Lloyd's Register Foundation

Insight report on global safety challenges

Challenges facing the safety community

June 2017

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About the Lloyd's Register Foundation

Our vision

Our vision is to be known worldwide as a leading supporter of engineering-related research, training and education, which makes a real difference in improving the safety of the critical infrastructure on which modern society relies. In support of this, we promote scientific excellence and act as a catalyst working with others to achieve maximum impact.

The Lloyd's Register Foundation charitable mission

- To secure for the benefit of the community high technical standards of design, manufacture, construction, maintenance, operation and performance for the purpose of enhancing the safety of life and property at sea, on land and in the air.
- The advancement of public education including within the transportation industries and any other engineering and technological disciplines.

About the Lloyd's Register Foundation Report Series

The aim of this Report Series is to openly disseminate information about the work that is being supported by the Lloyd's Register Foundation. It is hoped that these reports will provide insights for the research community and also inform wider debate in society about the engineering safety-related challenges being investigated by the Foundation.

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Executive summary

Many of us are not even aware of the critical infrastructures that make our lives possible, let alone how our lives or the lives of those that come into contact with these infrastructures are affected when they go wrong. By infrastructures we mean things like supply of water, power and food or transportation and communications.

This report summarises the results of an open consultation process that asked a simple question: Where is safety challenged? in particular, in the context of where people interact with critical infrastructure and where safety of critical infrastructure is itself threatened.

A consultation with those who best understand the infrastructures, industry and academia, was led by the Nesta Challenge Prize Centre using a combination of interviews, expert workshops, an open online survey, and outputs from previous Nesta projects.

As the consultation evolved it became clear that concerns not only centred on the infrastructure operated today but also about the infrastructure that will be enabled by technology tomorrow.

Twelve main themes were identified around the challenges identified:

- safe operation of drones now and in the future
- safe operation of autonomous systems
- critical infrastructure that is safe from cyber attack
- safety of complex systems in high-hazard industries
- fossil-fuelled transport and industry that do not create unsafe air
- safe supply chains for medical waste
- safe supply chains for electronic waste
- ensuring safety at sea
- safety in the fishing industry
- safety of supersized structures
- making food supply chains safe
- safety of water and water infrastructure.

What is clear from the above themes is that the challenges cover a broad range of industries. It has also been possible to try and identify some broad trends across multiple themes. These trends are:

- decommissioning (for example, disposal of e-waste, ships, medical waste, etc)
- cybersecurity, connectivity and internet of things (for example, malicious and accidental failures)
- human factors (how people's actions significantly affect safety)
- updating standards in light of new technology (for example, safety regulation for increasing complex connected infrastructures)
- controlled return to safe state (for example, emergency evacuation of large structures and controlled failure of complex systems).

Specific challenges identified in this report are based upon the opinions of the small sample that have taken part in the consultation process. Before any of these challenges are recommended for action it is very important to explore them further to better understand their relevance and significance.

Foreword

The world we live in is dependent on critical infrastructure that provides our food and water, power, transportation, communications, etc. Our safety can be compromised when these infrastructures fail or when we come into contact with these infrastructures.

Enhancing safety for the benefit of the community is central to the Lloyd's Register Foundation's charitable mission. It follows that in order to understand where safety is compromised that the Foundation should turn to the community to be given direction.

This report provides feedback from a consultation process that has engaged with a community of those with experience of critical infrastructure.

The findings of this report not only indicate where safety of life and property are at risk today, but also anticipate the risks associated with the technologies and infrastructure of tomorrow.

Not all challenges are global safety challenges. Defining what is meant by a global safety challenge is actually quite difficult but we know what they should contain: they should be an opportunity to reduce the risk to life and property; they should address global issues; they should be solvable; and they will involve people coming together to enable the solutions.

By publishing this report the Foundation is sharing its findings to allow others to create solutions. We do this because …life matters.

The findings of this report not only indicate where safety of life and property are at risk today, but also anticipate the risks associated with the technologies and infrastructure of tomorrow.

Professor Richard Clegg
Foundation Chief Executive
Lloyd's Register Foundation

Tris Dyson
Director, Challenge Prize Centre
Nesta


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Introduction

Lloyd's Register Foundation is an independent global charity giving grants towards enhancing the safety of life and property and to advance public education. A challenge for the Foundation is identifying where there are safety needs and where it can make a distinctive difference to society.

When the Foundation decides which grants to support, one consideration is where it can best use its influence and limited resources. There are two challenges for the Foundation in doing this. First, data related to safety of life and property is limited and there are gaps in coverage according to geography and sectors. Second, while there are several very clear global safety 'grand' challenges such as road traffic accidents and access to clean water and sanitation, there are also many 'hidden' safety challenges. These may not have a high public profile and may be hidden from wider society but are nevertheless very real to the people undertaking dangerous and life threatening tasks every day.

Many governments, regulators and charities are involved in addressing some of the high profile global safety challenges. The Foundation cannot act distinctively in these areas and its resources are dwarfed by the resources of others. However the Foundation has started the process of identifying the hidden safety issues with the aim of addressing them through our grant giving, through raising awareness, and influencing the actions of others.

As we go forward we will do two things to target our grant giving to where it can have the greatest impact:

- We intend to publish a trusted evidence base for safety that can be used as a shared resource by the global safety community.
- We will continue to identify global safety challenges. This insight report gives the output of our first consultation on this issue.

Background

The Foundation's initiative for global safety challenges aims to highlight where safety is challenged and allow the community to take appropriate steps to improve safety. This will be an ongoing initiative that has three key tasks: to identify the safety challenges; to address the challenges with appropriate courses of action; and to enable solutions through the correct support. This is illustrated on the next page.

This insight report represents the Foundation's first consultation to identify what are considered to be global safety challenges. It is based on a consultation exercise conducted between September 2016 and March 2017 by the Challenge Prize Centre at Nesta.

The report explores what a sample of those working in industry and academia consider to be the challenges to safety around the world. In the context of this report, safety challenges refer to situations where there is a risk to life or property at the point where people come into contact with critical infrastructure or where the safety of critical infrastructure is itself threatened.

To further its charitable mission of working for the benefit of the community, one of goals of the Foundation is to understand these safety challenges from the perspective of the community through a process of direct engagement.

The challenges reported in this document are informed by a broad range of experts with extensive professional or academic experience of safety issues around the world. The views expressed in this report should not be considered as representing the views of Nesta nor the Lloyd's Register Foundation.

This report reflects the unique experience and insights of those that participated in the consultation. A different group of participants would have resulted in a slightly different set of challenges and the findings are not intended to be definitive.

This report, commissioned by the Lloyd's Register Foundation, explores what a sample of those working in industry and academia consider to be the challenges to safety around the world.

Figure 1: The global safety challenges cycle - to identify, to address, to enable

By reporting what have been identified as the global safety challenges the Foundation is providing a valuable source of information to be used by the Foundation and others for the benefit of society.

The objective is to identify challenges which can be addressed by the Foundation or others. The routes to solution may take several forms including but not limited to: challenge prizes to encourage innovators to develop new technologies or business models in return for a financial reward or support in developing ideas; research grants to better understand the issues surrounding them; public information campaigns to aid understanding.

Tackling global grand challenges has become a popular approach for funders and philanthropic bodies in recent years. The precise approaches of these grand challenges vary, but they share the concept of setting key strategic goals, targeting specific problems within them, and challenging people - usually with a financial reward - to solve them.

The Lloyd's Register Foundation is a UK registered charity and owner of the Lloyd's Register Group Limited, a 257-year old professional services company providing independent assurance and expert advice to companies operating high-risk, capital-intensive assets in the energy and transportation sectors. This includes ships, oil rigs, power plants and industrial facilities.

This insight report has been produced by the Nesta's Challenge Prize Centre (CPC) for the Lloyd's Register Foundation. The CPC was established to increase practical evidence and understanding about challenge prizes - public challenges that incorporate development funding and practical support to solve problems.

The CPC sits within Nesta, a global innovation foundation. It backs new ideas to tackle the big challenges of our time and improve how the world works for everyone. Nesta uses its knowledge, networks, funding and skills to take on these big challenges - working in partnership with others, including governments, businesses and charities. Nesta is a UK charity that works all over the world, supported by a financial endowment.

The consultation

Purpose of the consultation

How should the world's safety challenges be identified? One approach would be to look to statistics and identify leading causes of death or injury around the world, comprehensive statistics on which are kept by the World Health Organization (WHO). These show the African region to have the highest fatality rate at 26.6 per 100,000 people, while Europe has the lowest at 9.3 per 100,000 people.

However, this approach would prioritise road deaths above all else and would be inappropriate for four reasons. First, the Foundation strategy focuses on critical infrastructure and many of the causes of road deaths are not due to infrastructure. Second, statistics are silent on how solvable a challenge is. Third, because statistics are backwards-looking it would risk missing emerging threats in a world where new hazards arise from technological and economic change. And finally, numbers alone do not give any guidance on how successful a grand challenge model might be at addressing them.

