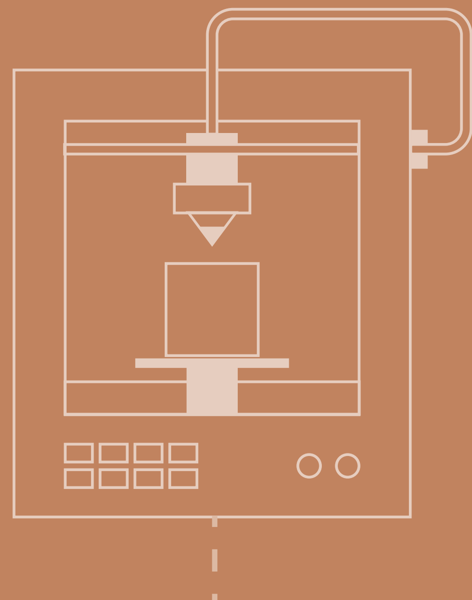
Lloyd's Register Foundation

Life matters

# Roadmap for additive manufacturing

## Safe adoption of additive manufacturing for safety-critical assets



Draft for consultation

October 2016
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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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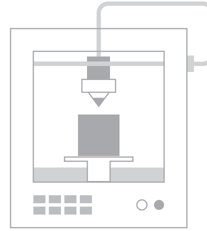
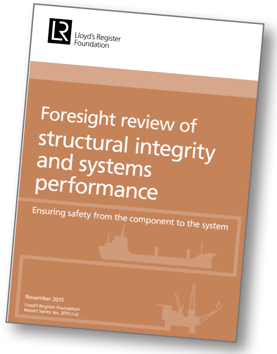


# Executive summary




The Lloyd’s Register Foundation has previously published a foresight review in the area of structural integrity and systems performance. A key observation is that additive manufacturing of metals and other materials has the potential to enter widespread industrial use but it is important that application of this potentially disruptive technology, for components of critical infrastructure on which we all depend, does not reduce the safety or reliability of these systems. In this context the Foundation has created a roadmap to indicate the work that it believes is needed to assure safe application of the technology and also identifies the unique activities where the Foundation could make a distinctive difference.

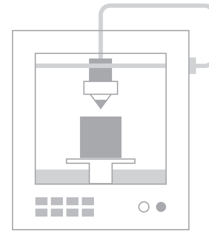
The Foundation has no commercial interest in the development or commercialisation of the technology, such as developing a better 3D printer that is faster or cheaper. In line with our charitable purpose, the starting point for our roadmap is the ultimate aim: The safe adoption of additive manufacturing to safety-critical assets.

With this aim in mind, existing roadmaps have been reviewed and some experts in the field consulted to identify the key challenges that once developed will lead to safe adoption of the technology. Three of the challenges focus upon reducing the risk of creating parts that can fail prematurely or unexpectedly and one challenge seeks opportunities on how additive manufacturing technology can deliberately be used to improve overall safety of an asset.

The four challenges are as follows:

- Qualification of technology
  In general, qualification is carried out for all important items to demonstrate that the item is designed well, can in fact be built and that it safely and reliably fulfils its intended function. For parts made with traditional manufacturing techniques these requirements are widely understood with qualification taking into account this knowledge. For additive manufacturing there is limited knowledge of the process or materials, which has the consequence of meaning that there are either no qualification routes available or there is extensive additional testing required. The goal here is to work with others to develop and collate knowledge in order to be able to find safe methods of appropriate qualification.





- Confidence in the supply chain
  Localised manufacture from digital designs creates a number of commercial opportunities but also increases safety risks. What is most important is that critical components are made well, that correct components are installed and that any repairs carried out do not result in unexpected failure.

  The goal here is to work towards: creating standardised ways of assuring that components are well made; ensuring that there are improved ways of avoiding counterfeit or rejected parts from entering service; that repairs can be relied upon; and that confidence in the supply chain is not damaged by the disruptive business opportunities that additive manufacturing will bring.

- A competent and qualified workforce
  Irrespective of the level of confidence in the ability of an additive manufacturing machine to be able to build a part, the function of the part will depend on the skill of the designer, and the quality of the part will depend upon the individual(s) responsible for the manufacture of the part. For a new technology such as additive manufacturing there is a need to have designers that are able to design safe and functional parts and machine operators that understand how to make the parts and know when and why problems have arisen.

