per se*, although it requires much more work to prove it is a viable approach to incident reduction.

3.4. Corporate social responsibility

Not previously associated with the science of safety, the introduction of Corporate Social Responsibility (CSR) in 2004 appears to have highlighted the significance of HSE performance (Mansley, 2002; Kolk, 2004; Rawlinson and Farrell, 2010). The UK had a much higher uptake of CSR than Germany and Holland, with most British companies associating it with Environmental performance, and Risk Management (e.g. HSE) (Mathis, 2004). In turn, CSR has helped reduce the UKs injuries over the longer term, as demonstrated in Fig. 1.

Reflecting the social imperatives and the social consequences of business success (Matten and Moon, 2008), Corporate Social Responsibility (CSR), has been in development for a considerable time (e.g. Barnard, 1938; Kreps, 1940; Bowen,1953). CSR came to the fore in the UK during the 1990s due to the Cadbury (1992), and Turnbull (1999) reports on corporate governance, with the Commission of The European Communities, 2001 firmly placing CSR on the European industrial landscape.

CSR is primarily an accountability and reputational issue (e.g. Al Hashmi, 2017). Similar to the safety culture construct, its many definitions based on the integration of economic, social, ethical, and environmental concerns in business operations, invite criticism (e.g. CBI, 2001; Frankental, 2001). An important aspect of CSR is that it requires business, alongside its profit maximising function, to maximise its positive impact on society. It therefore requires business to go beyond compliance to legislation and regulations. Many have made the business case for CSR based on its wide range of potential benefits (e.g. Jones et al., 2006), with some evidence showing ethical leadership positively impacts safety performance, although this is tempered by the prevailing safety culture (e.g. Khan et al., 2018).

The British Health & Safety Commission (HSC), in its strategy document *Revitalising Health & Safety,* (HSC, 2000) promoted greater corporate responsibility and accountability for health and safety. The CSR agenda introduced in 2004 (Sowden and Sinha, 2005), appears to have exerted its intended effects. For example, the UK construction industry, traditionally one of the most dangerous, recognised the growing importance of CSR and worked to integrate CSR agendas into their core business activity. In 2004, one company reported a 20 percent reduction in the number of accidents reported, the accident frequency rate, SIFs, and claims (Jones et al., 2006). Injury frequency rates commonly appear in CSR reports (Idowu and Towler, 2004; Roca and Searcy, 2012; Koskela, 2014), with OSHA(S) 18,001 accredited companies more likely to report them (e.g. Evangelinos et al., 2018). However, it appears there is still considerable room for improvement (Tsalis et al., 2018). Common HSE metrics in CSR reports preferred by investors relate to a named HSE champion at director level; reporting of health and safety management systems; the number of fatalities; the lost-time injury rate; the absenteeism rate; and the costs of health and safety losses (Zwetsloot et al., 2004), with investors often driving change by demanding improvements (Dyck et al., 2018). Unfortunately, many companies in high-hazard industries seek to fool investors by ignoring injury severity, instead focusing on high-frequency, low-consequence injuries (O'Neill et al., 2016).

It would be useful if the next phase of CSR research could identify the various safety interventions recorded in CSR reports and determine their impact on safety injuries. Desktop studies could achieve this by examining company CSR reports over a period of years, perhaps by industry and country. The advantage is that it provides a different view on the effectiveness of safety interventions, that might not otherwise reach the extant safety literature.

3.5. The impact of more recent safety science initiatives

More recent safety science concepts that have been introduced into the UK industrial landscape include Resilience Engineering (RE), Safety Mindfulness (SM) and Mental Health (MH); seemingly, not one of these initiatives exerted a clear impact on the UKs injury trends. According to Hollnagel (2014b), Resilience Engineering (RE) is concerned with developing systems that can sustain required operations under expected and unexpected conditions by adjusting its functioning prior to, during, or following changes, disturbances, and opportunities. Sharing a long history with HRO and HE (Le Coze, 2016), many RE concepts mirror exactly those found in Reason's (1998) model of safety culture (e.g. Azadeh et al., 2014). RE itself involves conducting gap analyses between work-as-done (WAD) and work-as-imagined (WAI) (Cuvelier and Woods, 2019) to try to ensure a work system or process can cope with uncertainty. As such, RE essentially promotes the risk appraisal and assessment of systems, with some advocates (e.g. Hollnagel, 2014b) placing an emphasis on what goes right, rather than what goes wrong. Based on the above, it seems fair to say that much of the domain encompassed by the RE construct is simply a rebranding exercise of the safety culture construct, focused on the Risk Assessment element of most safety management systems, which would help to account for its perceived lack of impact on the UKs injury trends from its introduction. To date, similar to the HRO literature, there is no empirical evidence available to demonstrate any impact of RE on safety performance *per se*, or injuries. As such, RE is a safety science concept awaiting evidence of its utility and efficacy.