A well-crafted set of global challenges should include problems that are solvable but currently unsolved and that could benefit from a wider pool of innovators. They should ideally be linked to measurable impacts and enable solutions that could be taken to market rather than languishing as prototypes or pilots.

Challenges such as these are not easily definable from the outside and are best crowdsourced from stakeholders and experts who are intimately connected to the issues.

For this reason safety challenges have been identified through in-depth conversations and an online survey. That means including some relatively niche problems - either because a challenge could make a substantial difference or because it has not yet become a serious problem (for instance several of the safety challenges identified are around the introduction of drones into cities). It also means ruling out some overly broad challenges.

A well-crafted set of global challenges should include problems that are solvable but currently unsolved and that could benefit from a wider pool of innovators. They should ideally be linked to measurable impacts and enable solutions that could be taken to market rather than languishing as prototypes or pilots.

Identifying the challenges

Interviews

The main source of insights comes from 51 unstructured interviews with stakeholders across a broad range of industries and sectors. The interviews canvassed opinion on the key safety challenges facing the industries that the interviewees represented.

Those interviewed and that gave permission to be named in this report are acknowledged in appendix 1 on page 54.

Expert workshops

Additional insights into three particularly complex areas were gained through half-day workshops with small groups of topic experts identified through the online consultation. The topics investigated in this way were: water and sanitation (organised in partnership with the University of the West of England); cybersecurity and infrastructure; and high-hazard industries. The participants in these workshops are listed in appendix 1 to this insight report.

Food safety-related insights from a Nesta-held expert workshop on the future of food (held in October 2016) also informed the findings of this insight report.

Survey

Broader insights were gained from an online survey of stakeholders from multiple industries; the survey was hosted on the project website[1] and promoted via various networks. The respondents of this survey disproportionately came from the maritime sector which is a reflection of the networks that promoted the survey and of the survey response rate of stakeholders in that industry.

Input from related Nesta projects

Independently of this consultation the Nesta Challenge Prize Centre has been conducting research projects on the future of food, air quality and the future of drones in cities, all of which include expert engagement (primarily in the form of semi-structured interviews). The safety-related findings from these related projects have also informed the contents of this insight report.

Prioritisation

This consultation process identified 218 safety challenges. The first filter applied reduced this list by removing the challenges that were out of scope for the Foundation's objectives (for example antimicrobial resistance), too vague (for example human error) or too broad (for example drowning at sea).

Using a defined process[2], the remaining challenges were clustered into 12 themes collectively containing 35 challenges that are reported within this insight report The themes are:

- safe operation of drones now and in the future
- safe operation of autonomous systems
- critical infrastructure that is safe from cyber attack
- safety of complex systems in high-hazard industries
- fossil-fuelled transport and industry that do not create unsafe air
- safe supply chains for medical waste
- safe supply chains for electronic waste
- ensuring safety at sea
- safety in the fishing industry
- safety of supersized structures
- making food supply chains safe
- safety of water and water infrastructure.

The challenges on this shortlist were subsequently ranked by priority in a dedicated workshop based on their fit with the Lloyd's Register Foundation's mission, innovation potential, potential to capture the public imagination and the scale of impact if solved. The participants in this workshop are listed in appendix 1.

The report ends with a list of the prioritised global safety challenges and some cross-cutting themes identified from all challenges reported in this document.

The following sections introduce the 12 themes and the challenges within them.

Safe operation of drones now and in the future

Unmanned aerial vehicles (UAV), unmanned aerial systems (UAS), or remotely piloted vehicles (RPV), commonly known by the public as drones, are finding increasing application around us. These range from small consumer devices to large complex systems and are used across a wide range of environments and industries.

As drone technology becomes commercialised and increasingly autonomous it will become part of the infrastructure on which society depends, be this for logistics through platform-led services (such as UPS and Amazon); automated transportation of people and goods performing similar functions to taxis or delivery vans today; inspection devices for structures and infrastructure; services such as delivery of transplant organs to hospitals; monitoring of traffic; or spraying of crops. There is a sliding scale of autonomy in drones from 100% human-piloted via remote control up to full autonomy, with varying levels of associated risk.

In the next 20 years it is expected that drones will be present everywhere. Analysts predict that drone sales worldwide will reach $12 billion in revenue by 2021, up from $8 billion in 2015, while the enterprise sector will overtake the consumer sector in number of shipments and therefore revenue[3]. With this increased uptake comes the risk of unintended harm to life and property as urban landscapes and traffic management systems seek to accommodate them.

Remote controlled drone	
Stage of development	In use; anyone can go and buy a drone. A 'dronecode' exists in the UK but it is not compulsory for manufacturers to supply it or for consumers to read it. In 10 years time - more drones in more people's hands.
Market/ industry use	Individual consumer (personal leisure). Scientific research (eg monitoring of pollution via sensors). Journalism (eg thermal heat monitoring of refugee camps). Industry (eg inspection of bridges). TV and film. Emergency services (eg search and rescue).
Function	Camera/video. Inspection. Maintenance. Heat monitoring. Pollution monitoring. Ad hoc uses with no need for complex interaction.
Risk	Flying into controlled airspace. Flying into other drones. Flying into infrastructure. Misuse of drones (eg to deliver drugs into prisons). Invasion of privacy. (NB Geo-fencing could therefore be improved to prevent invasion of restricted airspace).
Autonomous drone (drones that are not operated by individual controllers, but through autonomous platforms and monitored by operators)	
Stage of development	In early stage development; the capabilities exist however no country yet allows it to take place from a regulatory standpoint. Unmanned traffic management and beyond line of sight operations is being looked at by many countries who are looking into how to integrate drones safely with other air traffic and other close-to-the-ground operations.
Function	Drones can be used as vectors of any technology for any purpose. Platforms for collecting any information. Possibilities for use are limitless. From precision agriculture (currently being done) to carriers of people.
Risk	Increased collisions. More drones operating autonomously. Out of the line of sight. Across more complex landscapes (cities). Operators can more easily conceal their identities or purposes.

Table 1: Types of drone

The combination of cheap manufacturing prices and advances in unmanned traffic management has created significant demand across multiple domains including public service delivery, industry and consumer markets.

According to those interviewed, the large commercial interest in future drone use creates a pressing need to make sure the technology and modes of operation are developed with safety in mind; for the user, for the public, for the goods, between drones in flight and for surrounding critical infrastructure.

While it is clear there are many organisations working on the development of drones towards unmanned traffic management (for example, the UK's CAA [Civil Aviation Authority] and the Department for Transport, who concluded a consultation into drones on 5 March 2017[4]), this consultation has identified that work in this area is under-developed with regard to safety engineering. The problems identified in the consultation create conditions that could result in safety being compromised.

Challenge: Tracking mechanical failures

In the event of an accident, aircraft have black boxes in order to understand what has gone wrong, be it mechanical or system malfunction or human error. There is currently no such tool built into drones. If such a tool did exist, improvements in technology from understanding failures would increase safety. A black box could also act as a deterrent to misuse. Overall, this would increase the technological reliability of drones, provide data for development of testing facilities and make them less prone to malicious activity.

Challenge: Fail-safe modes for mechanical failure

Currently, if a drone suffers a catastrophic mechanical failure it falls to the ground. In the current stage of drone development this is not a priority safety issue as people tend fly their drones out in the open, away from critical infrastructure and people. However, this will become a priority for future drone technology as there will be a rapid increase in the use of drones in built up areas and therefore there will be a higher chance of collision with surrounding infrastructure if they fall. There needs to be increased attention to what a drone's fail-safe mode looks like and how the drone will land without causing damage to infrastructure and people. Ensuring drones can safely cope with failures is yet to be achieved.

Challenge: Certification of internal systems

The consultation heard from drone experts that development of safety regulations or standards for the design of autonomous drones is currently a barrier to their application. In the UK for example, the CAA is unable to predict what regulation and certification will apply to future designs, and manufacturers cannot create compliant drones unless they have criteria to design against. Creating standards of certification for the internal systems of drones would provide a steer for regulators and manufacturers and thereby give market stimulus for this technology.

Challenge: Priority for safety-critical use cases

When drones are engineered to perform autonomously through unmanned traffic management systems and operate beyond the line of sight, drone traffic will become heavier and more complex. There will be safety issues around prioritisation of airspace. For example, when an ambulance drives down a street with its siren on, cars move out of the way. How can we replicate this for safety-critical use cases for drones (for instance medical deliveries, police or fire service drones, even air ambulances). Should this be done, and what will the procedures be? As autonomous systems become deployed we should not experience an increase in accidents or delays with priority services. We need a management system or operational regime that can prioritise what is most important.

