CURTAILING INVISIBILITY OF HEALTH AND SAFETY RISKS

Paul Lindhout [a,b], Genserik Reniers [b,c,d*]

a Department of Care Ethics, University of Humanistic Studies, The Netherlands

b Faculty of Applied Economic Sciences and Engineering Management (ENM), University of Antwerp, Belgium

c Safety and Security Science Section, Faculty of Technology, Policy and Management, Delft University of Technology, The Netherlands

d Center for Corporate Sustainability (CEDON), KULeuven, Belgium

* Genserik Reniers, G.L.L.M.E.Reniers@tudelft.nl

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Abstract

Risk control in many areas in society is based on known danger and avoidance of predicted accidents. Between accidents as predicted and accidents as they actually occur, there is a gap however. This gap hides a multitude of relevant safety information which might therefore not be considered in safety management systems, risk inventories and accident scenarios. Hence, it might help to pay attention to the gap of "invisible" phenomena and mechanisms and study the concept of "invisibility". Wondering about the role of invisibility in this respect, the authors explore literature using a scoping review approach, in search of invisibility concepts: ways in which full or partial invisibility exists in a variety of areas relevant to safety. Some 202 of such concepts are found. They can be grouped into 22 frequently found types of invisibility, each capable of hiding relevant safety information. Using a theoretical object-path-observer model, deconstruction of invisibility concepts into their constituting parts, and a proposed systematic combination process, an inventory with many more invisibility concepts can be generated than presently found in literature.

This provides a new tool to search for currently hidden safety information and scenarios in the gap. Several examples of newly generated scenarios are discussed. The methodical limitations of this study make the current results indicative only. Both the 22 most frequently found invisibility types and the generation of new object, path and observer property combinations are recommended for use in safety management practice. Further research is recommended to gather more complete data for justification of an invisibility concepts classification.

RESEARCH HIGHLIGHTS

- Many accidents happen via not previously identified scenarios, this is pointing at a scenario-gap
- In order to find such scenarios the authors explore ways to assess the contribution of invisibility
- To this end a method is proposed which is based on known types of invisibility in many areas
- A new tool is described to search for hitherto invisible safety information and scenarios
- Insight in how invisibility occurs in safety management practice will improve hazard identification

1. Introduction

For ages, people have been dreaming about using invisibility to ones own advantage, while at the same time fearing invisible enemies. Some of these thoughts turned out to be not merely a fantasy but real possibilities and hazards. An example of this is the significant underreporting of language problem related accidents (LPRA) (Lindhout, Kingston & Reniers, 2019). It became clear that although this type of accidents is a manifest problem, the world observing this seems to be *turning a blind eye*.

A few notes, taken then with the intention to explore this point of view in relation to safety management, sparked several further studies, a.o. on company *risk appetite* and *assessing the unknown* (Lindhout & Reniers, 2017A), on introducing psychological *nudges* in the process industry (Lindhout & Reniers, 2017B), on structuring *inarticulate experiences* in qualitative health research (Lindhout, Teunissen & Visse, 2020), on an *unknown risk inventory technique* (Lindhout, 2019), and on *systematically reducing unknown risk* (Lindhout, Kingston, Hansen, & Reniers, 2020).

These studies made us aware of the importance for safety experts to focus on the '*scenario gap*', the gap between accidents as predicted and accidents as they actually occur (Lindhout, 2019). The risks, emerging from this gap as unpredicted yet actually happening accident scenarios, are also referred to as '*atypical accident scenarios*' (Paltrinieri et al., 2013-A; 2013-B). Similarly, Krausmann & Necci (2021) discuss extreme outliers among accidents, the so called 'Black swans', and argue that Natech risks (technological accidents triggered by natural hazards), hitherto being considered as unthinkable, or an "Act-of-God", can be reduced , starting from "corporate mindfulness of the risk". Extremely unlikely events also come with high uncertainty levels, in leading to their disposition as residual risks (Taleb, 2010).

In 2020, the results of our study on mapping *pandemic safety management* (Lindhout & Reniers, 2020) underlined the importance of invisible hazards, of awareness of their scenarios, of prevention and of listening to *weak signals* (Delatour et al., 2013).

In fact there is an ongoing history of scientific publications on risk identification in safety research since World War II. In the 1950s, disasters were assumed to always have some sort of *warning phase* at the beginning of their sequence of events, followed by an *incubation period*. In the 1960s and seventies, organizations' incapability to cope with emergent, unknown and uncertain dangers, led to difficulties to decide which dangers to prioritize for action. These problems were seen as an intelligence failure, meaning a lack of information exchange and insufficient collective awareness of its coherence, causing *failure of foresight* (Turner, 1976). Some 44 years later, an ESReDA (2020) project group pointed at the necessity of *foresight* in safety management and of attention for *early warning signals*. This illustrates the longevity of these problems.

Safety science embraced a range of safety theories, organizational theories, and human behaviour theories in the last 100 years of its history (Swuste et al., 2010; 2014). Currently, human error (Reason, 1990; Williams, 1986; Rasmussen, 1990), technological complexity (Perrow, 1984), complex organizations or systems (Turner, 1976; Hopkins, 1999; LaPorte & Consolini, 1991; Leveson et al., 2009), organizational imperfections, social and ethnographic aspects (Bourrier, 2011) and socio-technical systems (Hollnagel, 2012; Cuel et al., 2016) are all regarded as relevant for safety and for accident causality.

Accident history has shown however, that in spite of ongoing developments in safety thinking (Lindhout, 2019), a category of unforeseen, previously *unrecognized atypical* scenarios remains (Paltrinieri et al., 2013-A; 2013-B). Leveson et al. (2014, p73) conclude: *"the potential for additional approaches should be explored*".

Recently, various new methods for systematic risk inventory and prediction were developed, e.g. better use of recorded accident cases for prediction via risk horoscopes (Bellamy et al., 2015), better use of early warning signals collected from investigated accidents via the DyPASI technique (Paltrinieri et al., 2013-A), application of systems-theory in hazard analysis to check for new or missing risk factors, e.g. software bugs and human error, via the STAMP/STPA technique (Leveson et al., 2014) and an increased capability to model complex socio-technical systems via the FRAM method (Hollnagel, 2012; Patriarca et al., 2017).

These sources intend to make better use of available risk notions, past events, available signals, identified risks, existing accident data and methods available to safety management. The authors believe the sources describe well proven approaches which will stimulate the thinking during risk assessments. None of them explicitly or pro-actively checks for missing safety information during a risk identification process however.

We argue that it is logical to assume that the unknown, invisible, unlikely, unrealistic, unpredictable, unimaginable, unbelievable, unrecognized, uncertain, unthinkable, impossible, unidentified, newly emerging, inevitable, irreducible and residual risk related scenarios, are all hidden in the *scenario gap*.

Looking at this compilation of terms, extracted from current safety literature, we feel that building "generative" safety cultures in organizations still has many hurdles to overcome. Pro-active searching for hazards should be normal practice for safety engineers. Organizations with little "*risk appetite*" now make conscious decisions to not even attempt to pass some of these hurdles (Gjerdrum and Peter, 2011).

We feel that two of the terms stand out: "*unknown"* and "*invisible"*, since both seem often used as an argument when deciding not to act. Both these terms can - at first glance - appear to be insurmountable obstacles for safety engineers. After we studied the "unknown" obstacle and discovered that safety engineers can "*systematically reduce unknown risks*" (Lindhout, 2019; Lindhout et al., 2020), we became convinced that probably all of the extracted terms can be challenged, and can be overcome as an obstacle via new practical tools and techniques to unveil and prevent accident scenarios hidden in the scenario gap.

The "*invisibility"* obstacle is the subject of this study. Rather than safety engineers claiming that there are no further scenarios to add to an organizations' risk inventory because they see no reason to do so, they could systematically wonder what could be hidden in the gap because it is invisible to them for some reason. If the many ways in which invisibility can exist are identified, deconstructed and recombined to what we will call existing or new "*invisibility concepts*", the places which might be hiding something relevant to accident scenarios in an organization will stand out. This tool allows safety engineers to systematically search those places for causes leading to scenarios which are hitherto invisible.

All this made us wonder about a new *invisibility* oriented point of view, extending beyond *turning a blind eye,* and not just settling for shortcomings as they are observed, followed by corrective actions, but also questioning the completeness of such observations. This is in line with a *generative approach* to safety management and a proactive search for hazards (Parker, Lawrie & Hudson, 2006).