Safety Mindfulness (SM) is another approach linked to HE, HRO and RE. Weick et al. (2008) argue that what characterises an HRO is its "collective mindfulness" of danger, where a preoccupation with failure, facilitates a capability to discover and manage unexpected events, leading to greater operational reliability and asset integrity. Vogus et al. (2010) have also applied the concept of organised SM to safety culture in healthcare settings to address patient safety. Thus, SM as a concept is generally applicable to organisation rather than individual. Over time, however, the concept of SM has returned to its roots (Langer, 1989), looking at the mindfulness of individuals: for example, in terms of their decision-making in relation to safety performance (e.g. Zhang et al., 2013) or stress (Eby et al., 2019). Again, no research exists showing a direct impact of collective or organised SM on injury reduction. There is, however, some evidence showing that safety climate, and safety leadership exerts an influence on mindful safety practices (e.g. Dahl and Kongsvik, 2018). Thus, the concept of collective or organised mindfulness may be useful for improving safety and reducing injuries, but there is no body of empirical evidence to show this is the case. Certainly, there is no discernible impact on the UKs injury trends. As such, it is another safety science concept awaiting evidence of its utility and efficacy.

Mental Health (MH) was formally introduced into the UK industrial landscape by the HSE and professional safety bodies in 2016/17, based on the UKs annual labour force survey that purported to show 256,000 workplace stress cases and a rising number of suicides caused by work. In contrast, actual MH data reported by medical GPs during the 2013–2015 period (i.e. THORGP14) showed the numbers of stress cases did not exceed 2,172, with multiple causes allocated in at least one-third (i.e. 700) of the cases: 97.5 percent of the causes of workplace stress were introduced by Human Resource professionals. UK Coroner records also showed that 3.6% fewer suicides were registered in 2016 than the previous year: UK Suicides have halved since the 1980's. Despite the voluminous extant literature on workplace stress and MH, although it is suggestive, there is no direct evidence available linking workplace stress or MH to industrial accidents or injuries. There is certainly stronger evidence for the effects of overtime and long work hours on injuries (e.g. Dembe et al., 2005) than MH issues *per se*. Similarly, construction was the only UK industry to adopt a national campaign (i.e. Mates in Mind) focusing on MH during 2017/18. Unfortunately, this resulted in an *increase* in the number of construction SIFs (38 fatalities in 2017/18 compared to 30 in 2016/17): This SIF increase can be seen on Fig. 1. Thus, there is a very real danger that focusing heavily on MH can cause safety problems to arise (e.g. rising number of injuries). The difficulty is finding the balance. It could also be argued that the MH domain is the remit of the medical health professions (e.g. psychiatry) not the safety profession, and therefore has no place in safety science *per se*.

4. Serious injury and fatalities (SIF) research

There has been much research aimed at preventing serious injuries and fatalities over the past 90 years or so, with scientific journals focused on injury prevention starting around 1940, with a huge exponential growth occurring since the 1990's (Pless, 2006). Correspondingly, there has been huge reductions in the overall numbers of serious injuries & fatalities every year: in the UK, for example, workplace fatalities have reduced from around 6000 p.a. in 1900 to an average of about 142 p.a. over the past 6 years. While a remarkable achievement in many ways, in recent times it seems the UK and other industrialised countries such as the US have reached a SIF plateau.