Safe operation of autonomous systems

Autonomy and the role of the human in partially or wholly autonomous systems is a safety issue that cuts across many industries, including transport and logistics, manufacturing, healthcare, construction and agriculture. Its importance will rise as increasing numbers of safety-critical functions become controlled or supplemented by automated systems. These include self-driving technology on roads, computer-aided diagnosis, and next generation air traffic control systems.

As automation extends beyond current niche-use cases and becomes a widespread technology across industry and in the public arena, we do not want to see an increase in accidents caused by automated vehicles or a breakdown in trust in these systems' safety.

The consultation with stakeholders from shipping to software engineers, transport risk specialists and innovation organisations, has shown that the safety implications are especially potent in the 'mixed-mode' or transition phase from non-autonomous to completely autonomous - where humans and autonomous systems have to work together seamlessly.

Systems acting completely autonomously in sync understand the rules and codes of conduct between each other and even learn from each other, as Tesla's driverless cars do through its Fleet Learning Technology (they all form one connected learning network where one car's experience informs the others). Research and development into automation of cars (and ships) is already advanced with tests being carried out. Yet software engineers specialising in this area have reported in the consultation that the interaction between humans and autonomous systems - how they should behave around each other - remains an unanswered question.

Challenge: Trust between autonomous systems and non-autonomous systems

Autonomous systems cannot yet make critical decisions (outside what they are programmed to detect), which creates questions around how surrounding passengers, operators, and bystanders can trust the actions of autonomous systems and how the systems can react to the non-autonomous systems around them. One of Tesla's semi-autonomous cars recently crashed (killing its passenger) because it could not distinguish the difference between a white van and the pale sky behind.

Social cognition is key for human interactions, for example, drivers do not follow absolute rules, they react to subtle situations (such as the raised eyebrow of another driver signifying 'go ahead') and then do the most appropriate thing according to the situation. This human to human interaction is used to make the most effective decision. A key safety question is whether autonomous systems will be advanced enough to have the situational awareness and understanding that occurs between transport users, bystanders or workers, for safe passage or operation. Interaction as a collective in mixed mode, where there is a variety of technical, human, cognitive and social aspects, is very difficult. In society we trust people based on their reputations, our interactions with them, and how they respond, unlike digital systems which as yet do not have markers for trust in how they interact.

Challenge: Role of the operator

There are a number of safety concerns related to the role of the operators and users of autonomous systems. First, in this consultation experts have consistently said that it will be difficult for humans monitoring systems to react quickly enough when something goes wrong, for example, if a car suffers a tyre blow out. The problem is particularly serious where the user does not know how to operate the system in non-autonomous mode (for instance a passenger without a driving licence in a driverless car) but even systems with supervision by skilled professionals can be problematic.

One of the respondents talked about how Italy experimented with automating the spacing of aircraft in air traffic control, which made controllers largely redundant and only required to act when the stacks of aircraft left predefined conditions. This was problematic as humans had to suddenly take over, which was proven very difficult to do when not involved in the process from the beginning.

The second safety concern linked to this issue is how operators or users are able to trust (and respond to) the instructions of the autonomous systems they are interacting with.

Insurers in the shipping industry raised a case where a ship had caused damage to subsea cabling by lowering its anchor. The ship's captain had been acting on information provided by its Electronic Chart Display and Information System (ECDIS) equipment (mandatory for ships over 10,000 tonnes) which had shown there was space to drop anchor when in fact the data in the system was inaccurate.

Issues of trusting the data and what the screen is telling you to do is linked to system-level reliability. With increased autonomy in shipping there may in future be just a few crew operating ships and they will need to rely on the systems and the information provided. To what extent will employees be able to rely on their own knowledge to notice when common sense should be used over following directives from a system?

Third, issues have been raised around training the future workforce and consumer for operation of autonomous systems. How do you make sure the crew of a largely autonomous ship will be an optimal crew and how do you ensure drivers are trained to both understand a system and to notice when common sense should override in a future in which cars are largely capable of driving themselves?

Fourth, boredom and fatigue of current and future operators of autonomous systems has been raised as a safety concern. Respondents in the shipping industry were particularly concerned that for those future designated technicians, who may be sole operators on ships, this would be a significant problem.

Last, there are safety concerns around deskilling of workers and the implications this has for emergency scenarios. As automation takes more of a role in operations that previously required workers, people lose skills and memory of how to use the system they formerly operated. If we look into the future, there is a good chance that people will no longer be able to drive cars, operate ships, or control air traffic landing. In an emergency scenario where a system breaks down or unexpected conditions occur, how will people know how to take over? Autonomy is fast developing yet efforts to explore the role of operators of these systems or how to upskill these workers, if this is the necessary goal, have not caught up. Industries will require skilled employees that are comfortable interacting with autonomous systems as well as mitigating risks in emergency scenarios.

Challenge: Vulnerability of GPS for navigation

Automation requires dependence on external systems such as GPS for navigation and timekeeping. Ships, planes, cars, robots, drones and farm machinery, once automated, will be totally reliant on satellite-based systems to get to their intended destinations. Similarly, the signals that each vehicle emits will tell other critical infrastructure its exact location in order to avoid collisions. In the event of a solar flare, signal jamming or a cyber attack, serious damage could be done to the satellites that autonomous critical infrastructure depends on for smooth operation. GPS devices on ships, planes and cars would stop providing information on where they are, making navigation dependent on operators being able to read charts or use radar. In the event of satellite and GPS systems failing there should be some means to allow infrastructure to continue to operate.

Critical infrastructure that is safe from cyber attack

Critical infrastructures increasingly use digital systems to operate. Often legacy systems (such as water works) are fitted with connected devices that they were never designed to include.

Digital systems are complex; they are large and distributed with many subsystems and interconnections governing multiple functions. The scale and complexity of these networks make risks difficult to predict and difficult to manage once they have manifested themselves. Risks are often unanticipated, which makes them even harder to manage.

Respondents reported that cyber-physical infrastructure, which often predates current standards of cybersecurity, requires urgent attention to address safety concerns. As cyber attacks become more advanced and more prevalent, there is a pressing need to unleash innovation in this sphere to avoid the situation of critical systems we rely upon failing in their function.

A few examples of previous cyber attacks on critical infrastructure include: the attack on the oil company Saudi Aramco that threatened the distribution of 10% of the world's oil supply; the Russian attack on the Ukrainian power grid that left 1.4 million Ukrainians without power for six hours; ransomware attacks on hospitals in Europe and the US which prevented access to medical records unless ransom money was paid; an attack on a German steel mill that caused extensive damage to the plant's furnace; and the attack on Iran's nuclear facilities that destroyed its uranium centrifuges.

The Saudi Aramco cyber attack, as reported in 2015[5]
In 2012, in a matter of hours 35,000 of Saudi Aramco's computers were hacked and destroyed. Without access to the digital payment system, the company's ability to supply 10% of the world with oil was also wiped out and it had to stall the trucks waiting at its gates to take the oil away. Employees had to resort to using typewriters and faxes. All as a result of one employee opening one scam email which destroyed the entire system. While drilling and pumping of oil continued because it was automated, the business's operational capacity had to go offline to manage supplies, shipping and contracts. After 17 days Saudi Aramco had to start giving away oil for free to ensure supply could continue in Saudi Arabia. The knock-on effect was a constrained hard drive market as Saudi Aramco purchased 50,000 hard drives straight from factory floors in Southeast Asia, at a higher price to cut queues. The hackers were never caught and five months later the company was back online.

Characteristics of cyber attackers
• Difficult to predict and constantly evolving
• Only need to find one vulnerability in a system to get in
• Anonymous and hard to locate
• Evolve rapidly in response to defensive measures
Characteristics of cyber-physical systems
• Vulnerabilities can remain undetected for a long time; unless all vulnerabilities are fixed, everything is vulnerable
• Complex, interconnected, socio-technical
• Physical systems increasingly dependent on smart technologies, which increases risk of attack
• Increasingly infrastructure is cyber-physical; from autonomous cars to large-scale industrial control systems for water, electricity or manufacturing

Table 2: Characteristics of cyber attackers and cyber-physical systems as obtained from this consultation and from The Royal Society's Report, 'Progress and research in cybersecurity: Supporting a resilient and trustworthy system for the UK'[6].

During an expert workshop the following challenges were raised as those which require urgent attention.

Challenge: Ensuring integrity of datasets

The integrity of data is key to the safe operation of cyber-physical systems. Industrial control systems, such as the electricity grid, transport networks, or water supply, rely on the accuracy of data in order to create the right outputs; from bus timetables to weather forecasts, from economic data to data from sensors. If these datasets are manipulated or compromised, this can have major impact on the functioning of these critical systems. Data sabotage by hackers has been raised as a significant safety threat to the functioning of the critical infrastructure on which society depends.