The administrative and organisational problems encountered in our LPRA study findings (Lindhout, Kingston, & Reniers, 2019) rather well compare to *invisibility* as it occurs in e.g. physics, biology and military tactics. Besides the physical aspects, the observers' attitude, situational awareness, prejudice and limitations are likely to play a role. As Turilli & Floridi (2009, p105) describe it, there is also "*a condition of information invisibility*" to be included here. Also LaPorte & Consolini (1991) talk about the challenge to make administrative processes failure free. Bourrier (2011, p.12) underlines the importance of exploring the administrative and engineering processes in complex systems, since "*we depend on these invisible webs of teams, decisions, technology, infrastructures, and yet we know almost nothing about their daily operations*."

Based on these considerations the authors explore the possibilities of reducing, diminishing, constraining and curtailing *invisibility* since that hides hitherto undiscovered accident scenarios in the scenario gap. The assumption here is that if the ways how invisibility might occur – the invisibility concepts – are known and understood, there are also possibilities to assess whether such ways can hide hitherto not identified accident scenarios, simply because during risk identification activities nothing about such scenarios was visible, observable or noticeable.

Being invisible is appealing to the imagination (Woolley & Brown, 2015). We argue that it is imagination which can help the safety engineer to expose invisible hazards lurking in the scenario gap. Preferably this should be done before those hazards can lead to yet more unpredicted major accidents, rather than leaving companies and society unprotected against uncontrolled risks originating from hazards deemed 'invisible'. Considering that "unknown risks" aren't as unknown as one might expect, since they can be approached, analysed and reduced in a systematic way (Lindhout et al., 2020), we wonder whether "invisible hazards" could also be identified, exposed and brought under control in some systematic way. This study departs from the optimistic notion that unsafety almost always shows in one way or another before a major accident occurs.

Especially our earlier studies dealing with unknown risks (Lindhout, 2019) added to our surmise that '*concepts on how to achieve invisibility*' as a subject can be dealt with in much the same way as is being done in other inventory and classification oriented studies. It took quite a while before we could actually start though.

We started to wonder if it would be possible to develop a tool to find causes leading to scenarios currently residing in places where they are invisible due to an *invisibility concept* 'at work'.

In the beginning of 2021, at home, in lockdown, collectively fighting today's biggest invisible enemy Covid-19, and eagerly waiting for vaccination, we decided to further explore '*invisibility concepts*', guided by the following question: *Could - after separation of the realistic wheat from the fantasy chaff - making an inventory of invisibility concepts lead to a meaningful classification and to insight as to how this could contribute to industrial safety management?*

2. Methods

The research question is first of all a commitment to make an inventory of ideas how invisibility could be achieved. Ways to select realistic concepts and to characterize their quality in a similar manner must be found next. This requires a model, a definition and suitable appraisal scales, allowing clustering of similar '*invisibility concepts*'. To achieve this, data gathering is done via literature search, followed by analysis using meta-synthesis (Cronin et al., 2008; Timulak, 2014; Polit & Beck, 2006).

Because of the generic nature of this study a non-specialized database is most suitable for literature search. Google Scholar and its associated proprietary databases were therefore selected.

This indicates that a scoping review (Smith et al., 2015) approach is needed, using multiple successive searches with progressively refined combinations of search terms to gather potentially relevant sources from a wide variety of areas. A process following the approach of Byrne (2016) and Byrne, Daykin & Coad (2016) is then used to select admissible sources.

2.1 Inclusion/exclusion

This research cannot be done in a meaningful way without admitting several non-scientific information sources to this study (Wessels, 1997; Cronin et al., 2008). The generic nature of the subject makes the use of Google Scholar as a general database both practical and suitable since it provides access to multiple other databases.

Any concept of invisibility according to the definition used here can either be put to good use, or be exploited for e.g. unethical, immoral or criminal activities. Since this is a conscious choice of a user, and technically not part of invisibility concepts, this notion is not further investigated. This means also that in the present study we do not distinguish invisibility concepts by their intended use, e.g. for safety management or for security measures.

2.2 Theoretical model

Arguably, the word 'invisibility' is not only saying something about an object that people cannot see. Some part of invisibility is located on the path towards the observer and yet another part resides at the observer. Many psychological observer flaws play a role e.g. prejudice, bias, short-sightedness, lack of focus, being pre-occupied with other things, a lack of questioning attitude, and so on. Also medical issues, psychiatric problems or substance abuse may cause the observer to perceive an object in strange, unexpected ways. The generic situation of 1) an object, 2) a path transferring visual information about it, and 3) an observer, resembles the communication theory setting. This linear

communication model was first published by Claude E. Shannon (1948). There, information flows along a path via sender, transmission and receiver in one direction.

The application of this situational model to *invisibility* leads to three main research aspects: firstly, the properties of the emitting object, secondly the flaws or interruptions in the transmission path between the object and the observer, and thirdly, the properties of the observer, influenced by e.g. limitations, attitude, prejudice or epistemic injustice (Fricker, 2017; Groot, Haveman & Abma, 2020; Groot & Abma, 2021), see (Figure 1).

Visibility implies the presence of a flow of light. Although the human eye is only sensitive to a narrow wavelength band, the visible light between infra-red and ultra-violet, the meaning of *visibility* in practice is often extended to a wider band in the electro-magnetic spectrum. Nowadays, the human eye can be assisted by many kinds of technical means (Font-Casadó, 2017), e.g. infra-red camera, x-ray equipment, telescope, microscope, all processing photons.

Between full visibility and invisibility is poor visibility. Therefore, *invisibility* is not merely a condition of the object not emitting any photons or the result of poor transmission along the path, but is regarded here as a variable degree of failure to observe the object by a fallible observer.

As a measure of performance of an *invisibility concept* the *non-visibility percentage* (NVP) is chosen here. This approach allows *invisibility* to be expressed by e.g. a numerical value, here a percentage, where 0% means fully visible and 100% means completely invisible.

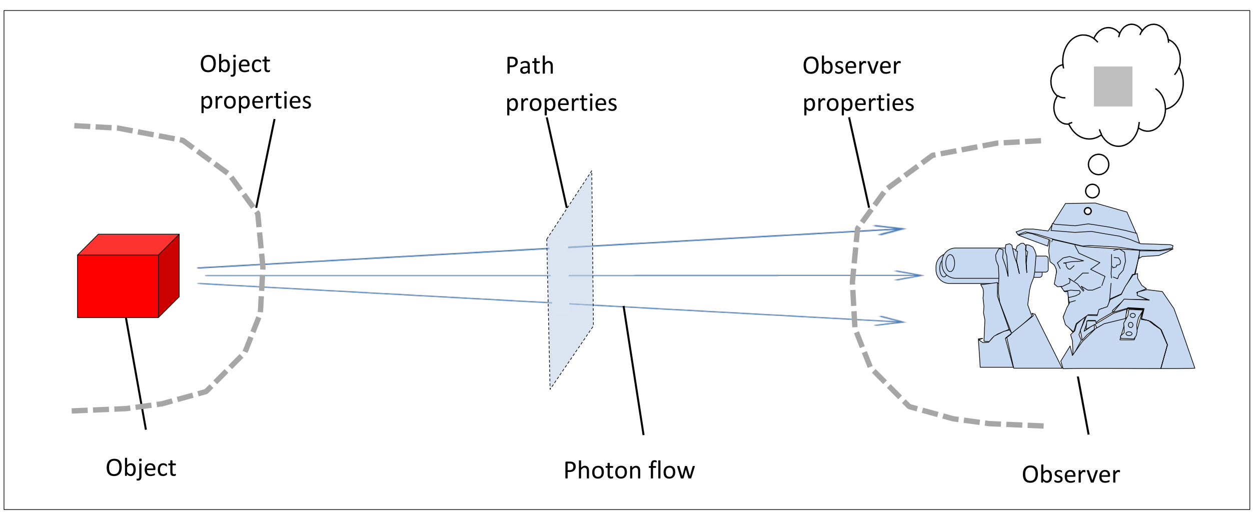

Figure 1 Design of a theoretical Invisibility Concepts Model (ICM) showing a flawed observation.

The above leads to the definition of *invisibility* being used here:

Invisibility is the degree of ineffectiveness of observation of an object, either with the naked human eye or technology assisted.

Several theoretical and practical issues require attention when aiming for an inventory and classification of invisibility concepts (Cronin et al., 2008; Sanderson & Croft, 1999).