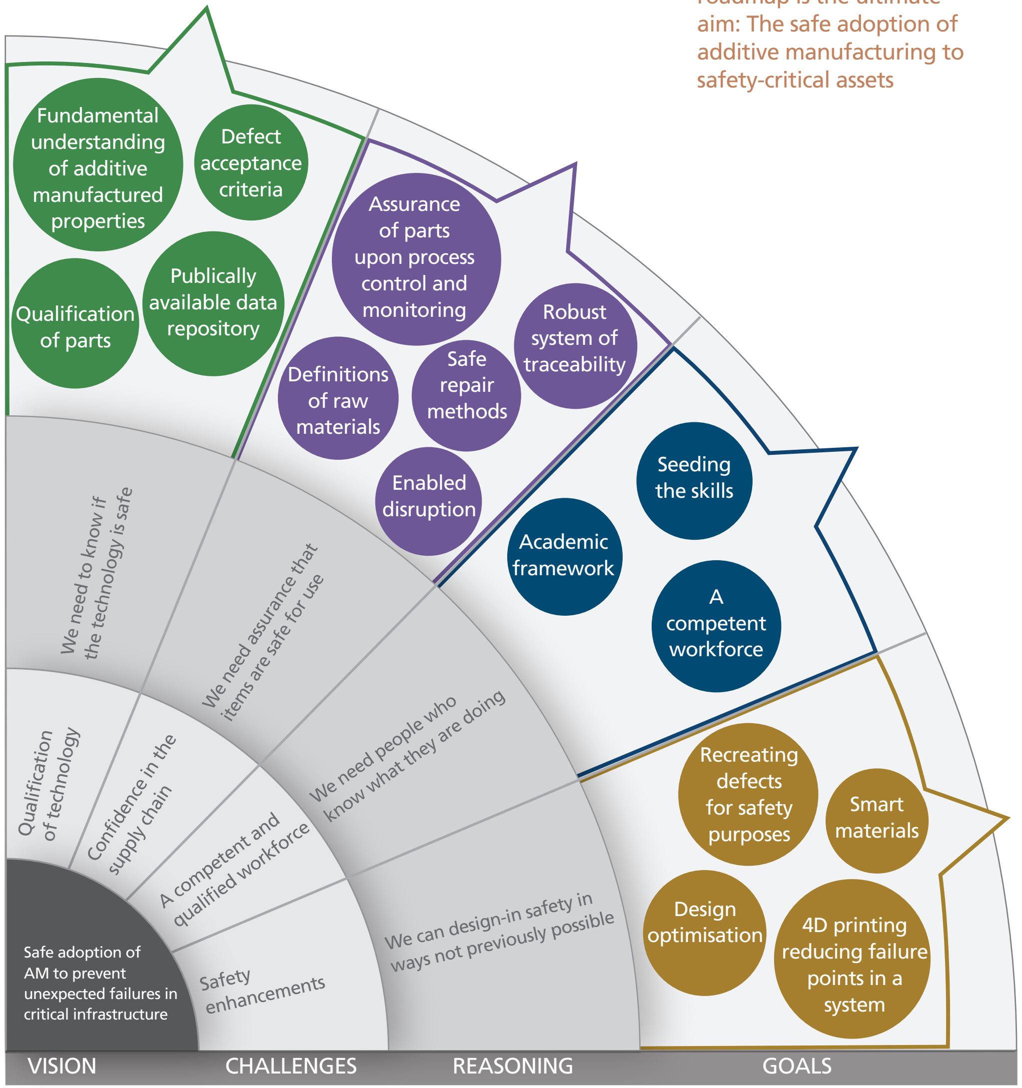
  The goal here is to work towards developing engineers with a fundamental level of knowledge about the process and operators who are competent enough to assure high quality parts are consistently produced.

- Safety enhancements (enabled by additive manufacturing / 3D printing)
  The previous challenges have focused on assuring that parts are well designed and made to be at least equivalent to current technologies. This challenge looks to how additive manufacturing can lead to improvements in reliability and safety over and above what is possible today. Opportunities exist for additive manufactured parts to be used to make systems that have fewer potential failure points and which are smarter, for example creating data about the environment they work within or providing crucial information about the parts themselves. There are also opportunities for improvement that we are only just beginning to understand.

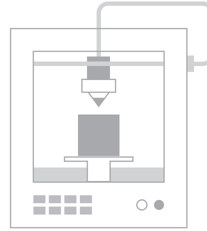
  This review looks at these challenges, both to control risks and exploit opportunities, in more detail. The purpose is to encourage others to work in these areas and for the Foundation to work with partners that can make a distinctive difference to making the world a safer place …because Life Matters.

# Additive manufacturing roadmap

The starting point for our roadmap is the ultimate aim: The safe adoption of additive manufacturing to safety-critical assets





# Foreword

This document is important in identifying where we, as a charitable foundation, can intervene in the technology of additive manufacturing to make sure that its development and applications are done safely, in line with our charitable aims. We have prepared this document to help direct our own grant giving and charitable activities in the field. We are also making it openly and freely available for others to build on and derive value.

Additive manufacturing is a disruptive technology that is finding applications across many sectors. From the Lloyd's Register Foundation perspective we are concerned with making sure that the technology is underpinned by an appropriate body of knowledge plus the necessary skills and standards, to help it achieve its full potential and in the process be used safely, particularly as applied to safety critical components and systems.

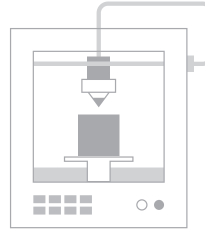
**Professor Richard Clegg**
**Foundation Chief Executive**
**Lloyd's Register Foundation**

# Background

A number of recommendations were made to Lloyd’s Register Foundation in the Foresight review in structural integrity and systems performance. One of these relates to the safety of systems containing additive manufactured parts and the original text is repeated below.

> ‘The potential to create a component from raw materials by additive manufacturing (sometimes called AM or 3D printing), anywhere in the world, at low cost and with high speed and quality, has the potential to revolutionise manufacturing industry. Shipping costs and lead times will be vastly reduced, with some analysts predicting a reduction of up to 40% in shipping freight once the technology becomes established. While applications of AM in safety-critical structural components are currently rare, this will change rapidly as the technology advances.
>
> Globally there is a diverse and intensive research effort into AM design and manufacturing techniques. Significant effort is being deployed to solve the barriers to its implementation and as such it is difficult to have or maintain a clear overview of the current state of development.
>
> The opportunity exists for the Foundation to act as a catalyst to bring together all stakeholders, from researchers through to users and regulators, with the aim of identifying the key issues that need to be addressed to ensure the safe application of parts made using this developing technology. This is anticipated to include development of manufacturing skills, standards, certification, legal responsibility, and underpinning research. The findings of this and any subsequent forums will be openly published.
>
> Until such a time as the research gaps are identified, the Foundation should consider investigating the following:
>
> - the new field of 4D printing, where the shape of a 3D printed item can change by a self-activated process triggered by the operating environment
> - research into the mechanisms of in-service degradation to ensure long-term integrity of additive manufactured parts; and
> - that appropriate recognised training exists for those that will operate and create parts by additive manufacturing; this links to the Foundation’s strategic theme of skills and education.’