Part of the reason for the plateau, may be Heinrich's (1931) ubiquitous Injury Pyramid which asserts there is a *predictive* relationship between lesser and more severe injuries. This has led to an almost unquestioned truism in the world-wide safety profession that due to common causes (e.g. hazards, unsafe behaviours, and poor risk controls) the frequency and types of lesser injuries at the bottom of the pyramid, predict the frequency of SIFs at the top of the pyramid (e.g. Marshall et al., 2018). In other words, controlling the common causes at the base of the pyramid will control both lesser injuries and SIFs. Although, this perspective focused people's attention on injury reduction *per se*, many simply do not recognise that frequency reduction does not necessarily mean equivalent severity reductions (e.g. Petersen, 1998; NCCI, 2006; Manuele, 2008): it is difficult, if not impossible, to predict (Tixier, Hallowell et al., 2016) or control the severity of every incident (e.g. Duncan et al., 1998). The destruction of the Deepwater Horizon platform due to the failed blind shear rams in the Gulf of Mexico's Macondo incident provides one example: 11 people lost their lives, while the leaking well caused one of the world's largest environmental disasters (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2011). As stated by Hale (2002), "*major incidents can sometimes be predicted by minor incidents, but not always; there are always precursor signals (close-calls and deviations) of major incidents; and not all minor incidents could result in major incidents. Many SIFs /catastrophes are unique and singular events, having multiple and complex causal factors that may have organisational, technical, operational systems or cultural origins*". All four of these factors were involved in the Macondo incident, indicating the multi-faceted nature of SIFs and industrial catastrophes.

Prompted by industrial disasters occurring on sites with very low personal injury rates, scholars (Petersen, 1989; Hale, 2002; Manuele, 2008; Krause, 2012) questioned Heinrich's work. They highlighted the difficulties in making predictions about where the next SIF may come from, as organisations do not experience enough high-potential/low-frequency incidents to make meaningful conclusions. Work by Mercer ORC HSE Networks (Wachter and Ferguson, 2013) showed 20 percent of all the incidents they examined were potential SIFs. They demonstrated [1] focusing injury reduction strategies solely at the inputs at the bottom of Heinrich's injury pyramid will not proportionally reduce the number of SIFs; and [2] because the causes and correlates for SIFs are often different than non-SIF injuries (e.g. Kines, 2002; Hinze et al., 2006; Groves et al., 2007; Lind, 2008; Rautiainen et al., 2009; Martin and Black, 2015; Lööw and Nygren, 2019; Shafique and Rafiq, 2019) it requires different control strategies to eliminate them.

They recommended [a] identifying, understanding, and controlling the precursors, exposure categories and underlying contributors of all potential and actual SIF Events; and [b] using potential & actual SIF metrics to track their prevalence (e.g. Number of potential SIFs / Man-hours Worked). There was a recognition this would require two changes in philosophy: [1] Developing a strategy that specifically targets SIFs at the top of the pyramid, separately from a focus on lesser injures; and, [2] not solely focusing on those events leading to an actual injury (a reactive response), but examining events that potentially could lead to a SIF - a proactive response, with every potential SIF Event triggering a Root Cause Analysis (RCA) (e.g. Ferjencik, 2011; Dien et al., 2012). Currently, most companies use RCA when an actual SIF has taken place, but tend not to allocate the same resources to minor injury events having the potential to be much more serious.

Thus, the safety profession's fundamental dominating philosophies, focused at the bottom of the Heinrich pyramid, while clearly impacting the UKs minor injuries, has not served to control the number of SIFs. Changing the primary focus to the top of the pyramid would help prevent SIFs, and simultaneously help to control minor injuries, as many of these also have SIF potential.

Assuming there is a willingness to recognise that focusing at the bottom of Heinrich's triangle won't stop SIFs occurring, and that a different strategy is required, the following briefly provides experiential and empirical evidence pointing the way forward for developing an organisation-wide SIF process.

4.1. Defining potential SIFs

Crucially, experience has shown that to eliminate SIFs each aspect needs defining, simply to ensure a consistency of approach across companies and industries: this would serve safety science equally well.

There are two approaches to defining potential SIFs: proactive and reactive. Both are valid as they reflect the experienced reality in organisations. Proactive refers to defining a potential SIF before an incident/injury occurs, that could result from an unsafe behaviour and/or unsafe condition. For example, *a potential SIF is an unsafe behaviour and/or unsafe condition that could feasibly and reasonably have resulted in a life-threatening or life-altering injury to the person or others.* Reactive refers to defining a potential SIF after an incident/injury has occurred. Two common reactive definitions are: [1] *a potential SIF is an incident that resulted in a minor injury that could reasonably have resulted in a life-threatening or life-altering injury*; or [2] *a potential SIF is a near-miss incident that resulted in human exposure and a release of some type of stored energy that could reasonably have resulted in a life-threatening, or life-altering injury*. Clearly, defining what is meant by human exposure would be important. For example, is it an exposure when [a] a person is not very close to the incident but in the vicinity, [b] when directly threatened, or [c] just in very close proximity to the incident (e.g. Cambraia et al., 2010)? Similarly, what is meant by energy release needs to be defined, perhaps based on the work of Harms-Ringdahl (2009).