A typology of invisibility concepts

Although dipping a transparent object in an equally transparent liquid with the same refractive index will render the object invisible, this is not the kind of invisibility suggested in "*The invisible man*". A chemical concept is suggested there, whereas the dipped object is invisible due to a physical, or more specific, an optical effect. Separating concepts by their nature or kind into a typology is at the base of an inventory and classification. This requires simple text analysis to recognize synonyms and group invisibility concepts as they emerge from the findings (Timulak, 2014).

Some form of credibility scale to appraise concepts

Lay information sources indicate many directions to look for invisibility concepts. Seen from an applied physics and engineering background, some directions seem credible, feasible or plausible at first glance, while others immediately appear unrealistic or even impossible.

A simple scale with indicative percentages is used to appraise the credibility of concepts. At the top end of the appraisal scale, representing the most credible ones, is 'well proven existing concepts'-100%. At the bottom end the most incredible 'sheer magic'-0% ones will be placed. In between the scale shows 'rather unlikely'-1%, 'seems plausible'-10%, 'possible in theory'-25%, 'being tested'-50%, and 'demonstrated principle'-99%, which are appearing in order of increasing credibility and indicative percentages.

A performance measure to assess achieved invisibility

The term 'invisibility' will need a rather precise definition since something can be not seen, hardly seen, seen but not recognized, seen but not noticed or seen but creating a false impression. Hence, amazingly, invisibility appears to come in different degrees and qualities. A fundamental choice can be made here between invisibility as a characteristic property of an object, as a path related problem, or as a flaw associated with the observer. Here, invisibility is – like beauty in the eye of the beholder – seen as a result observed by the observer. This makes *ineffectiveness of observation* a suitable measure of invisibility performance as it can be operationalized as a percentage.

For example: a bright red square box, observed from a distance through a haze, with help of binoculars, will appear as a light greyish pink square to the observer. The object's main characteristics 'bright red' and 'box' are lost, only 'square' is being observed. The ineffectiveness of this observation can be expressed as 2 out of 3, or 67% invisibility.

A theoretical model to uniformly accommodate a variety of *invisibility concepts*

Exploring invisibility and providing a structure to collect the findings requires a model. An adapted version of the Shannon (1948) linear communication model is chosen as the starting point (Shannon & Weaver, 1949). An object, an observer and a photon flow between them must be at the core of a physics inspired model. In the model the photons are leaving the object in a way determined by object properties. Underway, in the direction of the observer, the photons are thought to be affected by path properties. When arriving at the observer, the observer properties are decisive for how the photons are received. Finally, the observer limitations and attitude determine what happens to the photons received, in terms of recognition and interpretation. Together the influence of all three groups of properties adds up to a degree of ineffectiveness of the observation.

At this point it is necessary to stretch the model a little beyond the mechanics of strictly physical observation processes. E.g. accident statistics can be showing something else than the whole truth. The accident would be the object here. The information stream in the administrative process now represents the photon flow. The observer in this case is the manager receiving the information and acting on it. Poor accident statistics can be caused by any combination of flaws in these three process steps, just like in the physical process. In order to accommodate such administrative and human behaviour aspects, the model can be thought to use a flow of imaginary "*informatons*" or "*behaviorons*" instead of photons. In this way, the model allows gathering all kinds of invisibility concepts in a practical and uniform manner. It also enables straight forward comparisons between concepts and clustering them on basis of similarity.

This scoping review is used to explore an area which is not structured as a body of knowledge (Őren, 2005) and has no unified set of terms, the result can only be a preliminary inventory and typology. Neither of these two is likely to be complete as data saturation cannot be achieved within the limitations of the chosen method.

3. Results

Data gathering from literature was conducted in several consecutive searches (table 1). Details about the screening process are shown in figure 2.

3.1 Scoping search

Exploring *invisibility concepts* via literature search seems a daunting task at first glance. An initial search via Google on January 18, 2021, generates a stunning number of 108,000,000 references.

The term '*invisibility concept'* is not only mentioned in a wide variety of subject matter, originating from many scientific disciplines and societal areas, but also both in lay sources and in scientific sources. Narrowing down the search to scientific sources with Google Scholar, and searching only in titles however, shows that '*invisibility concept*' as the explicitly mentioned key subject of research is found only once: Woolley & Brown (2015) claim that children develop invisibility as a concept between 3 and 7 years of age and learn to distinguish two sides: the real world and fantasy.

Also Beyazıt & Ayhan (2020) look at the importance of concepts in the cognitive development and socialisation of young children and place this in the context of acquiring knowledge (Taylor, 2005).

Table 1 Search terms and successive searches

	Scoping search	Invisibility concept (search in all source types)
A	Preliminary search	Invisible, book, motion, picture, biology, mimicry, military tactics, visible, light, invisibility cloak (searching directions and terms)
B	Concepts search	"Invisibility concept" in source texts from a wide range of areas (in support of an inventory)
C	Safety search	Invisibility, administrative, industrial, safety, management, health, statistics, records, underreporting, hazard, NOT: hospital, psychiatry (where invisibility relates to safety)

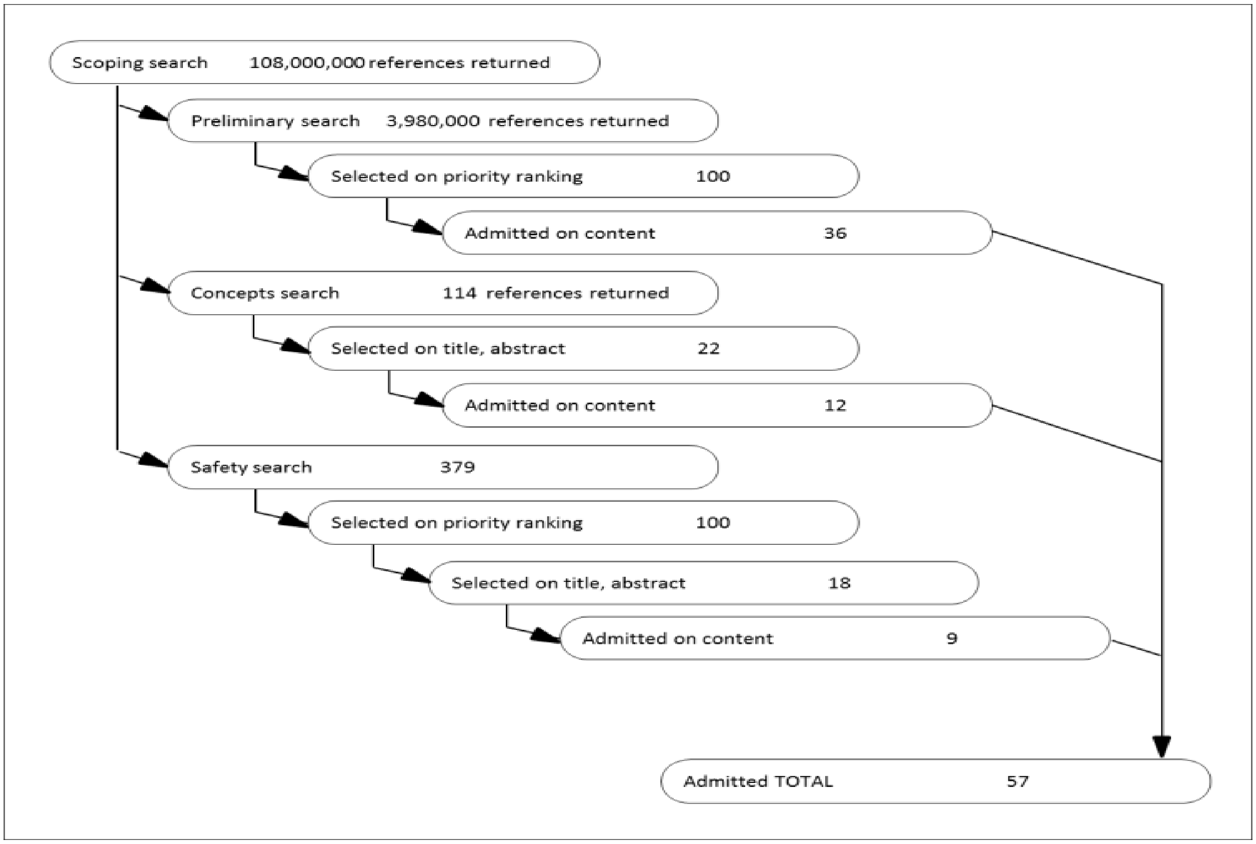

Figure 2 Flow chart showing literature selection process

3.2 Preliminary search

When looking for 'invisibility' some five categories of sources stand out. People immediately associate them with invisibility. These categories are not intended to be complete, let alone exhaustive. This preliminary search is intended to pave the way for safety specific searches by establishing frequently used terms. We have limited this search to five categories – books, motion pictures, biology, physics, and military tactics – for practical reasons. For example the societal invisibility of groups or making something or somebody invisible via ICT, software, virtual reality and social media are not included.