The development of additive manufacturing has the potential to be disruptive across industries in ways that we are only beginning to understand. Central to the Foundation’s mission is the enhancement of safety and advancement of public education, and in the fast developing area of additive manufacturing it is necessary to work towards first ensuring that the application of the new technology will not result in decreased levels of safety and second, that enhancements to safety that are possible with the technology are exploited.

Following a review of some of the published additive manufacturing roadmaps and interviews with experts in the field the Foundation has identified the space where it thinks it can make a distinctive difference. This document presents the findings of the review with the intention of being publically reviewed between now and the end of January 2017. Once we publish a final document we will look to engage with others to bring the roadmap to reality.

The ultimate aim of this roadmap is the safe adoption of additive manufacturing to safety critical assets

# Experts and resources consulted during preparation

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Professor David Wimpenny
Manufacturing Technology Centre (MTC)

William Wistance
Lloyd's Register

Professor Xiang Zhang
Coventry University

Guidance notes for additive manufacturing of metallic parts
Lloyd's Register and TWI Ltd, January 2016

The case for additive manufacturing
Positioning paper, March 2015

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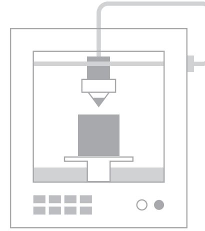
Royal Academy of Engineering, May 2013

Shaping our national competency in additive manufacturing
Additive Manufacturing Special Interest Group, UK Technology Strategy Board, September 2012

Rapid manufacturing: Techniques & applications for the Australian manufacturing industry
ISS Institute, September 2009



# Introduction



Additive manufacturing is the layer-by-layer build-up of material to create a three dimensional object; it is commonly known as 3D printing. This manufacturing technology differs from more traditional methods of manufacturing where materials are either created in volume then reshaped, machined or finished in some way (this is known as 'subtractive' manufacturing as material is removed); or 'formative' manufacturing methods where the component is manufactured rapidly in one manufacturing step, for example injection moulding.

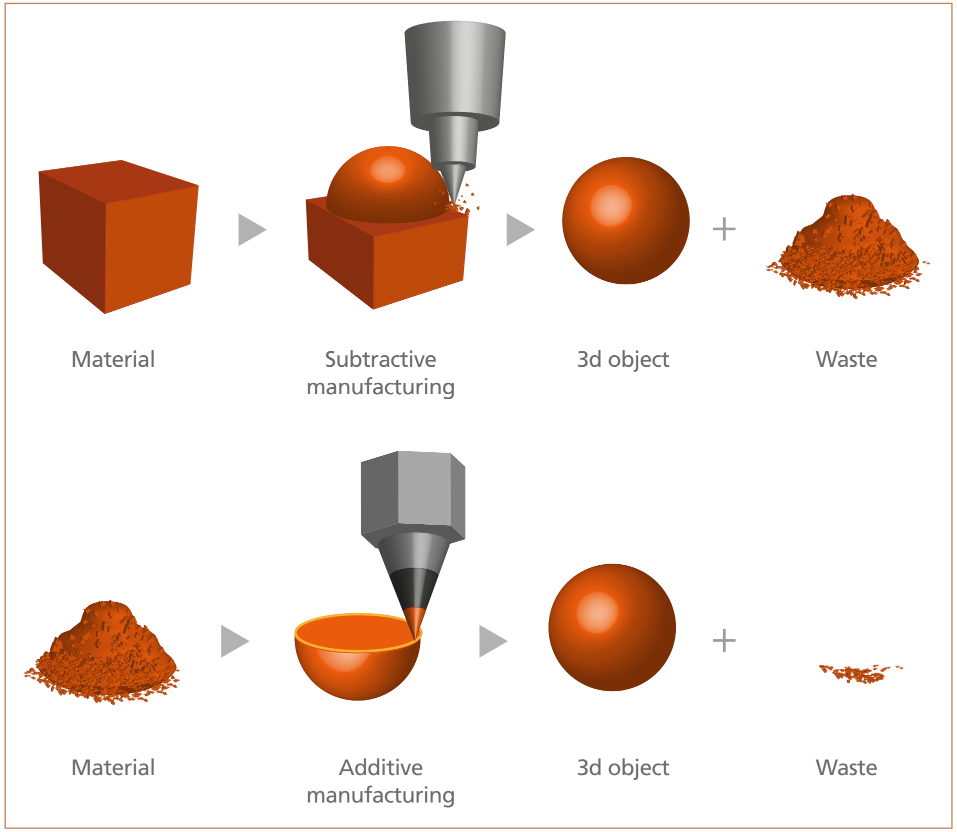



Fig 1: Subtractive manufacturing (top) and additive manufacturing (bottom)

The materials that can be used additive manufacturing vary widely from metals through to plastics, ceramics and even living cells. The term 3D printing (or 3DP) usually refers to manufacture of plastic/non-metallic parts and additive manufacturing refers to manufacture of metallic parts although outside the industry these terms are used interchangeably.