For example, pricing and dynamic demand information used by smart meters to optimise non-urgent uses of electricity (such as charging electric cars or running washing machines) could be manipulated to induce sudden surges or drops in demand, causing serious damage to the electricity grid. Equally, data essential to the functioning of autonomous vehicles if tampered with could induce mass traffic accidents.

Challenge: Interconnectivity causes vulnerability

Interconnectivity of devices through the internet of things (IoT) creates system-level vulnerabilities. A huge range of devices are now connected - from lightbulbs to toasters to cars and ships. These are based on standard computer architectures and are not often secure (safe) by design. This means that hackers can reprogram them easily to carry out tasks they were not designed for (for instance sending data as part of distributed denial of service attacks) and cause problems in entire systems. A number of major cyber attacks have already been carried out through hacked insecure IoT devices[7].

Challenge: Cyber-physical systems are complex and socio-technical

Cyber-physical systems include computers, physical objects and the people who operate them. This makes them very difficult for managers to visualise, understand or risk-assess, partly because it is impossible to see every dimension and interface within an entire system. As a result, there are many vulnerabilities to attack since there are many routes to failure, whether this be through human error (or failure to report when something is amiss), bad design or technical exposure. With the continuous upgrading of technology and increasing connectivity to other elements, human capacity to monitor everything diminishes. There is a need to assess entire systems as a whole not just as individual parts.

Challenge: Lack of standards and regulation

Cybersecurity and cyber risk are emerging fields and standards and regulation have not kept up with technological and economic change. While there are some standards and regulations around individual elements of systems, there is a need for a holistic view. This could include industry-wide standardisation of risk assessment, training, qualifications and sharing of best practice and also the creation of professional or industry bodies.

Safety of complex systems in high-hazard industries

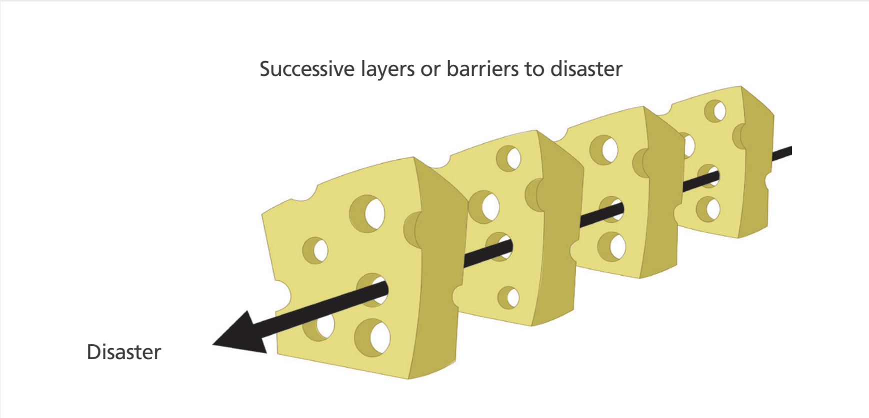
High-hazard industries such as nuclear, transport, chemicals, mining, marine, power, and oil and gas are complex, tightly coupled systems. Due to their highly interlinked nature, where outputs depend on the functioning of component parts and the handling of often potent materials (such as chlorine in water purification), there is potential for catastrophe in the event that one aspect goes wrong[8].

The *Deepwater Horizon* oil spill and the nuclear disaster at Fukushima are examples of when component parts of complex systems have failed and led to a major accident affecting surrounding people and environment. According to the US and Japan's national government reports on the BP oil spill and Fukushima, both these catastrophes occurred due to systematic failures in risk management where failings in both human action and technological integrity combined to create disaster[9, 10].

During the consultation process concerns were raised around a number of areas including ageing infrastructure, increasing technological advance vis-a-vis lack of worker upskilling, lack of fail safe modes, reactive rather than proactive approaches to safety, lack of system-level risk assessments, questions over how to monitor invisible infrastructure, and whether industries need better simulation of the range of possible consequences that could occur in response to unexpected external events.

Cascading disasters and the 'Swiss cheese' model

The 'Swiss cheese' model illustrates how disasters occur through a rare alignment of independent vulnerabilities at different scales. When each hole (the vulnerability) in each layer of Swiss cheese (the barriers created for safety) lines up, a disaster occurs[11]. This is seemingly rare and the odds are slim that these vulnerabilities line up, yet as industry becomes more complex with the addition of new technologies, there are increasing (and increasingly unpredictable) avenues for failure and the risk of an incident happening becomes more likely[12].



The Fukushima disaster occurred due a sequence of events that led to the cutting out of the power supply that was cooling the nuclear reactors which led to radioactive materials being released into the environment[9]. This can be described as a 'cascading disaster'. It originated as an earthquake under the sea, followed by a tsunami, then a landslide, then the knocking out of a pylon, which stopped the plant being cooled, partial meltdowns, a build-up of hydrogen gas and subsequent explosions. Further ramifications included radiation leaks into populated areas and detrimental economic effects both for Japan and for countries and continents that had relationships with Japanese industry[12]. Thinking about individual risks as potential future cascading disasters can help theorise which mechanisms should be put in place to prevent the individual risk becoming an eventuality[12].

Challenge: Ensuring adequate risk assessments

Risk assessment and certification generally focus on individual elements or subsystems. But safety or risk are emergent properties of complex systems. There are multiple elements that need assessing, including workers, the engineered systems, external events and the operating technologies themselves. A more holistic picture of the entirety of the system would enable a more advanced understanding of the level of risk in complete systems, rather than just component parts. As technology keeps being applied and layered onto systems, the need for this becomes even greater as the separation between technological complexity and worker knowledge widens. There needs to be a pragmatic reduction of risk in systems where complex interactions make elimination of risk impossible.

Challenge: New technologies overlaid on complex systems

As systems take on new technologies, the possibility for danger increases. New technologies overlaid onto existing systems increase the complexity, and therefore the possibility, of unpredictable interactions. Included in this increased complexity is the workers whose skills have not kept pace with technological uptake as well as the introduction of new technologies (such as new materials, connected sensors and nanotechnology) into systems that were not designed for them.

Challenge: Complex legacy systems

Ageing power stations, water plants and factories are frequently being patched up with new technologies and increasingly becoming internet-connected; this creates cyber risk in addition to the inherent increase in complexity that comes from modifying an existing system. Certifying that these are safe is not straightforward. Replacing underground networks and invisible infrastructure is very expensive and would cost millions. Keeping failure rates low in ageing infrastructure systems is a priority.

Fossil-fuelled transport and industry that do not create unsafe air

Air pollution is a major public and occupational health risk and one of the foremost safety challenges that global society faces today. WHO has recently declared (March 2017) that pollution is a higher risk to global health than HIV and therefore a higher priority to solve. Figures from its report suggest that pollution kills more than 1.7 million children per annum and in total causes approximately 7 million premature deaths a year globally (approximately 1 in 8 deaths)[13].

While the advent of electric vehicles (EV) will solve the problem of nitrogen oxide (NOx) and some of the toxic nanoparticles that are emitted from mobile diesel engines, we are still far away from a full electric vehicle transition in the developed world, particularly for commercial vehicles. The transition is likely much longer away in developing economies where regulatory environments are less strict and vehicles are replaced less frequently[14]. It must be noted that while EVs may lower emissions, power will still be needed to charge these vehicles. If this power is generated from coal or gas rather than using low carbon sources, the location of emissions will have shifted but total emissions may not have been significantly reduced[15].

Moreover NOx and nanoparticle emissions come from a range of other – more lightly regulated – sources, such as gas boilers and non-road mobile machinery.

Beyond transport, fossil-fuelled engines still proliferate across industries in both the developed and the developing world. While the transport industry (freight, trucks, HGVs, ships, cars) creates a significant proportion of nanoparticles and NOx, there are still high levels of emissions from energy generation, manufacturing, construction, and agriculture. A significant proportion of the world also relies on diesel generators for power or back-up power.

The European Environment Agency's 2015 report on emissions shows that the main sources of pollutants in Europe come from transport, energy, industry, the commercial, institutional and households sector, agriculture, and waste. The transport sector is the largest contributor of NOx emissions representing 46% of total EU emissions in 2013, meanwhile the agricultural sector is the worst performer in decreasing its emissions[16].

Challenge: Nanoparticle and NOx emissions

Nanoparticles and NOx from engine combustion in transport, industry, and other sources cause a serious risk to the health and safety of workers and residents. Emissions of these are falling thanks to improved design of vehicles and equipment and in the more distant future electrification of transport and motive power will largely eliminate the problem. Progress is slow, however, particularly in the developing world.

Based upon the timescales involved in removing nanoparticle- and NOx-generating infrastructure there is a need to introduce cheap and effective solutions that can prevent these pollutants from entering the environment.