The five categories explored here provide a starting point for finding invisibility concepts in literature. The findings comprise invisibility concepts varying from pure phantasy to evidence based physics, all of these areas are considered usable as a start for further exploration.

Books

A classic and probably best known example of a book about using and abusing invisibility is titled

"*The invisible man*", written by the British science fiction author Herbert George Wells (1897).

Here, invisibility is caused by unexplained chemistry (Bangham & Kaplan, 2016).

In the world famous of book series "The *Lord of the Rings*", by John Ronald Reuel Tolkien (1937; 1954A; 1954B; 1955), the wearer of the magic ring becomes invisible as soon as it is put on a finger. In the "*Ring des Nibelungen*" written by Richard Wagner (1876) it is a magic helmet which makes the wearer invisible. As a reminiscence of Greek, Nordic and Welsh mythology, the power of invisibility appears as a returning theme in literature (Perkowitz, 2011). An '*invisibility cloak*', as it was used by Harry Potter the first time in ". . . the Philosophers Stone" story (Rowling, 1997), still is an inspiring concept that stimulates the imagination of people engaging in art (Bialkowski, 2018), fiction, non-fiction (Webb, 2017) and in science (Fleury et al., 2015).

Motion pictures

The book of Wells (1897) inspired the entertainment industry to create an impressive volume of comic strips, movies and TV-series, starting from "*The invisible man*", a motion picture directed by James Whale (1933). The most recent example is a remake, written and directed by Leigh Wannell (2019). Starting from Gene Roddenberry's (1979) first *"Startrek"* movie, many science fiction motion pictures and TV-series episodes, showed entire space-ships being made invisible from the outside by the flick of a switch. The motion picture "*Predator*", a science fiction action story about a cloaked alien hunter, written by Jim and John Thomass (1987), sparked not only several sequels but also a vanishing Bond car, appearing in Ian Flemings' (2002) movie "*Die another day*". Several technical cloaking attempts, using camera's and flat TV screens to make a moving car invisible, were shown on TV (Mercedes, 2012; Top Gear, 2015). Pablo Giorgelli's (2017) prize winning motion picture with the title "Invisible" illustrates the anticipated social dimension of the desire to be invisible.

Biology

Some animals can imitate objects in their environment and by doing so, hide themselves in plain sight (Alcock, 2013). Many of these animals move very slow or simply sit still, using an appearance of e.g. a leaf, twig, rock or sand. Other animals expose only a small part of themselves while the rest is hidden underground. Others move very fast, like spiders moving back and forth with a high frequency so they are hardly visible, a bit like aircraft propeller blades. Some animals, like octopus and chameleon, even use amazingly complex coloured skin patterns, changing along with the animals' moving background. In this way they can both be active and still blend in with the background (Josef et al., 2012). Xu et al. (2020) describe the transparency of crustacean *Cystisoma* as a strategy to be invisible for predators. Raut et al. (2009) describe transparent jelly fish.

Animals also dress up like other animals or plant parts. Some mingle with their visual examples and remain unnoticed. Some 3000 types of stick insects have been identified by biologists, many of them looking like a twig or a leaf. In biology, this way of not being noticed is called imitation or mimicry (BE, 2000).

Physics

Any object can be invisible. The single biggest object people cannot see is the 27% *dark matter* in space which dwarfs the 5% ordinary matter we belong to ourselves. The remaining 68% of outer space is *dark energy*, the invisible "stuff" of space itself CERN (2021). Scientists currently suspect that dark matter consists of sub-atomic particles. Amazingly we cannot see any of it in a direct way. These extremely small assumed particles have no interactions with photons whatsoever. However, thanks to their interaction with gravity at the scale of a galaxy, scientists concluded dark matter exists (CERN, 2021). Any other, more ordinary object in every day life can be *invisible* for many different reasons. In the material world, governed by the laws of physics, invisibility can be due to the object having the same colour, shape or pattern as its environment. Thanks to limitations of human sight, people cannot distinguish such objects from the surrounding scene, although they are present in plain sight. Alternatively, an object could hide in darkness or shadow, be fully transparent, be too small to see or perhaps too big. This is much like the ignored proverbial elephant in the room, e.g. global warming (Judge, 2008). Climate change used to happen too slow to be noticed. Light could be led around an object, thereby taking it out of the observer's sight (Gharghi et al., 2011; Zhang et al., 2011; Zheng et al., 2018).

Light from any object may get lost before it reaches an observer. Once underway, the path of photons is not necessarily a straight line between object and observer. Photons can be absorbed, reflected, refracted, strayed or delayed while crossing through matter and bent by optically active *metamaterials* (Shalaev, 2008; Coudert & Evans, 2019). A demonstration video shows what such materials can do (HB, 2018). In space, light can be bent under extreme gravity conditions in the proximity of black holes (Cunha & Herdeiro, 2019) resulting in pockets in space, in which objects are invisible from specific positions elsewhere.

An observer may not notice arriving photons for a variety of reasons. An observer might look straight at the object but miss it due to a blind spot. The observer may also be blinded by a bright light shining from just next to the object. The observer might be colour blind and therefore unable to recognize an object by its colour. The object may be too far away or laterally move to fast. An observer can simply look in the wrong direction or at the wrong moment. The arriving number of photons may be too small to exceed the detection threshold of the observer. The object might be too inconspicuous to be noticed by the observer. An object might be among many similar objects and therefore not stand-out enough to be noticed. Examples of this are a single person in a crowd, a single grain of sand on the beach or a single leaf in a forest. Another object may block the view, or the object may be outside the observer's field of view.

Huge distances in outer space make it impossible for recent events on remote objects to be seen from earth. Their light has not yet arrived at the observer. Light from distant objects might never arrive on earth due to expansion of the remote part of outer space itself, faster than the speed of light (Hawking, 1988). Perhaps the major part of space – if it exists at all – remains invisible because it is beyond the calculated 46.5 billion light years radius of currently observable space. In due course the main part of currently observable space will become invisible too as it crosses the event horizon caused by further expansion of space reaching light speed (Davis & Lineweaver, 2003). Today, most of the objects in observable space are seen as they were a long time ago. The further away the longer photons have taken to reach us.

Military tactics

Everybody knows about the element of surprise, staying hidden behind inconspicuous objects like a tree or a scrub or in a dent in open field, not being seen until just prior to an attack. Not being recognized can be achieved with camouflage. This is allowing soldiers, military equipment or even a command post or living quarters to merge with the forest or field environment (Shell, 2012).

Ensuring that a vehicle, a fighter jet or on a seagoing navy vessel cannot be easily recognized is also possible by using a colour pattern to distract or disguise. In this way military ships can be made unrecognizable from a distance. Old military tactics also include deception and disguise, decoys and diversion, hiding in trenches and using smoke screens. These tricks distort the perception of the observer, make the observer look elsewhere; or block the view of the observer (Kopp, 2005; Cuthill, 2019). Use of new technology such as radar and infra-red cameras rendered a part of these traditional hiding and camouflage techniques useless though. In turn, new stealth technology counteracts radar (Shchelokova et al., 2015).This indicates an interaction similar to biological evolution where predator and pray can be engaged in a co-evolutionary mutual adaption process trying to do better in respectively finding or avoiding each other (Vermeij, 1994).

3.3 Concepts search

Exploring whether scientific literature mentions something which qualifies as an *invisibility concept* is both difficult and relevant. It is difficult because *invisibility concept* is not in use as a widely accepted term among scientists. At the same time it is most relevant in this study, since it indicates that invisibility is e.g. intentionally being pursued as a goal, identified as a subject of interest, recognized as a key property or considered as a relevant aspect. The areas where invisibility relates to safety, resulting from this search, are of a predominantly technical nature. These are:

- *Experiments* with specially designed surfaces structures, special optical and magnetic materials, nano-grid based optical-, radiofrequency- and microwave cloaks to hide an object have shown some proof of concept for slow moving or static situations. Active cloaking achieves partial invisibility at best. Most concepts deal with small objects, a narrow wavelength band or two dimensions only (Shchelokova et al. 2015; Xu et al., 2020; Teperik et al., 2017; Caravantes et al., 2016; Gaillot et al., 2008; Raut et al., 2009).