Manufacturing an item with additive manufacturing needs a digital plan of the object to be made, a digital file that provides instructions of how to divide the object into many individual layers, a machine that can deposit multiple layers of material in such a way that they create the three dimensional object and, depending on the component, equipment for finishing that can include thermal treatment, and polishing, among others.

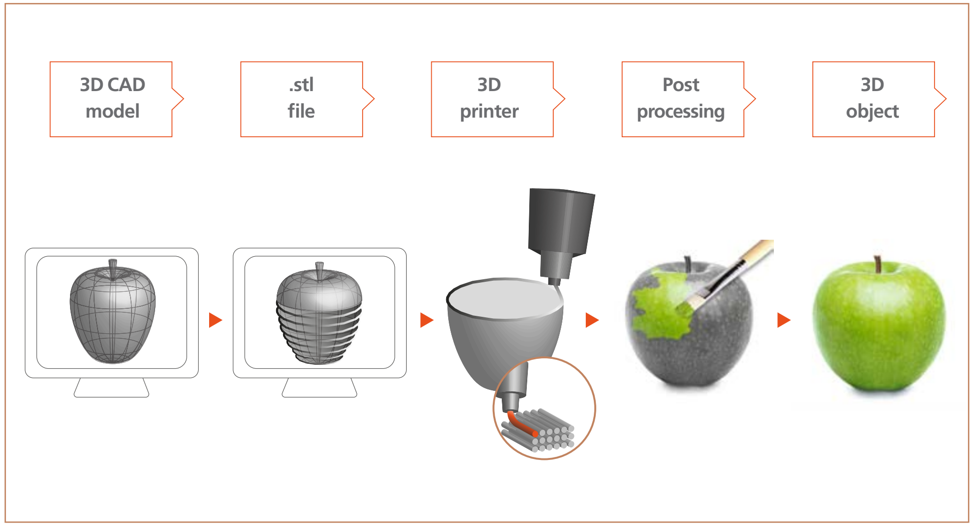
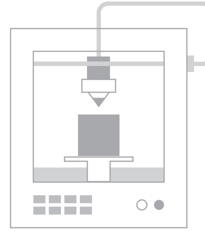



Fig 2: The additive manufacturing process

This technology has captured the public’s attention in many ways: from 3D-printed cartoon characters that can be made at home to spare parts made on the international space station; from the kitchens of Michelin-starred chefs to replacement parts for the human body; and from components for passenger aircraft to buildings on earth and even maybe the moon.





When it comes to the critical infrastructure on which society depends the adoption of additive manufacturing can provide some significant advantages. It can recreate parts from digital files at any location in the world enabling: product runs of one upwards being started at the touch of a button, leading to faster and more flexible supply chains; new optimised and simplified designs that could not be previously manufactured or fabricated due to manufacturing limitations; significant reductions in waste and energy; recreation of obsolete parts, etc.

This is a rapidly evolving technology with development driven by its early adopters.

When looking at the technology from the perspective of the Lloyd’s Register Foundation, the widespread adoption of this technology for components within critical infrastructure systems must not reduce the overall safety of an asset. This provides the focus to the roadmap developed by the Foundation for additive manufacturing: The safe adoption of additive manufacturing to safety-critical assets.

## Challenges

The road-mapping process has identified four challenges currently faced in the application of additive manufacturing technologies that are directly aligned to the Foundation’s charitable aims.

One of the challenges is the advancement of safety that can be enabled by application of additive manufacturing.

The Foundation will focus on these four challenges:

- Qualification of technology
- Confidence in the supply chain
- A competent and qualified workforce
- Safety enhancements (enabled by additive manufacturing / 3D printing)

Each of these is examined in more detail in the following sections.

# Qualification of technology

Additive manufacturing is a new technology that is already being applied by early adopters. However, there is significant work to do before there can be codes, standards and regulations that define every aspect required to assure safe design, manufacture and repair of components or structures made with this technology.

The key goals are: fundamental understanding of additive manufactured materials; publically-available data repository; qualification of parts; and defect acceptance criteria.

## Fundamental understanding of additive manufactured materials

There are many variables that affect properties and performance of items made with additive manufacturing. Understanding the properties and performance and how to reliably measure them are key to the design and build of safe products.

There is already significant research within the space to understand the influence of essential variables such as raw materials (powders) and processing parameters. There are areas that receive less research attention such as how to measure appropriate properties and performance under operating conditions in order to generate relevant and repeatable information, control of powders both new and when re-used, etc.

As part of this challenge area there is recognition that accelerating the uptake of existing research can be hindered by preferential funding for low technology readiness level research but less funding for translation of this research towards impact.

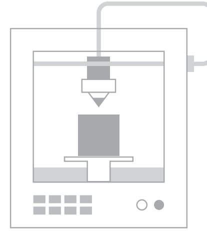
## Publically-available data repository

Before design codes and standards can be written there is a need to have knowledge and experience to justify the content of these codes and standards.

Early adopters are accumulating data on the materials and processes that they are developing but, for commercial reasons, this information is not often made available.