4.2. SIF precursor situations

Wachter and Ferguson (2013) defined an SIF precursor as "*a combination of hazard(s) and underlying human factors and organizational or managerial deficiencies that if left unaddressed can result in a fatal or serious injury*" In other words, SIF precursors refer to high-risk situations in which management controls are either absent, ineffective, or not complied with, and which will result in SIFs if allowed to continue (Krause and Murray, 2012). Unsurprisingly, it appears there are different precursors in different industries (e.g. Kyriakidis et al., 2012; Gnoni and Saleh, 2017; Baldissone et al., 2018), with much more research required to identify them. Tixier et al. (2016) applied machine learning to unstructured incident reports in the construction industry to extract precursors, demonstrating how safety science can harness Industry 4.0 to provide greater insight into the SIF problem.

According to Manuele (2008) and Krause (2012) most potential SIFs are disproportionately related to unusual or abnormal precursor situations. (e.g. emergency shutdowns, unexpected maintenance). The author defines an abnormal SIF precursor situation as "a *situation not generally encountered during the course of normal operations*", though others may beg to differ. However, it is important to recognise everyday routine precursor situations also carry significant SIF risks. A routine SIF precursor situation is defined as *"a situation which is repeated on a regular basis during the course of normal operations"*. When analysing two years of contractor incidents, the author found 90 percent of *potential* SIFs were related to routine, everyday situations. The percentage of *actual* SIFs, however, was higher for abnormal events (59%) than routine events (34%). A high proportion of routine SIF precursors were related to driving, maintenance, equipment use, and access/egress. Experience shows every company will have its own unique SIF precursor profile which will reflect the risks present in their sphere of operations (e.g. Smelting, Oil & Gas, Construction, etc.), although only a small percentage of these will explain the bulk of the actual and potential SIFs experienced.

4.3. SIF exposure categories

Within both abnormal and routine SIF Precursor situations, it appears potential SIFs are disproportionately related to activities 'managed' by certain safety controls (e.g. chemical handling, confined space entry, lifting operations, etc.) commonly termed 'exposure categories' (e.g. Lay et al., 2017). Activities identified as having a high proportion of *potential* SIF events include: mobile equipment (operation and interaction with pedestrians); confined space entry; jobs requiring lock-out tag-out; lifting operations; working at height; chemical handling; and use of tools/machinery. These categories differ by industry, signalling a need to identify them for all industries, but, again, only a relatively small percentage of exposure categories will explain the bulk of actual and potential SIFs experienced.

4.4. Underlying safety culture contributors

Both Hale (2002) and Manuele (2008) linked SIF precursor situations to an organisation's safety culture, but many (e.g. Martin and Black, 2015) overlook the cultural root causes of SIFs. It makes sense to link any SIF analysis with the underlying psychological, behavioural, and situational aspects of safety culture. This makes it possible to distil the focus to a smaller number of areas that address a larger number of precursor situations and exposure activities (this is not to argue precursors and exposure categories are ignored): i.e. adopting the principle of focusing on the cultural root cause to eliminate many opportunities for recurrence in one go. Psychological contributors include Human Error categories (Reason, 1990) such as failures in task planning – knowledge & rule-based mistakes; failures in execution – attentional & memory errors; and, behavioural choices – short cuts, necessary, or optimising behaviours. Behavioural contributors include leadership, job planning, and resource allocation. Situational contributors encompass features under management's direct control such as job methods, job pressures, manning levels, the provision of sub-standard equipment and poor working environments. Cooper (2018b) examined 642 potential SIFs recorded from safety leadership observations, finding 432 (67%) were attributable to Human Error categories, inadequate job methods, and the provision of sub-standard equipment. Such results point to areas of opportunity for managerial safety leadership (e.g. Cooper, 2015), while reducing down-time, the amount of effort and the costs associated with eliminating SIFs.

4.5. SIF process implementation

SIFs are the outcome of organisational failings that previously should have been identified and addressed (Reason, 1998). There are usually many signals for impending incidents, typically taking the form of 'close-calls', albeit, there is a reliance on people being able to recognise and report these.

Encouraging the reporting of close-calls and actual events presupposes [a] there is a willingness to receive these reports openly and proactively, and [b] there is the means to easily capture and record such information (Roe et al., 2011). Krause (2012) found 87 percent of all potential SIFs are identifiable from safety observations using behavioural safety processes and safety leadership 'walk-rounds'.