- *Limited visibility of routine activities* in socio-technical systems and the people doing these. This work can be partly invisible yet present in plain sight, complicating e.g. assessing malfunctions, taking corrective actions and change management (Cuel et al., 2016). Font-Casadó (2017) reflects in a phenomenological way on how to "observe invisibility" and wonders if an object in plain sight can also be partly invisible.

3.4 Safety search

The role of invisibility in relation to safety is explored here without constraints. Invisibility might touch upon safety management in many ways. It may vary from e.g. being a causal factor in accidents, a social problem aspect for specific worker groups and a lack of meaningful deviation data in records or statistics. This search explores explicitly mentioned relations between invisibility and safety resulting in the following areas:

- *Invisible safety hazards*, e.g. electrical hazards Zhao & Lucas (2015), remote or encapsulated installation parts (Alibage, 2020; Perrow, 1984), new technology bringing new safety risks (Nawaz et al., 2019), suffocating, explosive or toxic atmospheres in confined spaces, not only life threatening for a worker but also for fellow workers violating safety procedures in their attempt to rescue a victim (Selman, 2019), heat strain for agricultural workers (Wagoner et al., 2020), radiation (Lindee, 2016).

- *Early warning signals not recognized or not acted upon*, thereby not preventing safety incidents occurring afterwards, e.g. chemical impurities, contamination, air pressure, vapour, poor maintenance, ageing equipment, poor knowledge management, failure rates, deviations, trends, poor metrics or metrics used as target (Esreda, 2020), darkness, poor visibility (Noy, 2020).

- *Superficial or incomplete accident reporting, records and statistics* which fail to prevent avoidable repeats of known types of incidents, due to e.g. infrequent government inspections, victim language barriers, ignoring new emerging incident types, poor database taxonomy, organisational forgetting, spreading "good-news" biased information, or "most severe incidents" based selective information, or deceptive, false or incomplete information (Lindhout et al., 2019; Barnetson, 2012; Downer, 2014).

- *Administrative processes hiding safety information* e.g. improper work practice, health and safety problems related information (Sarfaty, 2020; Rasmussen et al., 2014; Turilli & Floridi, 2009).

- *Administrative processes hiding people*, e.g. via creation of standardized forms and notebooks, move an individual or a group out of view, shaping records and archives (Bangham & Kaplan, 2016; Jardine, 2016; Lindhout & Reniers, 2021).

- *Administrative processes hiding activities,* e.g. corporate transgression and improper conduct as an industrial safety risk (Lindhout & Reniers, 2021; Bandura et al., 2000).

- *Invisible knowledge and skills of workers,* affecting safety and health due to e.g. workers not raising their voice about hazards due to poor social circumstances and their vulnerability (Wagoner et al., 2020; Wilmsen et al., 2015), or workers contribution to safe work being ignored (Eakin, 2010; Bourrier, 2011).

- *Invisible economical activities*, jeopardize safety management and government inspection all together, e.g. the informal economy (Afolabi, 2019) or a stay at home workforce (Von Oertzen, 2016).

- *Safety culture and safety behaviour*, when treated in a superficial or non-visible way, might consist of rituals and symbols only (Alibage, 2020), and be limited to the outer safety culture layer (Guldenmund, 2000). This can adversely influence safety via unsafe acts, e.g. originating from poor workplace hazard awareness, from lacking records and indicators, from lacking presence of visible safety measures (Azmat, 2020), from disregarded psychosocial safety risks such as absence of- and animosity among workers, from assuming the management to take care of safety (Jiménez, 2019), and from workers evading supervision (Anteby & Chan, 2018). We consider the invisibility of both safety hazards and of health and safety measures as safety culture aspects which can be interpreted via the TEAM-model (Vierendeels et al., 2018).

4. Analysis

4.1 Compilation of invisibility concepts

The 57 sources admitted to this study are screened for text parts describing an *invisibility concept*. Each description found is extracted from the source text and then assessed on how it matches with the ICM model observation process (see figure 1). Next, each description is split-up in descriptions of properties which can be allocated to the applicable object-, path- and observer positions in the ICM model. Any non-realistic invisibility concepts, e.g. the Tolkien (1937) magic ring and Roddenberry's (1979) spaceship cloak, are excluded from further analysis by using a cut-off criterion of <1% on the credibility scale. Each admitted *invisibility concept* is characterized by a unique short summary identifier text. Finally, in an iterative process, the *invisibility concepts* are clustered on basis of similarity in their identifier texts using meta-synthesis (Timulak, 2014).

The textual data extracts for each invisibility concept found are tabulated in three separate columns for object-, path- and observer property values. Because of the way this set of *invisibility concepts* is obtained, the result must be regarded as indicative only and cannot be used or interpreted as a complete inventory. Nonetheless, this work results in an indicative compilation of realistic *invisibility concepts* (n=202).

More than half of the *invisibility concepts* match with a single column (n=109), that slightly less than half of them consist of a combination of properties in two columns (n=92) and that only a single concept has properties spread over three columns (n=1). Hence, *invisibility concepts* with three "active" columns are rare in literature. Remarkable differences in frequencies between ICM model object, path, observer position combinations are observed (see table 2).

The most frequently found contributor to invisibility are the object properties (150 out of 202 concepts) while the observer properties (74 out of 202) and path properties (72 out of 202) are found to contribute significantly less often. The least found combination is the observer and path properties combination (7 out of 202).

Table 2 Frequencies of allocated positions in the ICM model

ICM model position (1= "active")			**Invisibility concept frequency**	**Summary description of where invisibility is achieved**
Object	**Path**	**Observer**		
0	0	0	0	-
0	0	1	24	observer properties and limitations
0	1	0	21	path properties
0	1	1	7	observer and path properties
1	0	0	61	object properties
1	0	1	44	object and observer properties
1	1	0	44	object and path properties
1	1	1	1	object, path and observer properties
Total			202	

4.2 Estimated performance

The commonly used term "poor visibility" covers many aspects, e.g. shape, colour, pattern, full or partly in view, and so on. Rather than attempting to develop a complex multi-parameter concept of partial invisibility, we prefer - for practical reasons - to simplify it to a percentage, indicating the estimated effect of an *invisibility concept*. To this end we introduce the *Non Visibility Percentage* (NVP). The NVP value would then vary between 0% (fully visible) to 100% (fully invisible).

In most cases the NVP of *invisibility concepts* found in literature is not, or not accurately, known. The NVP value can only be roughly estimated using the accumulation of contributing visibility reduction effects as encountered by the flow of photons moving from the object towards the observer. Although in some exceptional cases, e.g. 'active cloaking', *amplification* may occur (Shchelokova et al., 2015), most, if not all other *invisibility concepts* manifest themselves as *reduction* effect of transmission along the way from sender towards the observer.

The visibility reduction effects as contributed by object-, path- and observer property values are modelled as three numerical transmission factors f1, f2 and f3 which can simply be multiplied to establish their combined effect, since they reduce transmission sequentially.

Each transmission reduction factor is limited to between 0 (=full invisibility achieved) and 1 (=no effect on visibility). The actual values of reduction factors are highly dependent on situation and conditions for a given invisibility concept. In order to be able to compare performance of both existing and newly conceived *invisibility concepts,* the transmission factors which are not readily available from literature, are roughly estimated by using a simple transmission factors scale:

- 1.00 full transmission (=no effect on visibility)
- 0.90 minor reduction effect
- 0.50 somewhat reduced transmission
- 0.10 significant reduction effect
- 0.01 almost complete reduction effect
- 0.00 no transmission (=fully invisible)

The estimated NVP for *invisibility concept* i then follows from:

$$NVP(i)= 100* (1 - f_{1,i} * f_{2,i} * f_{3,i}) \quad [\%]$$

Example: for a soldier looking at camouflaged military equipment on the other side of a field, through a morning haze, with no obstacles limiting the field of view, the NVP can be estimated from:

NVP = 100*(1 - 0.1[camouflage]*0.5[haze]*1[free view])= 95%

4.3 Typology

The set of n=202 *invisibility concept* identifier texts, as allocated to object-, path- and observer is grouped into clusters, based on similarity. E.g. a safety related activity or piece of information may not be noticed due to poor work quality monitoring, or due to workers in the supply chain not being aware of its relevance.

This clustering process leads to some 22 *invisibility types,* groups of similar *invisibility concepts,* listed in table 3. Detailed descriptions, identifying the boundaries between types, are presented in table 4. As shown in table 3, these 22 invisibility types are ranked by their frequency in literature, e.g. "invisibility cloaks" were encountered 17 times and are ranked 3rd after "ignored" (19 times) and "not noticed" (18 times).