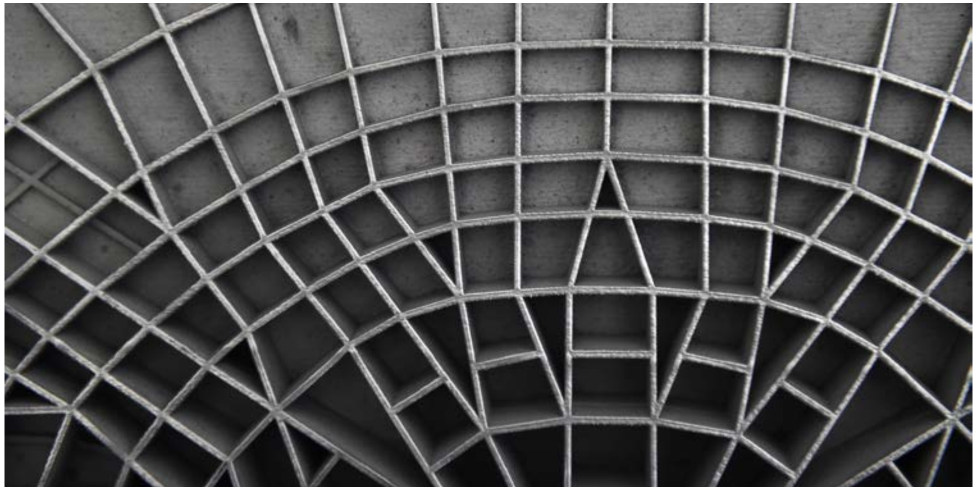
There is a need for the establishment of an international, publically-available database with a wide cross-section of academia and industry willing to populate it with safety-relevant and validated data. There is also an opportunity to work with those that restrict information to find ways of releasing safety-related information that does not harm competitive advantage.





## Qualification of parts

When new parts are designed for critical applications they undergo a period of testing to demonstrate that they meet the required design, can be manufactured, that they function as expected, and that they comply with any associated standards. The extent of testing depends on the criticality of the part and the operating environment in which the part will be used. For items made with established manufacturing technologies the testing concentrates on the item function as the material properties are generally well understood and taken into account. This is generally not the current case for additive manufactured parts where both the materials (manufacturing technology) and the design are tested during qualification. Wider adoption of the technology will require qualification programmes that are similar to those made with traditional manufacturing technologies while, importantly, maintaining the level of safety. There is a challenge in being able to balance the appropriate level of safety with the amount of testing.



The underside of a wing flap produced in a 3D printer, at the Airbus factory in Bremen, Germany. In view of the technical possibilities offered by 3D printing, Airbus is once again focusing on its own production of parts.

## Defect acceptance criteria

Imperfections that have a significant risk of causing a failure are known as defects. Defects can form at any time during manufacture, during fabrication and during service, with inspection for defects conducted at each of these phases.

With additive manufacturing there are some additional challenges associated with: imperfections in to each layer, among the thousands of individual layers, having the potential to create defects; new defects that are unique to the additive manufacturing process; and the difficulties of inspecting complex three-dimensional shapes.

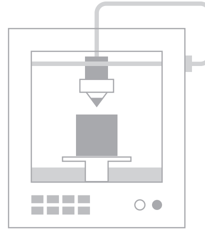
Standards exist which define the techniques that are applicable for inspection, the different types of imperfection that can occur and limits on when these imperfections are considered as defects that need to be removed.

Standards committees have started to set defect acceptance criteria for additive manufacturing based upon comparison with tradition manufacturing technologies but what is lacking at this time is the foundation work to justify or better define defect acceptance criteria.

A further indication of proposed activities that fall under these goals can be found in Appendix 1 – Qualification of technology.

Image courtesy of National Centre Additive Manufacturing, MTC, UK





# Confidence in the supply chain

As a society we have an expectation that critical infrastructure will operate safely and reliably deliver the services that we rely upon. To achieve this it is essential to have confidence that what has been designed and qualified will be delivered and that it will function as intended. A key element of this is being confident that every component supplied is genuine, meets the design specification and is safe.

The key goals are: definitions of raw materials; robust system of traceability; assurance of parts based upon process control and monitoring; safe repair methods; and enabled disruption.

## Definitions of raw materials

A fundamental building block in the integrity of additive manufactured parts is the raw materials from which they are made such as powders, wires, etc.

There is already significant research into developing and optimising raw materials, and how they can influence the properties and performance of final parts.

At this stage of the technology development there are no published standards for how to define the raw materials that are used. Although there are steps to develop international standards these will take time so it is important to establish a framework for raw material definition as quickly as possible. Such a framework with allow powder suppliers to specify their products in a uniform way, introducing universally applied quality controls at the raw material suppliers, supported by independent certification.

In some additive manufacturing processes only a small proportion of the raw powder materials available in the machine are fused to form a manufactured layer meaning that the remaining unfused materials can be used to produce subsequent layers. There comes a time when the re-circulated powders degrade to the point that their continued use can negatively affect the quality of the parts, so it is important to understand how these powders degrade and then develop measures to ensure that they are appropriately controlled and removed from the production cycle before they can affect safety.

## Robust system of traceability

It should be possible to trace back components to the original manufacturers and often to their suppliers and sub-suppliers; this is known as maintaining traceability. Traceability assures that parts are made well and that only genuine products are installed but is equally important in tracing components that are later suspected of being substandard.

The use of components that are not genuine (either as alternatives to originals, restored parts or counterfeit parts) can affect the safe operation of a system. Ensuring traceability of parts is already a challenge, however, the introduction of additive manufacturing technology introduces increased risks to the supply chain. In principle it is possible for anybody with access to a 3D printer to create a part provided that they have the digital design to recreate parts. This introduces a significant risk to the supply chain, uncertainty on liability if the part fails, and ultimately the safety of the systems in which these components are installed. The general area of traceability is rapidly evolving. It is important to understand how the traceability of parts, including additive manufactured parts, will be assured in the future to enhance safety.