Safe supply chains for medical waste

In the developing world, medical waste and its lack of proper disposal is a mounting safety hazard for people and the surrounding environment. Currently, there is increasing access to healthcare services and products in developing countries. However, the supply chain for products such as drugs and medical devices frequently ends at the point of delivery (at the hospital) because there is inadequate infrastructure and training in place to deal with disposal of medical waste.

According to WHO, medical waste refers to all waste that is created through any healthcare activity and includes materials ranging from 'used needles and syringes to soiled dressings, body parts, diagnostic samples, blood, chemicals, pharmaceuticals, medical devices and radioactive materials'[17]. WHO states that it is crucial to separate and dispose of each different sub-stream of medical waste appropriately (for example, sharps, non-sharp infectious waste, non-sharp non-infectious waste, hazardous waste) in order that health workers, patients, people and the surrounding environment are not exposed to hazardous effects[17]. Hazardous waste (approximately 15-25% of all medical waste) is a particular problem as it can cause disease transmission or chemical and toxic threats and can pollute water supplies.

Interviewees from international health organisations have highlighted that hazardous waste is currently disposed of at best in incinerators, but that these are often poorly run, and at worst the waste is dumped openly on the ground and burnt, or put in badly sealed landfill sites. Despite this being known anecdotally as a huge safety problem in the developing world, the issue appears to be largely neglected.

Experts from international health agencies who have extensive experience of medical waste disposal methods, from working in the field, were consulted. The table on the next two pages reflects knowledge gained through conversation with these experts. The information in the rows on developing economy practices reflect practical methods of waste separation and ad hoc approaches used by Médecins Sans Frontières (MSF) in dealing with particular waste streams in the safest way available – using inexpensive and practical methods rather than simply importing practices from the developed world.

Issue: Expensive to deal with properly without causing harm to people or the environment

Developing economy practices
There is currently no long term set plan for medical waste.

Developed economy practices
High income countries use expensive medical waste disposal solutions costing between $1 and $4 per kg for infectious waste. Non-infectious waste is often landfilled.

Issue: Safe disposal currently requires high tech high cost processes for hazardous waste

Developing economy practices
Semi-industrial incinerators are imported and can cost from $25,000 - $30,000 or even more with running costs for an industrial incinerator at $3,000 per month in fuel outlays. But such investments can potentially only be done for big hospitals that are well supported. And these incinerators are often not suited to deal with real hazardous waste either.

Cheaper models of incinerator exist, some of which can be built locally. They are suitable for smaller health structures in more rural areas and function rather well for certain kinds of medical wastes, but they are not suited to hazardous waste.

Developed economy practices
All types are disposed of with high tech incinerators and/or other processes.

Issue: Multiple different waste streams, from less dangerous to hazardous

Developing economy practices
The medical supply chain often does not extend to medical waste disposal.

Developed economy practices
The healthcare supply chain includes disposal methods for medical waste.

Issue: There are regulations on medical waste disposal but these are not universally applied (even in some rich countries)

Developing economy practices
Laws on medical waste disposal are rarely set, and when they are they require large investment in high tech solutions. There has been lobbying and some countries' healthcare systems have adopted pragmatic recommendations based on MSF's methodology.

Developed economy practices
Disposal occurs in accordance with specific laws that are set.

Table 3: Medical waste practices around the world

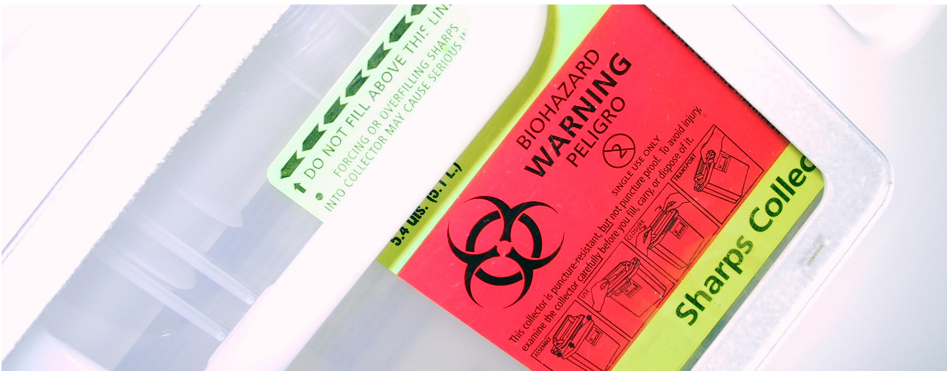
Developing economy processes
Medical waste in general Expensive to deal with properly without causing harm to people or the environment. Practice Currently no general scheme for hazardous and bio-hazardous medical waste (approximately 25% of all healthcare waste). There is huge growth in hazardous waste as diagnostic testing advances (eg for HIV) and uses more and more toxic materials (eg cyanide). There are currently no long term solutions for dealing with this waste stream.
Type of waste: Sharps (metals) Can be incinerated but are not completely consumed so need to be put in properly sealed landfills. Processes Can be put in sharps pits that are sealed properly; incinerators can also be used but small incinerators require manual removal of residue including needles that remain sharp.
Type of waste: Softs Materials, like packaging, that can burn easily (easiest to deal with). Processes Must be burnt in incinerators with double combustion chamber (at 760°C, then at 860°C and held for 2 seconds); if nothing has been installed by an agency, it can be burnt with kerosene in open pits.
Type of waste: Organic waste Placentas, amputated limbs, blood bags, organs. Processes To burn these properly all humidity has to be boiled off, which takes a long time and is expensive due to fuel costs. A simpler and cheaper solution is to conceal these in ventilated pits away from groundwater to avoid contamination.
Developed economy processes
Types of waste All. Processes All medical waste is segmented by type and processed accordingly by paid professionals operating high tech, high cost equipment.

Table 3: Medical waste practices around the world

Challenge: Hazardous medical waste is not disposed of properly

In high income countries hazardous waste is dealt with effectively through high tech processes that require expensive inputs. Low income countries do not have the capacity to provide the same solutions, so there is potential to extend the healthcare supply chain to deal with all medical waste streams, though the hazardous waste stream is currently the greatest risk.

According to MSF, the disposal of hazardous waste streams is an area in desperate need of innovation, especially given fears that institutions may give up on incinerators as disposal methods due to an inability to run them properly, or for environmental reasons. If this happens, it would lead to general dumping of waste. The key challenge for organisations extending the healthcare supply chain would be to find a new solution that can make all kinds of waste inoffensive and harmless with good volume reduction. Solutions would have to be either cheap to import and run, or able to be built locally.



Safe supply chains for electronic waste

Discarded electrical and electronic devices and products (often referred to as e-waste) make up the fastest growing waste stream in the world. The developing world receives 80% of the developed world's e-waste[18].

Developing economies are attractive locations for other countries to export their e-waste to on cost grounds, mainly resulting from fewer regulations on worker's rights, lower wages and weaker health and safety and environmental laws[19]. Simultaneously, growing economies in the developing world have a high demand for the raw materials that can be extracted from e-waste[20]. The huge recycling value to e-waste means the demand for this type of waste is high; in addition it provides a large number of jobs for people in the developing world[20].

Electrical and electronic product categories[21]

- Large household appliances (fridges, cookers, microwaves, washing machines, dishwashers)
- Electrical and electronic tools (drills, saws, sewing machines, lawnmowers)
- Small household appliances (vacuum cleaners, irons, toasters, clocks)
- Toys, leisure and sports equipment
- IT and telecoms equipment (personal computers, telephones)
- Medical devices (dialysis machines, medical freezers, cardiology equipment)
- Consumer equipment (radios, TVs, hi-fis, camcorders)
- Monitoring and control equipment (thermostats)
- Lighting equipment
- Automatic dispensers (hot drinks, ATMs)

Challenge: Electronic devices emit toxins when recycled

The process of recycling that occurs in informal economies in the developing world is rudimentary. The extraction process of valuable metals like copper and nickel exposes workers and the environment to more than a thousand different toxic substances, such as dioxins that cause cancer. Workers, including children, simply burn electronic products to melt away non-valuable plastics[20].

There is a need to put in place, and implement, national and international regulations on safe recycling. There are economic and environmental reasons for governments to do this as safe recycling is able to recover more of the valuable materials and prevents hazardous materials from being dumped in landfills that can pollute groundwater.

Challenge: Driving corporate and consumer awareness of e-waste

Companies cannot always reassure their customers that recycling is done properly as there are no universally agreed rules and there is little public awareness of the issue. Not much is known about where products go when they are finished with. Stronger verification and certification of processes – in relation to both how products are built and of where they are shipped to be recycled – would help companies empower their customers to make informed decisions on what to buy and how to dispose of it. This would reduce the risk to workers recycling e-waste.