The performance of each invisibility concept group type must be expressed as an NVP% range. This is because the estimated performances of the individual invisibility concepts, included within a cluster of an invisibility concept group type, may differ considerably.

Table 3 shows an indicative NVP performance range per invisibility type, originating from the minimum and maximum estimated NVP values within each type group. E.g. for the 17 invisibility concepts based on "cloaks", found in literature, the NVP estimates vary between 90% and 99%. For the 18 "not noticed" invisibility concepts the NVP estimates vary between 50% and 99.5%.

Table 3 Invisibility concepts (n=202) clustered into 22 invisibility types with estimated performance range [NVP %] and contribution of object-, path- and observer properties [frequency counts].

NR	Invisibility type description	Frequency type count	Performance NVP %			Contributing factor counts f1	f2	f3
			min	average	max	object	path	observer
1	ignored	19	90	98,7	99,5	18	16	3
2	not noticed	18	50	93,6	99,5	18	14	3
3	cloak	17	90	91,1	99	17	0	0
4	emission distorted	16	50	60,6	99,9	16	12	0
5	emission reduced	15	50	80,1	99	15	1	2
6	observer weakness	13	10	83,0	100	6	1	13
7	cannot see danger	11	99	99,0	99,1	11	0	11
8	mimic shape & colour	11	50	86,4	90	11	0	3
9	path blocked	10	90	93,8	100	7	3	0
10	not standing out	9	50	90,0	99,99	9	0	6
11	observer bias	9	90	90	90	0	0	9
12	observer subjective	7	99,5	99,9	99,95	0	7	7
13	out of view	7	90	95,1	99	2	5	2
14	transmission reduced	7	50	85,6	99	0	7	0
15	observer looking away	6	90	94,7	99,1	3	0	5
16	emission blocked	5	90	95,4	99	5	0	0
17	poor view	5	90	90	90	0	0	5
18	time effect	5	10	58,8	100	4	2	2
19	transmission distorted	4	90	92,3	99	0	4	0
20	blinding by	3	90	90,7	91	3	0	3
21	fast movement	3	10	63,3	90	3	0	0
22	emission zero	2	100	100	100	2	0	0
		+				+	+	+
	Total n=	202				132	56	71

The sometimes low end of an estimated NVP range does not jeopardise the effectiveness of an entire invisibility type however, since there are individual invisibility concepts with estimated NVP's above 90% within each type.

An example of this is type NR 14 "transmission reduced". Some 7 concepts of these were found in literature. Their estimated NVP performance ranges from 50% to 99%. As reduced transmission is primarily related to path properties, hence all 7 of them are allocated under f2 path.

Another example is type NR 18 "time effect". Here the NVP performance ranges from 10% to 100%. Out of the 5 concepts found in literature, several consist of a combination of f1 object , f2 path or f3 observer properties, in this case 4,2 and 2 respectively. The table 3 right hand side columns show the factor f1, f2, f3 counts reflecting the object-, path- and observer contributions to each type.

At first glance a strong presence of object property based invisibility types can be recognized on top of the frequencies list (NR 1 - 5), either combined with path properties or not. A second group of invisibility types standing out is observer properties based, part of them combined with object properties (NR 6 – 11).

Finally, this analysis shows that the 10 most frequently found *invisibility types* represent over 68% of the 202 invisibility concepts found from literature. We include a detailed description of each of the 22 invisibility types in table 4. This mentions causes, conditions and activities which are found in literature, leading to invisibility of safety related information and hence to potential scenarios. The 22 types are kept as they emerged from clustering the 202 concepts found in literature on similarity. We kept the 22 emerging types and checked for overlaps and only minor overlaps were found which we corrected by refining the boundaries between the types. This results in a first set of invisibility types.

4.4 Finding new invisibility concepts

Looking at the "not noticed" invisibility type in table 3, the total number of invisibility concepts in this type group, found from literature, is 19. Out of these, all 19 have an object property, some 15 also have a path property and 3 have an observer property. This not only illustrates that the invisibility types may significantly differ, as was suspected on basis of table 2. It also suggests that, besides these existing combinations derived from literature, there could be more combinations of object-, path- and observer property values generated from the deconstructed data from the 202 invisibility concepts found.

Although it is likely that not every possible combination of currently known property values identified from the three columns of the 202 concepts will be meaningful, there can – certainly in theory – be relevant, yet unexplored within the methodical limitations in this study. It would seem likely that also new and hitherto unknown, invisibility concepts can be generated from them.

To incorporate those as a possibility, the three properties – object, path and observer – can be regarded as independent variables. This implies that any single chosen combination of specific object-, path- and observer property values constitutes an invisibility concept (See Figure 3).

It is logical to assume that the property value ranges, as derived from the current incomplete set of 202 concepts, are themselves also incomplete. Hence, the actual ranges can only be wider. Some 150 object property values were identified, some 72 path property values and some 74 observer property values. (Note: also "null" property must be considered in each column since a concept may consist of 1, 2 or 3 active columns, hence: 150+1, 72+1, 74+1 properties).

Table 4 Detailed descriptions of 22 invisibility types as clustered from invisibility concepts found in literature

NR	Invisibility type description	NR	Invisibility type description
1	Ignored deviation presence in installation, procedure or process, ignored incidents analysis, actions, metrics, records, reports, statistics, trends, ignored persisting major problem, organizational memory loss/forgetting, plant ageing, plant maintenance cost cutting effects, poor knowledge management, ignored worker experiential knowledge	12	Observer subjective due to acquaintance, complex instruction, independent analysis, lay observer, mechanical, prejudice, social norms
2	Not noticed danger due to complex installation, dehydration, electricity, heat strain, new technology/risk, poor safety measures, poor work quality monitoring, psycho-social, poor work relations, violence, superficial change, very slow, lack of awareness, poor work conditions, worker abuse, worker deception	13	Out of view due to economic/political bias, use of standard forms/notebooks, social groups out of view, victims out of view, administrative process flaw
3	Cloak using shroud, screen, layer, metamaterial, mirror, grid, IR /RF waves, transformation, submerging	14	Transmission reduced by dust cloud, fog, haze, medium scattering, reflective objects, smoke screen
4	Emission distorted due to coating or surface pattern, due to not telling in incident reporting/statistics because of "good news" bias, fear for job, fear to speak, vulnerability/migrant, claim, compliance, regulator inspection, financial compensation, absence of employers, selected cases, poor safety performance, poor indicators.	15	Observer looking away due to salient thing, looking selective, looking elsewhere by chance, look in other direction, is distracted, looking at wrong moment by chance
5	Emission reduced due to darkness, shadow, insulation, stealth surfaces, by poor database taxonomy, incomplete statistics, poor access to data, superficiality, discrimination, underreporting, language barrier, non-transparency, ineffective safety improvement	16	Emission blocked by baffle, cover, dent, trench, staying out of sight
6	Observer weakness due to blind spot, blinking, colour blind, limited fov, mental delusion, substance abuse, not all wavelengths, poor eyesight, poor night vision, sensitivity threshold, too small things	17	Poor view due to bias, lack of concentration, pre-occupation, prejudice, superficial lack of focus
7	Cannot see danger due to combustible vapour, gas, toxicity, oxygen, pressure or contamination and spatial confinement	18	Time effect due to blind moments, delay in medium, long distance, synchronicity
8	Mimic shape and colour by adapting skin properties, camouflage nets, covering, imitate characteristics of surroundings, colour pattern, wear camouflage clothing & mask, same colour as background, same pattern, same shape.	19	Transmission distorted due to atmospheric reflections (fata morgana), light beam, lensing, interference
9	Path blocked by blindfold, dents, scrubs, trees, object in front, by informal enterprise activities	20	Blinding by bright spot or bright background
10	Not standing out because of many in crowd, forest, beach, not socializing, be inconspicuous, evading cameras, workers laying low, workers in routine job	21	Fast movement due to high velocity, moving back & forth
11	Observer bias to protect reputation, shed doubt, use deceptive expert knowledge, false knowledge, ignorance, influence by institutions, protect future interests, label it exceptional, deem it tolerable	22	Emission zero due to non-interaction or full absorption

4.5 Huge potential

If these property ranges would consist of fully independent parameter values only, the number of theoretically possible combinations of these three value ranges is (151*73*75=) 826.725, which far exceeds the number of 202 combinations in the invisibility concepts derived from literature in this study. If these parameter ranges would only be some 50% independent, the number of combinations drops to some 99.900 and for 25% to about 12.488, still far higher than the currently found number of concepts. This suggests the presence of a huge potential, far exceeding the 202 currently identified ones, of as yet undiscovered invisibility concepts. Possibly there are also more clusters, hence invisibility concept group types, than the 22 identified here. Such new concepts, found via new combinations of object, path and observer properties, are interesting for further research.