## Assurance of parts based upon process control and monitoring

There are many individual steps involved in the process of manufacturing a part by additive manufacturing. These steps span the design of parts (including generation and translation of the required computer file), the raw materials, the manufacturing machines, the operators, post processing, inspection and testing, through to final certification. In order to have confidence in the integrity of the part each of these individual steps must be carried out correctly.

Although it is possible to build and certify additive manufactured parts for critical infrastructure, the current maturity level of the technology requires significant testing that at present is not standardised. Standardisation at a time of rapid technology evolution has a risk of being out of date at the moment it is issued. Ideally what is needed is a rapid method of qualifying processes based upon control and monitoring of critical fundamentals rather than being machine specific.

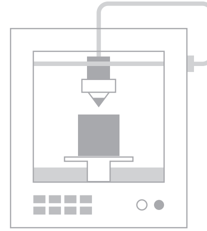
As understanding, control and confidence in the technology improves, the amount of inspection and testing will reduce, with monitoring of systems becoming more relevant.

Work is needed to standardise the way that parts are certified today, to develop technology to better control and monitor the manufacturing process, and ultimately reduce physical inspection and testing without compromising quality.

## Safe repair methods

Additive processes cover a wide range of technologies that can be used not only to build new parts but also to repair, rebuild or enhance parts that have degraded in service. In some circumstances it is more attractive for industry to rapidly repair a part than to replace a part, as downtime and costs are reduced compared to manufacturing, sourcing or storage of replacement parts.





When repairing parts for critical assets it is important to have confidence in the integrity of the repaired part that will be relied upon during service. Depending on the situation, parts may be expected to work for a specific time that is less than required for a new part; they may be expected to have a life that is equivalent to a new part; or may be required to have a life that exceeds that of a new part. In each case the process applied needs to be understood and controlled to provide the anticipated service.

## Enabled disruption

The impact that additive manufacturing will have on current business models, supply chains, services and safety is at this moment unknown. By horizon scanning and identifying the disruption that is coming at the earliest opportunity it will be possible to manage the disruption in such a way that safety is not compromised.

> A further indication of activities that fall under these goals can be found in Appendix 2 – Confidence in the supply chain.

# A competent and qualified workforce

The safety and function of any engineered system relies on the competence of those that have designed the system (including all component parts of the system), those that have manufactured and assembled the system, and those that assure the safety of the system.

The key goals are: seeding the skills ; academic framework ; and a competent workforce.

## Seeding the skills

The uptake of any technology, no matter how good and disruptive, is dependent on having a workforce with the necessary knowledge and skills. These skills need to cover a number of aspects:

- a basic understanding of the technology
- understanding the digital and hardware aspects
- health, safety and environment
- production
- quality assurance; and
- quality control.

These skills are all important because no matter how good the initial design, the final quality of the component will rest with the individuals that are responsible for operating the installations that manufacture components, systems or structures.

Additive manufacturing is a new technology and the skills needed to enable uptake and the routes for delivering these skilled individuals, in the quantities required, are not yet established.

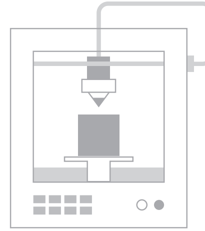
## Academic framework

Additive manufacturing is a new technology. If the assets of tomorrow are to rely upon components made by additive manufacturing then it is important that those designing the components understand the technology in order to be able to apply it safely.

Training given to engineers at university level is already developing within countries that have been early adopters of the technology; however, even in these countries the quality and content of training is varied.

The opportunity exists to develop a framework of what good additive manufacturing education at university level should look like to enable development of essential training across the globe.





## A competent workforce

The demonstration of competence is an integral part of the quality assurance of critical infrastructure projects starting with the designers all the way through to the operators. Essentially people have to prove that they know what they are doing: this will also apply to additive manufacturing.

In other related industries there are national and international schemes that demonstrate competence through combinations of education, training and ongoing activity. Examples can be found in welding and inspection industries. National or international frameworks for demonstrating competency will need to be established.

A further indication of activities that fall under these goals can be found in Appendix 3 – A competent and qualified workforce .

Image courtesy of National Centre Additive Manufacturing, MTC, UK

# Safety enhancements
## (enabled by additive manufacturing / 3D printing)

Additive manufacturing technology creates opportunities to do things that were not previously possible. One application for these opportunities is in enhancing safety of critical infrastructure.

The key goals are: design optimisation; smart materials; recreating defects for safety purposes; and 4D printing.

### Design optimisation

Design optimisation refers to making parts that are either less complicated and/or better designed for their operation.

Parts and structures can be complex for many reasons, often related to the restrictions imposed from traditional manufacturing techniques. By way of example, some assemblies are made up of a number of subassemblies that are then joined together either mechanically, chemically, or by welding. Each of these connections can be the initiation point of a failure that results in loss of function. Using additive manufacturing it is possible to create an assembly in one continuous process that avoids the need for having as many joints, which in turn reduces the need for inspection.

Another example of optimisation can be to use additive techniques to enhance existing parts by adding more durable performance. Consider as an example a part that is found to wear prematurely. It is possible to rebuild the surface using a material that will be less prone to wear.

There is work to do to understand what optimisation is possible and simultaneously ensuring that optimisations are applied in a way that does not increase risk.

### Smart materials

The embedding of sensors into additive manufactured parts will enable systems to function in ways that make them safer and more resilient.

At a component level embedded sensors will enable in-service monitoring of the operating environment and the components themselves. The data from these systems will provide assurance about the:

- Condition of the asset (temperature, pressure stress, etc.). These data can provide valuable information about the operation and state of the system; infer the future condition of a system; and be used to design better systems in future.