Ensuring safety at sea

Shipping is a global industry. Standards and regulations are created centrally by the International Maritime Organization (IMO) and classification and statutory services are provided by members of the International Association of Classification Societies (IACS) to enhance safety for ships, the environment and seafarers all over the world. Safety at sea affects not just professional sailors but also passengers. The consultation engaged with protection and indemnity insurers, master mariners, pilots, government agencies, NGOs, maritime lawyers, trade unions, engineers and risk specialists.

While reported fatalities are decreasing year on year[22], respondents have stated that this industry has further steps to take in creating safer working conditions for seafarers and safer engineering practices now and in the future.

Challenge: Unsafe passenger ferries

From 2002-2016, there were 163 reported passenger ferry accidents, causing over 17,000 deaths[23]. Twenty-five percent of all passenger ferry accidents happened in Bangladesh, 16% in Indonesia, 11% in the Philippines, 6% in China and 42% in the rest of the world[23]. The Southeast Asia region has the worst fatality rates in the shipping industry.

Many respondents stated that lack of standards and regulation, or lack of their implementation, along with lack of investment in safety practices, leads to unsafe design and dangerous practices on board passenger ferries. Loss of life on passenger ferries in Southeast Asia and South Asia is particularly serious and occurs due to overcrowding, lack of standards implemented on size and type of cargo, the use of inappropriate boats not designed to carry passengers, inappropriate (cheap) design, human factors and misjudgement of weather conditions.

Risks to the safety of passenger ferries are of global concern given both the broad geographical spread of accidents and the potential for large-scale loss of life. Following the sinking of the *Titanic*, the UK official enquiry made 24 safety recommendations, of which just 12 have been implemented. The sinking of the *Costa Concordia* off the coast of Italy in 2012 (killing 32 people) pushed the IMO to implement the twelth recommendation, exactly 100 years after the *Titanic* sank[24].

Challenge: Safety of lifeboat lowering mechanisms

Safety of seafarers in the process of lowering lifeboats in mandatory monthly drills was voiced as a priority concern by many respondents to the consultation, both in interviews and in the survey responses from people in the shipping industry. Also in offshore activities, lifeboat incidents ranked the fourth most deadly in the Centre for Offshore Safety's 2015 Annual Report[25]. The design of the lowering mechanism (hooks, wires and winches) and their long term integrity in sea conditions have been called into question during the consultation. Designs of on-load release systems have been described as dangerous because 'safety is treated as a boundary condition rather than a design goal to be maximised'. Respondents stated that there is little incentive to design for safety beyond meeting minimum IMO rules. The practice of seafarers, in how they operate the mechanism, was also called into question.

Challenge: Safe transfer of personnel from ship to ship and shore to ship

Unsafe pilot ladders, a result of their design and fastening onto ships, was raised as a significant safety issue (and is one already subject to a Foundation Safety Grand Challenges project). Marine pilots, inspectors and crew all over the world put their lives at risk every time they board ships from other moving vessels or from shores. A pilot recently died boarding a ship from shore on the Thames in October 2016[26]. In order to investigate the worrying rise in fatalities from ship-to-ship and shore-to-ship transfer, the International Maritime Pilots' Association conducted a safety study on the standard of pilot ladders in 2016, using statistics from 2,709 returns from participating IMPA members. The feedback showed that 10.4% of all ships in question were non-compliant with regulations on safe transfer, with the pilot ladder making up 42.2% of all defects mentioned and 52% not being attached properly[27].

Challenge: Preventing asphyxiation in enclosed spaces

Entering enclosed spaces causes fatalities when there is a lack of oxygen. Seafarers are trained in how to enter enclosed places safely, for instance by wearing breathing apparatus, and there are procedures in place associated with entering these spaces. Despite this, the instances of deaths from entering enclosed spaces are frequent according to shipping insurers.

Ships carry breathing apparatus for when maintenance needs doing in enclosed spaces, however they are not always used by seafarers, nor are they necessarily used properly. It has been suggested that these breathing apparatus may be too large and bulky making them awkward for the small spaces that crew have to enter; there are also human factors around training, culture and incentives which need to be explored.

This is a multi-domain issue that occurs in places such as construction sites and grain silos. If this problem can be solved in shipping, there could be transferable lessons for other industries.

Challenge: Safety in the shipbreaking industry

Not only can ship breaking practice be hazardous for the environment, but workers can be killed in the process, particularly when ships are dismantled on beaches without strict controls. Shipbreaking is an issue that the IMO sought to address through the Hong Kong International Convention for Safe and Environmentally Sound Recycling of Ships, 2009, but this has not been implemented by flag states (states in which vessels are registered) because it has not yet been signed by a necessary 15 states, only ratified by four states[28].

The convention aims ‘to prevent, reduce, minimize and, to the extent practicable, eliminate accidents, injuries and other adverse effects on human health and the environment caused by ship recycling, and enhance ship safety, protection of human health and the environment throughout a ship’s operating life.’[28]. In Pakistan, this has not been implemented and as a result nearby fishing activities have ground to a halt due to pollution from ship breaking[29].

The majority of the world’s ship breaking happens in Pakistan, India and Bangladesh, where some of the world’s most hazardous working conditions exist. In Bangladesh, a man who works in ship breaking has a life expectancy 20 years below the national average.

Lack of personal protective equipment for workers, explosions, hazardous chemicals, asbestos poisoning and dismantling without proper waste management systems leads to pollution of the soil, sea, air and groundwater, decreases marine life and poses occupational health and safety risks for workers and local communities alike.

Challenge: Safety of mooring systems

Respondents expressed concern over the integrity of mooring ropes and bollards; the two key components necessary for the safe mooring of a ship. It has been widely cited that often ropes and bollards snap from excess wear, placing people in the surrounding docks at serious risk when tension from the rope is suddenly released. There are no widespread practical ways of monitoring the condition of bollards or ropes; additionally there may be opportunities to change mooring processes for ships as automation of shipping progresses.

Challenge: Fatigue in seafarers

The IMO's regulations on minimum hours of rest or maximum hours of work entitles seafarers to 10 hours of rest a day, where the hours can be divided into two periods. Hours of work should not exceed 14 hours a day in any 24-hour period and 72 hours in any seven-day period[30]. Most respondents from the shipping sector raised the issue of human error as a result of tiredness in crew members, some of them citing 96-hour weeks as realities for many seafarers. It was illustrated that fatigue is a growing issue as crew sizes become downsized and as ships become larger. With growing automation, fatigue has been mentioned as a future concern for the few designated crew who may be in charge of manning entire ships.

Safety in the fishing industry

Fishing is widely understood to be a very dangerous profession. In the UK in 2015, seven fishermen died at work[31], out of an estimated total of 12,107[32], representing a fatality rate of 57.81 per 100,000 workers. This compares to a UK all-industry fatality rate of 0.46 per 100,000[33]. The next worst industry for fatal accidents is agriculture with a fatality rate of 7.73 per 100,000. This makes fishing seven times more dangerous than the next most dangerous profession in the UK. Worldwide the problem is just as serious - the Food and Agriculture Organization estimates that over 24,000 fishermen die every year globally[34].

The consultation included many stakeholders in the fishing industry from governmental organisations, trade unions, foundations and experts in fisheries law.

From the consultation it became clear that safety problems stem from a variety of causes. Some are intrinsic to fishing such as the need to operate at sea in a dangerous environment subject to extreme weather. Others were related to design such as the construction of fishing boats, floatation devices, and protection from cold. Others were caused by the paradox of regulation that can incentivise unsafe activity. Finally, there is considerable tolerance of risk, both by fishermen themselves and by society, 'fishermen risk their lives putting food on the table'[35].

Challenge: Reducing risks of falling overboard

Falling overboard is the biggest issue raised by the consultation and the most common reason for cause of death[36]. Currently there are technologies that mitigate risk once in the water, for example flotation jackets and GPS trackers. However once a person has fallen into freezing water they have a very short time to survive unless pulled out very quickly. According to experts, after six minutes in freezing water limbs seize up and strength fails and it becomes impossible to climb out of the water. Cold water creates a huge shock to the body on entry, which then gives a tiny window for rescue even if someone has a flotation jacket on.

We heard from our respondents that there is a lack of exploration into how to reduce the risk of actually falling overboard in the first place, as the approach so far has focused on helping people once they have fallen into the water. Research into what would make fishing vessels safer to operate would help mitigate the risk of falling overboard. The UK's Marine Accident Investigation Branch finds that the core causes of falling overboard are being dragged by fishing equipment, washed over by a wave, and slipping or tripping over the side[31].

Challenge: Safe fishing boat design

The design of fishing boats can be a problem, ranging from inappropriate boats repurposed into unsafe fishing boats, to modifications of fishing boats that may jeopardise safety, to fishing boats designed to avoid regulations based on length, which may mean they are inappropriately wide or deep (a practice known as 'rule beating')[37]. These factors mean that fishing boats are not necessarily well-suited to the activities and weather conditions that they are being used in.