4.6 Invisibility concept generator tool design

This work could be done by systematically generating and exploring the many possible new combinations achieving NVP values up to 100% using the tool design depicted in Figure 3.

To illustrate the potential of this approach with the ICM model and combinations of independent object, path and observer parameter values, several example combinations were generated with estimated NVP percentages over 90%. They are not coinciding with the 202 *invisibility concepts* found from literature. These examples are:

1. An inconspicuous object might not be noticed by an observer instructed to look for salient things
2. Something happening very slow may take a long time to reach the observers' sensitivity threshold
3. An event might not get noticed by an observer via a path including a flawed administrative process
4. A path suffering from interference will cause difficulties for an observer with insufficient training
5. An object with a directional property might not be recognized by lay observers
6. A repeat incident previously not analysed due to administrative flaws is not recognized
7. A toxic vapour in a morning haze is unlikely to be spotted by a prejudiced observer
8. Directionally moving across interference of transmission with poor training on electrical danger
9. Time variating object not maintained due to cost cut while observer unable to interpret view
10. Poor access to accident data due to darkness and observer looking in other direction

Some of these examples look familiar and some may appear strange to safety specialists. Some examples require imagination as to how these property combinations could happen in practice. Some examples do not make sense. Hence, the usage of this generator tool must be accompanied by some sort of selection mechanism.

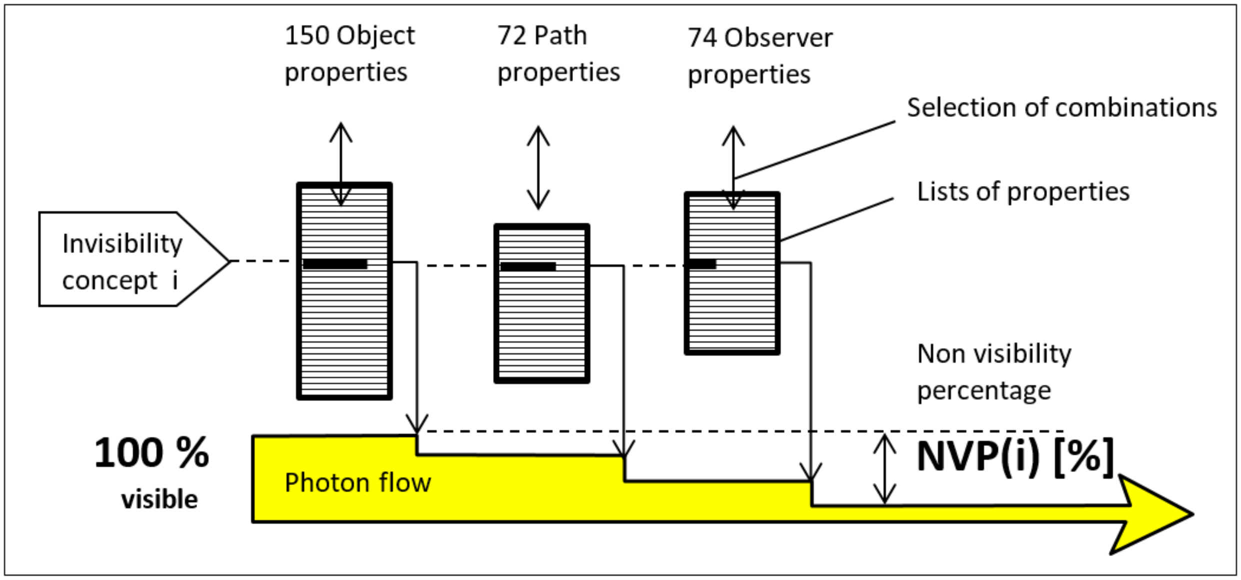

Figure 3 Non visibility percentage NVP [%] of a newly generated *invisibility concept i,* derived from a new combination of existing object-, path- and observer property values

5. Discussion

This explorative, subjective and incomplete study of invisibility concepts and their potential relevance for safety management can only have indicative results. A complete inventory and classification of *invisibility concepts* relevant for safety management cannot be made at this point, given the methodical limitations of the present study and the high number of possible object, path and observer property combinations. Nonetheless, this first, still preliminary inventory and typology of invisibility concepts could be used to improve safety management by using the findings of this study as a starting point. A more comprehensive future study may expose more rare invisibility types and could result in combinations of currently found types, e.g. for practical reasons.

5.1 Examples with relevance for safety management

Many of the 202 *invisibility concepts* and their object-, path- and observer property values can be related to safety via simple logical reasoning. Although there might be subjectivity in each concept assessment, their existence points at an area where safety management might be vulnerable for invisible, hence unknown danger.

5.2 Towards practical use

The findings in this study can be used in several ways. The first way would be to use the insights in how invisibility is deliberately achieved - or just happening - most frequently. In practice, a safety manager could e.g. use the top-10 of invisibility types listed in table 3 to explore invisible dangers thus far hidden in the scenario gap. This can support risk assessment and lead to a more complete set of accident scenario descriptions.

Alternatively, as a second way, a company specific relevant selection of the 150, 72 and 74 object, path and observer properties could be used to generate new combinations following the generator tool approach shown in figure 3. Such new combinations allow searching the scenario gap more thoroughly on a generic level. Estimated NVP percentages could be used to prioritize the search results.

A third way would be to extend the lists of object, path and observer properties. A closer look into a specific situation might lead to additional company, process, organisation or technology specific property values, since these may not have been found in this study due to the generic approach chosen and due to exclusion of several areas via search criteria. Adding such new properties to a company specific concept generator list, is recommended. The generator tool approach can be used for a wide variety of settings, e.g. technical installations, administrative processes and human interactions, even more thoroughly and on a situation specific level. Estimated NVP percentages can be used here too.

5.3 Safety culture aspects

Safety culture has its own invisible domains – climate and motivation – adversely affecting attitude and inquisitiveness when looking for danger (Meyer and Reniers, 2016). This is referred to as a "*lack of risk appetite*" (Gjerdrum and Peter, 2011). The quality of risk assessments is vulnerable for non-observable parameters such as knowledge, skills and perception (Lindhout & Reniers, 2017A).

The TEAM-model of safety culture describes three measurable domains in an unmeasurable environment within the perimeter of safety culture (Vierendeels et al., 2018; Guldenmund, 2010). Hence, we argue that the presence of invisible hazards and the non-presence of visible safety measures are both aspects of *observable safety*, in particular of procedures and behaviour of people. Furthermore, we contend that non-action on unexplored invisible danger can be regarded as a flaw in risk assessment practice.

The introduction of systematic risk reduction activities, focusing on invisibility related danger, would need to be started from this notion. This

could be done in any of the three ways as sketched in the above, and from invisibility concept types found.

5.4 Limitations

The 202 invisibility concepts found in this study are, due to the methods chosen in this exploratory study and the narrative nature of the data, vulnerable to subjective interpretation and may have some unforeseen overlaps. New research and other methods may lead to more elaborate data and a choice for different clusters than now presented in table 4.

Nonetheless, the core of 22 invisibility types found in this study will be useful as a tool for safety professionals searching for places in organizations where causes and scenarios related to safety may be hidden because of an *invisibility concept* 'at work'.

5.5 Further work

Not all object, path and observer property values are applicable in each situation. Part of the property combinations may be not meaningful at all or be not relevant to safety. Systematically generating 826.725 combinations, assessing which of those combinations are meaningful and then exploring their bearing on safety is a daunting task.

Moreover, the lists of object, path and observer property descriptions are probably not exhaustive. Further research is most likely adding to their numbers which will then become higher than the 150, 72 and 74 respective counts we found in this study. This implies that future research may lead to a number of possible combinations well in excess of the present estimate of 826K.

6. Conclusion

Invisibility plays a role in safety management. Over 200 invisibility concepts were found from literature in a wide range of areas in society. By means of a theoretical model these could be described in a uniform way and then clustered on basis of similarity into 22 invisibility types. This indicative analysis shows that object properties are the most frequently found factors contributing to invisibility. Object properties take part in some 2/3rd of cases found, while combinations with either path or observer properties occur somewhat less often, in roughly 1/3rd of cases. Combinations of all three - object, path and observer - properties, are rare.