- Condition of component parts (cracking, corrosion, etc.) providing warning when parts require inspection, maintenance or repair. This will reduce the risks associated with sending individuals to carry out tasks that are inherently dangerous but also reduce the risks to equipment associated with human error after inspection, maintenance and repair.


### Recreating defects for safety purposes

Imperfections that have a significant risk of causing a failure are known as defects. Defects can form at any time during manufacture, during the fabrication process and during service, with inspection for defects conducted at each of these times. When detected there are usually three options: repair, replace or accept.

The decision taken can have significant consequences. Repairing may be an option but can take time. Replacement can be a safe option but often associated with time to find a replacement part, the cost of replacing the part, and associated downtime of the asset until the part is installed.

Acceptance can be the quickest way to continue service but the risk of failure remains. The decision process to accept a defect depends on the likelihood and consequences of failure, in other words, risk. For low risk items a decision to accept can be simple. When the risks are high, as in nuclear power stations or aircraft, the decision to accept is usually based upon a safety case that demonstrates that the risks of operating with the component are acceptable for a specific time after which point the item must be repaired or replaced.

Safety cases require a good knowledge of the defect and how it will behave in service. It is possible to recreate the defective material with additive manufacturing and use this to better understand the effect of the defect or alternatively to prove that a calculated prediction is acceptable.

The International Organization for Standardization (ISO), BSI and ASTM International have established committees in this area but it is unlikely that the knowledge and experience yet exist for a standard that can be used across industries.

## 4D printing

4D printing describes 3D printed components that are able to change their shape or other physical function based upon the addition of an external stimulus such as heat, pressure, and chemical interaction. There is potential for this new technology to enable significant improvements in safety.

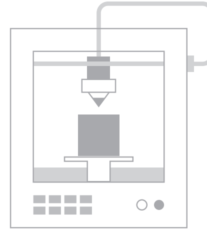
Consider for example, pipes that ‘pump’ fluids without the need for mechanical pumps within the system. The pipes could in principle be activated by pressure, temperature or the presence of the liquid (think of how the human body moves food from start to finish). With such systems the risk of mechanical failures of pumps and valves is significantly reduced.

This is a new area of technology subject to fundamental scientific investigation at this time.

A further indication of activities that fall under these goals can be found in Appendix 4 – Safety enhancements.



# Next step: Consultation

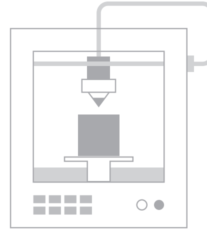


First, thank you for reading this review. We hope that we have captured the main points in the adoption of additive manufacturing for safety-critical assets that align with our charitable mission: enhancing the safety of life and property at sea, on land and in the air. We welcome your feedback to ensure that we have identified the most important aspects.

After the consultation is completed, when published the document will help governments, industry, academia and the public to understand the safety related risks and opportunities associated with additive manufacturing.

The appendices contain our thinking on where the ‘white spaces’ exist or how to find them: the white spaces are areas where the Foundation can make a unique and distinctive contribution to the safe adoption of additive manufacturing technology. Please tell us if we have correctly identified the white spaces under the four challenges and if not, tell us why and where you think we should change focus to meet our charitable aims.

Please send your comments by 31 January 2017 to: am-roadmap@lrfoundation.org.uk



# Appendix 1: Qualification of technology

## Fundamental understanding of additive manufactured materials

### Fundamental science

**Scope**: PhD research to conduct systematic programmes of work to identify appropriate methodologies and procedures for testing materials made with additive manufacturing processes. This research will be identified through competitive research calls. The work should start at technology readiness levels 1-3 with a clear pathway to impact.

**Duration**: up to 6 years

**Outcome**: Targeted research that is adopted by the wider community for the demonstration of safety.

### State-of-the-art review

**Scope**: Take a step back to look at the landscape of additive manufacturing and determine where gaps exist in our understanding of the area that affects our ability to be able to assure the safety of additive manufactured parts.

**Duration**: 6 months

**Outcome**: Recommendations on work required to assure safety and recommendations for how the Foundation can make a distinctive input.

Programme?

Programme?

Programme?

### State-of-the-art review

**Scope**: Take a step back to look at the landscape of additive manufacturing and determine where gaps exist in our understanding of the area that affects our ability to be able to assure the safety of additive manufactured parts.

**Duration**: 6 months

**Outcome**: Recommendations on work required to assure safety and recommendations for how the Foundation can make a distinctive input.

### Research to impact

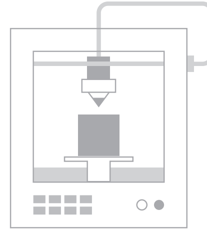
**Scope**: Translational activities for taking fundamental research that has been completed and supporting the acceleration of this research into safety related activity associated with qualification of technology.

As an example, the Foundation will consider supporting researchers to participate in standards committee activity with the purpose of their work being included in standard development.

**Duration**: 5 years

**Outcome**: Demonstrable translation of research into impacts.

2016 2017 Timeline (not to scale) 2018 2019 2020 2021 2022 2023



# Appendix 1: Qualification of technology
(continued)

## Publically available data repository

**Data repository**

**Scope**: A study to understand the need for a data repository, what it should contain and associated threats and opportunities.

**Duration**: 6 months

**Outcome**: Overview and recommendations on how to proceed.

**Data repository**

**Scope**: Engage with stakeholders to address recommendations.

**Duration**: 6 months

**Outcome**: Engagement plan.

## Defect acceptance criteria

**Non-destructive testing technique review**

**Scope**: A review of commonly available methods for non-destructive inspection of additive manufactured components, both in-line and other, to determine their accuracy and reliability of identifying defects.