Challenge: Rise in subsea infrastructure

There has been a significant rise in subsea cabling for uses such as windfarms, internet cabling and electricity interconnectors[38]. Simultaneously, the size of fishing vessels has increased, mostly in the last 30 years. The infrastructure is vulnerable to strike by fishing vessels, particularly by vessels deploying bottom-towed gears. In 2013 there were 37 subsea cable faults on the UK continental shelf, the vast majority because of commercial fishing or ships anchors[39]. When ships and subsea infrastructure come into contact this can risk the safety of the ship and result in the subsea infrastructure being damaged or unavailable and requiring expensive repairs. The global safety challenge is to establish safe practice around subsea infrastructure for the benefit of both the fishers and the cable operators[39].

Safety of supersized structures

City skylines around the world are increasingly dominated by skyscrapers, with 436 buildings over 20 floors on the drawing board in London alone. At sea, a similar revolution is under way with larger ships: the top 20 cruise ships by tonnage were all built since the year 2000[40] including what is currently the largest cruise ship in the world, *Harmony of the Seas*, which carries up to 8,975 passengers and crew.

Even with the best design, larger structures are inherently more difficult to evacuate and there are safety implications of construction methods used to build them.

According to those consulted, construction standards - for instance around resistance to fire - do not all necessarily adapt well to the increased size and new materials used in these structures.

The science and engineering challenge of designing these structures so that they are quick and easy to evacuate is also not fully developed. Testing of evacuation procedures often only extends to computer simulations and these are based on limited real-world data on how people react in emergency situations[41]. Finally, the way these supersized structures are designed - both their physical layout and the design of signage, and evacuation routes and procedures - affects the manner and speed of people trying to escape them.

Stakeholders in the shipping industry said that they are concerned that the capacity of emergency fire services on ships have not increased with the size of containers ships, cruise ships or tankers.

Challenge: Accurate fire resistance tests

The main fire resistance test used for building materials - in which the materials are heated in a furnace - is not relevant to new materials as it was originally used to measure fire resistance of concrete. Building materials are changing quickly towards renewables, including use of composites, recycled materials and wood. Fire resistance metrics for buildings based on the furnace test need updating for new and mixed materials. Similar issues apply to ships where fire tests are based upon steel.

The Costa Concordia and the World Trade Center

The *Costa Concordia* incident is one of the few cases of an emergency evacuation of a large, modern cruise ship. The case is not necessarily fully representative - the circumstances of the accident and mismanagement of the evacuation owed a great deal to human error rather than inherent problems with the ship. Moreover, by luck of topography the ship settled on a rock ledge and so did not fully submerge, meaning the loss of life was relatively low (33 dead out of 4,252 people on board). However the official report into the disaster is clear that there were inherent problems with evacuation procedures and how they were implemented, for instance with the information provided to passengers, lack of evacuation analysis carried out during design, and suitability of evacuation procedures for a listing ship[42].

Tall buildings, similarly, have very rarely been fully evacuated, according to those interviewed. One of the few examples in history of the complete evacuation during a disaster of a large building was in the truck bombing of the New York World Trade Center in 1993. This revealed similar issues to the *Costa Concordia* report, with slow and confused evacuation taking up to nine hours in the case of one disabled building occupant[43].

Challenge: Knowledge and research into evacuation procedures at large scale

Large-scale evacuation and its interaction with structural stability (duration during which evacuation is possible) and the implications for 'last-minute options' may not be fully understood, according to the consultation respondents. Similar concerns have been raised for large ships, where simply extending traditional evacuation approaches to the larger size may not adequately account for limited evacuation time.

There have been very few full evacuations of large buildings or ships in emergency situations; even drills and experiments have been rare. The understanding that engineers and builders have, and the models they use, could be extended according to the size of these structures. This is both about how the design of structures affects flows of people, how to evacuate effectively, as well as the psychology of people in these circumstances - how they will respond, whether they will follow instructions, where they will seek information.

Making food supply chains safe

The world population is expected to hit 9.7 billion by the middle of the century[44]. Feeding these extra mouths will mean current practices will change. We will see new foods and new ways of processing and producing food.

This is likely to mean novel food production processes such as laboratory-grown meat, single cell protein, seaweed, and increased use of insects, as well as further intensification and mechanisation of agriculture. It is also highly likely to involve greater use of waste products in food; whey (liquid waste from cheese production) is already being used due to its valuable protein content, but companies are working on solutions based on products as diverse as spent grain from breweries, soy milk manufacture and hummus production. Other promising ingredients that are underused include blood from slaughterhouses (a high-protein product that is currently largely turned into fertiliser) and sludge from potato processing.

Alongside these innovations in food manufacture, urban populations are rising and a shrinking proportion of the world's population works the land[45]. We are getting ever further away from the production of our food.

Although overall food is very safe, particularly in the developed world, a number of very high profile scandals have shown the potential for widespread disquiet and fear about food safety and the potential for safety to be put at risk when things go wrong. These include the horsemeat scandal in 2013 in the UK, the BSE crisis of the 1980s and 1990s, and widespread melamine contamination of dairy products in China in 2008 and 2010.

In developed countries, consumers and regulators are demanding more information about our food - certification that it has been produced safely, traceability of ingredients and reassurance that what we buy is what we think it is. Part of this comes from regulatory pressure, for instance the US Food Safety Modernization Act which mandates preventive controls (proving proactively that batches are safe, rather than through reactive checks)[46]. Part also comes from consumer demand, as evidenced by the proliferation of certification schemes such as Soil Association, Fairtrade or Rainforest Alliance certification. Over 440 of these were in operation across the EU in 2010[47] and one interviewee indicated that this number is now likely to be over 500.

Agriculture, retailers and food manufacturers, particularly large ones with long and complex supply chains, are not well equipped to provide this information about food. Traceability of ingredients and batches is limited; fraud and mislabelling are widespread, for instance in seafood (frequent substitution with cheaper varieties[48]) and olive oil (with widespread fraud related to country of origin and quality[49]). Traceability of meat tends to be more effective[50], a result of concerns surrounding BSE, hormones and bovine TB, but even this did not prevent the horsemeat scandal.

Challenge: Supply chains are increasingly long and obscure

Supply chains are long and complex, obscuring the origins and quality of ingredients. This can, to some extent, be avoided by shortening supply chains where possible, eating locally for instance. But the pressure on the food production system is for a trend towards long and complex supply chains to continue. Food manufacturers and retailers - let alone consumers - struggle to know what is actually in their products, and this could become more problematic if these trends continue.

Making supply chains more transparent and improving traceability would help avoid future food scares, cut fraud, build resilience, help build public confidence, and aid compliance with food safety regulations. There is now a range of promising technologies for traceability, ranging from centralised databases like greenfence to bitcoin-like distributed ledgers like Provenance and Everledger.

Challenge: Opportunities and risks of algorithms and big data

Growing datasets and advancements in data science are both a challenge and an opportunity for food safety. They can help with real-time monitoring and tracing of food safety issues; for instance Fera's HorizonScan[51] system gives early warning to food manufacturers based on insights drawn from large datasets of food safety information and the early warning tool developed as part of the EU's FoodIntegrity project[52] can predict food fraud based on economic data such as prices.

The implications of approaches like these are yet to fully emerge. They are highly promising, but if these approaches displace traditional inspection and compliance strategies, this could have unintended consequences: the integrity and reliability of these datasets could be compromised, and the transparency and reliability of algorithms can be problematic[53]. To what extent can data replace more traditional assurance activities?

Safety of water and water infrastructure

Systems supplying safe water and wastewater services are under stress as climate change drives uneven distribution of rainfall, leading to floods and droughts. Meanwhile, the population in many parts of the world is growing and, in the developing world, there is a trend towards greater urbanisation. This places increased stress on water systems around the world. It is estimated that 663 million people around the world do not have access to safe drinking water and 2.4 billion people lack access to safe and secure sanitation services[54].

Water is at the heart of a variety of risks. There are consequences from irregular rainfall patterns arising from climate change. Increased rain in some areas can put infrastructure at risk of flooding, disrupting transport networks such as roads and trains. Decreased rainfall in others can cause drought[55].

The need for better water systems in the face of uneven rainfall is further driven by rising population trends worldwide that will place ever greater demand on water supplies for things other than water and sanitation. Water crises will affect other related systems, such as energy and food. As populations worldwide grow and urbanise, demand on agriculture increases and with it demand for irrigation and food processing water. In 2012, the Organisation for Economic Co-operation and Development (OECD) estimated that global water demand will have grown 55% by 2050[56]. As developing countries' GDPs increase, demands on water from electricity production, industry and urban supply will be in stiff competition with demand for water from agricultural production. This global future safety problem is being called 'the water, energy, food nexus'[57] and the OECD argues that 'innovation has a major role to play in promoting sustainable water resource management'[56].