It is highly likely incident reporting databases will need to be adapted or developed to record and analyse the potential SIFs identified via 'close calls', in conjunction with those identified from behavioural observation processes (e.g. PEER®), to facilitate computation and tracking of a *potential SIF* metric (i.e. number of potential SIFs/hours worked) that is regularly reviewed. At a minimum, all incident reports should provide a clear description of the event and highlight [a] what happened; [b] any pre-existing risk controls at the time of the event; [c] actual hazards present at the time of the event; [d] actual consequences, [e] potential consequences; [f] the precursor situation; [g] the main exposure activity; [h] any underlying cultural contributors, and if available [i] any root causes, in addition to normal information such as location, date, etc. People will also need training to identify potential SIFs, perhaps as part of a Hazard Identification process. Training is one area where the definitions of precursor situations, exposure activities and underlying cultural contributors are useful for developing focused potential SIF training programs so people know exactly what to look for.

5. Summarising the past

Examining the impact of safety science topics in the past shows a concerted and determined application of the safety culture construct helped to reduce injuries in the UK. This involved the engagement of managers & employees in proven initiatives, that included: [1] ongoing safety culture assessments and benchmarking; [2] optimised behavioural safety processes, inclusive of leadership; [3] the development of effective safety management systems, that were regularly audited for their effectiveness and, [4] publicly holding organisations to account for their Health & Safety performance via their annual CSR reports.

The efficacy of safety science constructs that are uncertain include Human Error, High Reliability Organisations, Resilience Engineering, and Safety Mindfulness. Empirical evidence showing an influence on actual injuries or safety performance is negligible or non-existent.

The striking aspect of the UK's experience is that its safety efforts have mostly impacted the number of temporary disabilities not SIFs. To some degree, the UKs injury experience is influenced by the prevailing unemployment rate. Regardless, the safety science initiatives introduced over the past 32 years appear to have made very little difference to the number of SIFs in the UK (which is seemingly the same in other countries), which begets the question why? Answers to this question could provide the necessary focus for the future of the science of safety. Certainly, existing strategies are not reducing SIFs: something new is required or existing strategies need changing.

The safety science domain needs to urgently consider how it will help address serious injuries and fatalities in the workplace. Strongly urged to focus their future work on eliminating SIFs, safety scientists should ensure that validation against various incident/injury outcomes is the norm rather than the exception, to help ensure their work is on the right track. If evidence accumulated over time shows any safety intervention is not consistently and demonstrably related to incident and injury reduction, it may not be worth pursuing, and attention should be re-focused on other interventions. To support this, journal editors and reviewers must filter out intervention submissions not reporting attempts at establishing external criterion-related validity against actual outcomes (i.e. incidents/injuries). The regulators (e.g. EU-OSHA, HSE, OSHA) can help by introducing the SIF metric (actual & potential) into the regulatory landscape, and requiring companies to report these on an annual basis in their CSR reports.

The science, the tools, and the knowledge are available to reduce workplace SIFs, but the volume of published research on SIF prevention is miniscule, and led by industry rather than safety science. Research has a long way to go to empirically link the safety culture construct to actual safety performance, particularly SIFs. Similarly, the efficacy of behavioural safety processes specifically targeting SIFs, from both employee and safety leadership perspectives, need assessing and evaluating. Additionally, there is no empirical evidence exploring the actual impact of Human Error initiatives on injury prevention, as this topic is still in its evaluation and augmentation stage. Moreover, we need to know *why* the various aspects of the safety management systems leading to SIFs (and catastrophes) are breaking down and how to address the issues. Past research has identified *what* has broken down, but it has not satisfactorily addressed the *how* and the *why*. Perhaps if auditors focused on the effectiveness of these systems as their criterion measure, safety science might make progress. In sum, addressing the research gaps highlighted in this manuscript could provide an important impetus to SIF reduction.

Certainly, meta-analytic studies combining the results of a multitude of studies reporting actual safety outcomes would be useful (Hunter and Schmidt, 2014). For example, meta-analysing the safety climate literature to compare those studies using self-report outcome measures against those using hard criterion data such as actual injury outcomes at the time of distribution, would be extremely useful. Meta-analysing the behavioural-safety literature to assess the degree to which managerial leadership adds or detracts from the process would be very useful. The findings should be followed up with rigorously designed and executed longitudinal field studies to test the moderating parameters identified in these analyses.