It is expected that many – hundreds of thousands – more combinations between the three kinds of properties can be generated, out of which many can be meaningful and worth analysing. This will provide not only an insight in vulnerability for invisibility scenarios but also a means to reduce the gap between accident scenarios as predicted and as actually occurring. Alternatively, a safety manager can apply the 22 most frequently found invisibility types in risk assessment and in accident scenario descriptions.

Further research is recommended, firstly to gather more complete data in order to be able to justify a classification of invisibility concepts, and secondly to find a method for selecting meaningful property combinations.

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Addendum List of object path and observer properties

Object properties

absenteeism of workers
ageing plant
Avoidance of claims
be among many similar in a forest
be inconspicuous
be transparent
camouflage nets military equipment
cloak cameras and projectors
company compliance attitude on accident statistics
complex installation sections
cover uniform for short whiles
create a diversion
plant in declining state
deviation installation noticed
deviation process noticed
disappear for short whiles
evade camera field of view
explosive atmosphere confined
hard to identify employers accident statistics
having a big ignored problem in group of persons
heat insulation
hidden unobserved informal enterprise
hide in dent or trenches
hide under snow cover
high air pressure in container, invisible from outside
imitate rock
change implemented superficially
incomplete statistics for Language Problem Related Accidents
insufficient safety measures
irregular informal enterprise
language problem hazards
little attention for environmental damage
low oxygen content, invisible
maintenance cost cutting on plant
metamaterial screen
move directional
moving fast hi speed
new technology with new unknown risks
non-specific database taxonomy
only looking at most severe cases in accident statistics
opposite cameras & LED screens
less emission (plasmonics antennas)
poor knowledge management
poor safety performance data
poor work relations among workers
present a salient decoy
pseudo layer cameras screens
quality of work problems among workers
records of incidents
road dangers - unknown
same colour as background
same shape as closest objects
skin actively matches environment under water - octopus
stand in shadow
statistics of incidents
stay out of sight
stealth shape material surfaces airplane
superficiality of accident reports
toxic gas, invisible air toxic gas, confined space
transformation optics
trends in incidents
underreporting of accidents
unknown object properties
abuse of workers in work practice (slavery, trafficking)
analysis of incidents
be among many in a crowd
be before a high intensity light background
be small among many on a beach
be very small
change very slow
come from the suns direction
complex compensation rules after accident
contamination with invisible chemicals
covert regulator inspection
deception of workers
worker dehydration signs not clear
deviation procedures noticed
is dipped in same refraction index transparent fluid
electrical hazards
explosive atmosphere
few regulator inspections accident statistics
has time variation
heat insulating suit
heat strain signs not clear
hide behind baffle
hide under shroud
hide under water surface
Illegal-, black market-, clandestine-, informal enterprise
imitate twig or leaf
in backyard informal enterprise
initiate action incidents
interrupted place / time in sync
lack of Health Safety & Environment awareness
large distance, far away
little help for victims of disaster
low oxygen content, invisible in air confined space
memory loss in organization
move back and forth fast
moving away fast
Nano-scale metal grid
no photon interaction
not affecting light
only prosecuting easy legal cases in accident statistics
opposite cameras & plasma screens
poor access to accident data
poor metrics
poor validity of indicators
poor working circumstances
presenting only “good news”
psycho-social risks among workers
recently happened far away (celestial) event
reports about incidents
role unclear safety representative workers
same pattern
skin actively matches environment in jungle- chameleon
stand between reflecting mirrors
standing in a crowd
stay between scrubs/trees
staying out of field of view
stealth shape material surfaces navy vessel
toxic gas, invisible
toxic vapour cloud, invisible
transparent scattering cancellation
underground, subterranean
unexpected failure of installation
unorganized

unreported, shadow
use bright light to outshine
use flash light in sync
use special colours
use thermal IR blanket
using camouflage clothing/mask
victim language barriers
wave flow device
worker fear for retaliation
worker vulnerable - low social economic situation
workers avoiding socializing
workers unaware of own position while abused
use a paint colour pattern
use darkness at night
use retroreflective cover
use stealth reflective cover
use wavelength
vapour cloud, invisible fuel
violence among workers
worker experiential Health Safety & Environment knowledge
worker vulnerable - immigrant
workers afraid to speak
workers laying low
workers with routine tasks

Path properties

administrative flaw deviation installation information
administrative flaw deviation process information
administrative flaw identifying dehydration risk
administrative flaw in records and archives information
administrative flaw incidents analysis information
administrative flaw incidents records information
administrative flaw incidents statistics information
administrative flaw maintenance cost cut information
administrative flaw objective procedures information
administrative flaw plant ageing information
administrative flaw poor knowledge management information
administrative flaw psychosocial behaviour
administrative flaw psychosocial poor work relations behaviour
administrative flaw subjective processing information
administrative flaw unexpected failure information
administrative process flawed for a social group information
delay time in medium
disturbing light beam distorting transmission
fog absorption poor transmission
hot air - fata morgana distorted view
interference distorting transmission
light bending by gravity
path blocked by blindfold
scattering in medium reducing transmission
smoke screen absorption poor transmission
standardized forms flawed for an individual
standardized notebooks flawed for an individual
supply chain info exchange
supply chain poor info exchange deception
supply chain poor info exchange Health Safety & Environment
sustainability goal overrules new risks
administrative flaw deviation procedures information
administrative flaw fair treatment of individuals information
administrative flaw identifying heat strain risk
administrative flaw incident initiating actions information
administrative flaw incidents poor metrics information
administrative flaw incidents reports information
administrative flaw incidents trends information
administrative flaw no separation observer-analyst information
administrative flaw org. memory loss information
administrative flaw plant declining information
administrative flaw poor standards of conduct information
administrative flaw psychosocial absenteeism information
administrative flaw psychosocial violence behaviour
administrative flaw subjective system information
administrative flaw work quality monitoring
darkness reduces sight
dents, scrubs, trees reduce field of view
dust cloud poor transmission
haze reduces transmission
inner safety culture layers not influencing behaviour
large distance delay time
other object in front blocks transmission
reflective objects scatter transmission
scrubs and trees reduce transmission
standardized forms flawed for a social group
standardized notebooks flawed for a social group
strayed in dust cloud poor transmission
supply chain poor info exchange abuse
supply chain poor info exchange fear to speak
supply chain poor info exchange worker position

Observer properties

avoidance of discrimination charge - language issues
bias considered exceptional
bias cultivating doubt
bias false knowledge
bias influence by institutions
bias protect future interests
blind spot
blinded by close bright light
blinking, eyes closed
cannot distinguish has same pattern
cannot interpret field of view
cannot see all wavelengths
cannot see danger explosion contaminant in substance
cannot see danger explosive atmosphere confined space
cannot see danger hi air pressure
cannot see danger low oxygen confined space
cannot see danger toxic gas confined space
cannot see small things
bias avoid stain on reputation
bias considered tolerable
bias deceptive expert knowledge
bias ignorance
bias organisational forgetting
blind moments
blinded by bright background
blinded by the sun
cannot distinguish has same colour
cannot distinguish has same shape
cannot notice inconspicuous
cannot see danger due to unknown object prop
cannot see danger explosion fuel vapour cloud
cannot see danger explosive atmosphere
cannot see danger low oxygen air
cannot see danger toxic gas
cannot see danger toxic vapour cloud
cannot single out among many

cannot single out among many same
cannot single out in crowd
economic political bias with respect to environmental damage
follow subjective complex instructions
ignorance of language issues
insufficient awareness of poor safety measures
insufficiently understood workplace
limited field of view
looks at selective things only
looks at wrong moment by chance
looks selectively at flaws only
mental delusion
poor eyesight
poor view due to not concentrated
poor view superficial, lack of focus
pre-occupied with other things
short-sightedness
subjective norms, moral, political, legal, ethical, field of view
take dominant position ignoring worker knowledge
cannot single out in crowd
is colour blind
economic political bias with respect to help to victim
has inverse time variation synchronicity
ignoring elephant in the room
insufficient training (electricity danger)
lay observers subjectivity
looks at salient things
looks at something else by chance
looks in other direction
mechanical subjectivity
mental flaw due to substance abuse
poor view due to bias
poor view due to prejudice
prejudice subjectivity against individual
sensitivity threshold not reached
subjective knows individual
subjectivity due to observer-analyst not separated
unknown vision limitations