Challenge: Lack of safe water infrastructure

A lack of safe water infrastructure is a problem that is preventing safe access to water and to sanitation facilities which contributes to the huge burden of excess disease and death globally[54]. There are a vast number of solutions and applications being worked on, but no solutions have so far proven themselves scalable or sustainable.

There is a need to develop models of service provision that combine supply chains with socio-technically embedded engineering solutions (that is, not imposed solutions) that will be acceptable to the communities they serve. Such solutions need to be built and maintained locally and used by the people being served through acceptable business models that make this essential service part of a thriving value chain.

Challenge: Uneven distribution of rainfall and extreme weather

The increasing prevalence of floods and droughts due to extreme weather has been marked as a key global risk in 2015 by the World Economic Forum[58] and by the UK Cabinet Office Risk Register. With increasing urbanisation, dependence on our built environments and demand for more water to support industry, agriculture and consumer demand, we need to manage water better to ensure constant provision; and to protect critical infrastructure against the detrimental consequences of extreme flooding. Increased flooding is a safety risk for critical infrastructure and a cost risk for governments. Similarly, drought is a risk for water companies, governments and societies. Water needs to be captured better, drained better, and understood better to maximise the utility of increasingly uneven and unpredictable rainfall, to protect our services, and to inform how future services can be built more resiliently.

Challenge: Protecting and maintaining critical water infrastructure

Infrastructure under the ground is difficult to monitor for faults and when one pipeline goes wrong the effect on the entire system or network could be catastrophic. Already there have been significant failures leading to impacts on people and the natural environment. In New Jersey in 2016, there were instances of lead in the water being supplied to public schools as well as other contaminants[59]. In 2000 in Walkerton, Ontario, seven people died and thousands were made ill when E. Coli contamination of the water network was not detected[60]. In 2014 more than 100,000 residents of Flint, Michigan were inadvertently exposed to high levels of lead as a result of ill-planned changes to the water supply. The inability to analyse the integrity of ageing infrastructure that is hidden is a huge problem; it costs tens of billions to replace and creates untold human impact. We need safe and secure water systems that can be effectively monitored for faults.

The so-called 'invisible infrastructure' that supports water services, such as ageing pipe networks that lie below the ground is another area of risk. Cast iron water mains rust over time and can rupture; and in the developed world, much of this infrastructure is many decades old.

Prioritisation and findings

Having identified a number of challenges throughout this document an attempt has been made to prioritise the challenges. The prioritisation process is based on the opinions of participants invited to a workshop, as listed in appendix 1, scoring the challenges based upon:

- fit with the Foundation's mission,
- innovation potential,
- impact if solved, and
- ability to catch public imagination.

The table on the next three pages lists the challenges that were ranked as the top 17 by this process.

Having identified a number of challenges throughout this document an attempt has been made to prioritise the challenges.

Theme	Safety challenge	Potential solutions could include
Safe operation of autonomous systems	Trust between non autonomous and autonomous systems	Research into how human operators will respond to automated vehicles. How will this affect how people behave around them? And how will autonomous systems respond to this behaviour? Design an analysis method to understand how systems and stakeholders of systems will interact.
Safe operation of drones	Public service delivery vs commercial passage (in future unmanned traffic management)	Develop safe delivery models and management systems for drone delivery services.
Safe operation of drones	No fail safe mode	Develop safe failure modes that can automatically bring a drone to a safe condition under any circumstance.
Making food supply chains safe	Long and obscure supply chains	Create an open, decentralised food traceability tool that gives manufacturers, retailers and producers real-time monitoring of food safety and compliance.
Safe supply chains for medical waste	The healthcare supply chain stops at the hospital in the developing world	Develop the healthcare supply chain in the developing world to include disposal of medical waste.
Critical infrastructure that is safe from cyber attack	Interconnectivity	Build a standardised platform (software and hardware) for internet of things devices, which can receive software updates but that cannot be hacked to act outside of its parameters of normal operation.

Theme	Safety challenge	Potential solutions could include
Critical infrastructure that is safe from cyber attack	Integrity of data sets is key to safe operations	Design a tool or piece of software that can spot manipulation of data in critical datasets.
Critical infrastructure that is safe from cyber attack	Cyber-physical systems are complex and socio-technical	Develop a holistic risk assessment tool that analyses cyber risk for an entire network (taking into account the cyber and the physical).
Safety of water and water systems	Lack of suitable water infrastructure in the developing world	Develop a package of 'full spectrum solutions', combining supply chain integration with engineered 'socio-technical' solutions that increase access to safe, secure and sustainable drinking water and safe, secure and sustainable sanitation, with a delivery model, a business model, a capacity model and a financeability model. Also needed are registration and certification schemes for prospective solutions monitored by third parties so users can have greater confidence in their safety and security.
Safety in the fishing industry	Falling overboard	Redesign flotation devices so that fishermen wear them (ie they are as light and as non-bulky as possible) and so that they generate heat once in cold water Redesign of work clothing worn by fishermen to incorporate free movement, buoyancy and warmth. Design a retrofitting kit that can be used on boats to prevent fishermen falling overboard.

Theme	Safety challenge	Potential solutions could include
Ensuring safety at sea	Passenger ferries	Seek to influence the IMO to enforce regions to take up regulations that would make ferries safer in design and methods of use.
Ensuring safety at sea	Transfer of goods and personnel from ship to ship and ship to shore	Redesign the method of ship-to-ship and shore-to-ship transfer for personnel and goods to do so safely.
Ensuring safety at sea	Integrity of ropes and bollards in the mooring process	Design a method for measuring the integrity of ropes and bollards. Redesign the mooring process using alternative methods or materials.
Ensuring safety at sea	Lifeboats	Redesign lifeboat lowering mechanisms for optimal safety.
Safety of building materials and evacuation processes	Lack of knowledge of evacuation processes at massive scale	Research into how you can make people aware of what they are supposed to do in emergency scenarios, and how can you make people do what they know they are supposed to do in emergency scenarios? Can further data be gathered (through experiments or drills) to inform the computer models that engineers use to predict flows of people in emergencies?
Safety of complex systems	Inadequate risk assessments	Develop a better holistic risk assessment framework for complex high-risk systems. This could include new technology such as machine learning.
Safety of complex systems	Uptake of new technologies	De-risk the introduction of new technologies (such as Nano, CRISPR, AI/ML)

In addition, a number of cross-cutting themes emerge from the challenges reported throughout this insight report. These are listed below.

Decommissioning
On a number of occasions throughout this report the topic of decommissioning has been raised, for instance in the shipbreaking industry, disposal of e-waste, medical waste. Decommissioning refers to the end of life of assets, products or devices. There is a need for end of life to be part of design, allowing for repair or repurposing where possible, but beyond that design should consider dismantling and recycling, including materials that are less damaging. To enable all of these appropriate skills and infrastructure are needed.
Cybersecurity, connectivity and the internet of things
As devices increasingly connect to the internet, new avenues for malicious activity - as well as new modes of failure - emerge. This is relevant to the development of autonomous systems such as cars, cybersecurity of critical infrastructure, algorithimic and data-based approaches to food safety, and the rollout of drones in urban areas.
Human factors
Throughout this report there are many examples illustrating how people's actions significantly affect safety. Understanding people is essential when designing critical systems or infrastructure; even the most efficient design is potentially flawed if it fails to take into account the people that will interact with it.
Updating standards in light of new technology
Standards have not always kept up with technological change. New building materials in buildings and ships are not appropriately evaluated by tests. Safety regulations for critical infrastructure have not kept up with the introduction of connected devices. Complex high-hazard systems change fundamentally when new technologies are introduced, but these changes are not always well understood.
Controlled return to safe state
This report has many examples of infrastructure failures and the need for a controlled return to a safe condition. This includes the mechanical failure of aerial drones, controlled shutdown of systems that have been subject to hacking, and the evacuation of large structures such as buildings and ships. How can safety be assured in emergency scenarios?

Appendix 1 Contributors

Nesta project team

- Tris Dyson - Director
- Constance Agyeman - Head of International Development and Communities
- Olivier Usher - Research Manager
- Clementine Vandeleur - Researcher
- Orpa Haque - Research Coordinator

The following Nesta colleagues also contributed:

- On drones; Kathy Nothstine, Lead of Future Cities; Deran Garabedian, Senior Adviser
- On pollutants; Richard Duffy, Foresight Researcher

Reviewers

The research team would like to thank the following individuals who commented on early drafts of certain chapters.

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- Dr Mark Everard, Associate Professor of Ecosystem Services, UWE
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Workshop on cybersecurity and critical infrastructure, held at Nesta on 15 February 2017

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Workshop to select and prioritise safety challenges, held at Lloyd's Register Foundation on 3 March 2017

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Interviewees

This insight report would not have been possible without so many experts being so generous with their time and knowledge.

The following interviewees have given permission to be named:

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Appendix 2
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