Funding for pure safety science research is a big issue: there is never enough, and much published safety science research arises from scientists engaged as practitioner consultants in the field, who then write and publish their studies as a public service with the permission of the companies involved. Perhaps the ILO, EU, OSHA, NIOSH, the World Bank, and other associated bodies, could be persuaded to fund pure safety science research aimed at eliminating workplace SIFs, provided the funds were matched by industry stakeholders.

If safety science is to assist industry in making significant progress in eliminating workplace SIFs, it must also recognise one size does not fit all: it requires different strategies to control minor and severe injuries. Researchers, practitioners, and regulators must direct their efforts at the top of Heinrichs pyramid. In practice, this likely means [a] improving incident data management; [b] integrating any SIF findings into existing safety management systems; [c] providing SIF education to all concerned; [d] enhancing the quality of managerial safety leadership, who should test, question, and manage tasks with high-risk exposures and SIF potential; [e] developing and using potential SIF and actual SIF Rates that are widely shared with all via CSR reporting; and [f] periodically reviewing the effectiveness of SIF reduction processes. It may also be useful to determine the ratio between actual and potential SIFs experienced, to facilitate benchmark comparisons with others, to help determine how dangerous an industry, company or site is. As safety science faces the future, a concerted, collective, and focused effort on SIF reduction should help to significantly impact the annual toll of deaths and serious injuries around the globe.

6. Safety science in the future

It is good news that the safety culture construct has utility going forward, as does CSR with its ethical basis of publicly holding companies and organisations to account for their safety performance. Both will be vital tools as the world is deluged by the outcomes of the 4th industrial revolution. One specific example, akin to the long-term effects of asbestos exposure, is the concerns of biological safety at various electromagnetic wave frequencies - think 5G Wi-Fi – that present a clear and present danger to human health (Di Ciaula, 2018). Paradoxically, there are lower exposure limits recommended for the public, while higher exposure levels for workers are deemed to be safe (Wu et al., 2015). Workers will be involved in developing 5G applications, assembling, testing, installing and operating 5G equipment and infrastructure. Insurance companies, including Lloyds of London, have a specific exclusion, and will not insure against radio frequency induced health effects because of the known carcinogenic risks, a fact acknowledged by the very same companies involved in the transmission of electromagnetic fields. Clearly, there are large financial rewards on offer for those who can harness 5G Wi-Fi to create and dominate the Internet of Things (IoT). From a safety science perspective, the question must be asked: what are these same companies doing to mitigate the risk to their workforce? The amount of effort these companies put into protecting their workers from the known hazards associated with 5G Wi-Fi provide a strong indicator of their safety culture and CSR ethics. Equally, many companies are going to want to take advantage of the opportunities presented by 5G and IoT. As consumers, how are these companies going to manage the risks to their workers. Will their safety cultures be strong enough to prevent them exposing their workers to the risks, or at least mitigating them, or will the financial rewards on offer over-ride their safety culture instincts? This leads to the question, to what extent will these new technologies alter the parameters of the safety culture construct? How will behavioural safety processes be adapted to cope with 5G risk mitigation? Are current safety management systems good enough to cope, or will they need to be adapted. What kind of risk controls will be required? How different will these be from existing risk control methods? Will there be entirely new classes of risk controls? Will the safety culture construct fragment into industry specific tools and methodologies or will validated universal models still be applicable? Clearly, in many safety science domains there are going to be many challenges to existing paradigms from the 4th industrial revolution.

Such challenges will, I suspect, also lead to the fragmentation of the safety science domain itself: Its current diversity is both a strength and a weakness: It's a strength because of its inclusive attempts to cater for safety issues in a multitude of domains and settings, where nothing is left behind; It's a weakness, because the domain is so broad and the science so diffused that it tends not have the same impact that it could have if safety scientists focused on a smaller number of topic domains. The existing HRO, RE, and SM literature that caters for essentially the same construct, provides one example of a diffused focus in safety science that has not lived up to its promise. As such, I can foresee a time when the number of Safety Science Journals expand to separately cater for the domains of industrial/occupational safety, public safety, governmental issues, patient safety, etc., so each provides a much greater focus on the salient issues of its time. The downside is safety science could descend into silos that do not communicate with each other. Without a doubt, interesting times lie ahead for the safety science domain.

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Declaration of Competing Interest

None.

Appendix A. Supplementary material

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