**Duration**: 6 months

**Outcome**: A published authoritative review of non-destructive testing methods.

**Defect acceptance criteria**

**Scope**: A programme of research to automatically define acceptance criteria from digital drawings.

**Duration**: 5 years

**Outcome**: Algorithms ready for application and standards included.

## Qualification of parts

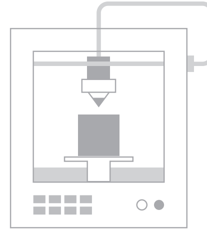
**Rapid qualification process**

**Scope**: Support to trial a rapid qualification process which enables the technology to be demonstrated as safe and continue to be valid for new developments. Seed funding towards testing prototypes.

**Duration**: up to 2 years

**Outcome**: Learning points to be incorporated into qualification standards and procedures.

2016 2017 Timeline (not to scale) 2018 2019 2020 2021 2022 2023



# Appendix 2: Confidence in the supply chain

## A robust system of traceability

### State-of-the-art review

**Scope**: A review to identify the risks and opportunities associated with traceability across supply chains in critical infrastructure industries. The review should consider the role that additive manufacturing plays in the risks and opportunities and how traceability can be improved within critical infrastructure industries by either sharing best practice or further development of technology.

**Duration**: up to 6 months

**Outcome**: Published review with recommendations for industry and also recommendation for how the Foundation could make a distinguishable difference.

### Traceability trials

**Scope**: A programme to create a test bed for traceability trials.

**Duration**: 2 years

**Outcome**: Derisked traceability infrastructures ready for deployment.

## Definitions of raw materials

### Publish specification for definition of powders for additive manufacturing

**Scope**: With an independent partner develop and issue an industrially acceptable specification for how to define powder raw materials for additive manufacture.

**Duration**: 9 months

**Outcome**: Publically available specification for definition of raw powder material.

### Assess need for specifications for other raw materials

**Scope**: A review to define specification and best practice landscape of raw materials from original creation, through to re-use.

**Duration**: Up to 6 months

**Outcome**: Published review of specification landscape across material types and associated raw materials.

### Publish specification for re-use of powders in AM

**Scope**: With an independent partner, issue a specification for powder re-use.

**Duration**: 9 months

**Outcome**: Publically available specification.

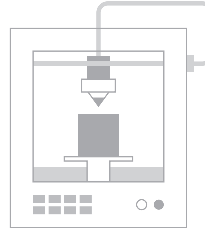
### AM safety specifications

**Scope**: Work with academia/industry to define best practice for safe installation.

**Duration**: 1 year

**Outcome**: Public specification against which can be audited.

2017 | Timeline (not to scale) | 2018 | 2019 | 2020 | 2021 | 2022 | 2023



# Appendix 2: Confidence in the supply chain
(continued)

## Assurance of parts based upon process control and monitoring

### Assurance research

**Scope**: Research programme to identify critical parameters for common additive manufacturing processes, assess how these are used for quality assurance today and develop algorithms to efficiently assess data for future systems.

**Duration**: 4 years

### In-line non-destructive testing

**Scope**: Seed funding to assess systems that conduct in-line defect monitoring and develop algorithms that can quickly and efficiently assess machine data.

**Duration**: up to 2 years

**Outcomes**: Algorithms that can be deployed in systems to demonstrate quality of products.

### Reliability assessment

**Scope**: A study to understand differences in quality between manual and automated inspection systems.

**Duration**: 1 year

**Outcome**: Published report highlighting results of the comparison and recommendations.

## Safe repair methods

### Review of repair methods

**Scope**: A critical assessment of the main additive repair processes, their technical maturity and maturity of assurance systems.

**Duration**: up to 6 months

**Outcome**: A published review highlighting where additional activity is required for the processes to be considered suitable for critical components.

## Enabled disruption

### Review of additive manufacturing impact on supply chains

**Scope**: A review specifically looking at the disruption that additive manufacturing is expected to have on supply chains; looking at the opportunities and threats this disruption will have on the safety and resilience of systems.

**Duration**: up to 3 months

**Outcome**: A published report showing thought leadership related to uptake of this technology.

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**Duration**: up to 3 months

**Outcome**: A published report showing thought leadership related to uptake of this technology.

2017 | Timeline (not to scale) | 2018 | 2019 | 2020 | 2021 | 2022 | 2023

# Appendix 3: A competent and qualified workforce

## Seeding the skills/ Academic frame work/ A competent workforce

### Review the landscape

**Scope**: A global review in the areas of seeding the skills, academic frameworks and a competent workforce to identify the state-of-the-art and identify the gaps where the Foundation can make a distinctive difference.

**Duration**: up to 6 months

**Outcome**: A published review on the landscape with specific recommendations for where the Foundation can make a distinctive difference.

Programme?

Programme?

Programme?

### Review the landscape

**Scope**: A global review in the areas of seeding the skills, academic frameworks and a competent workforce to identify the state-of-the-art and identify the gaps where the Foundation can make a distinctive difference.

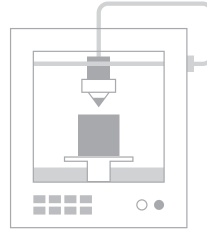
**Duration**: up to 6 months

**Outcome**: A published review on the landscape with specific recommendations for where the Foundation can make a distinctive difference.

2017 Timeline (not to scale) 2021 2023



# Appendix 4: Safety enhancements enabled by additive manufacturing / 3D printing



## Recreating defects for safety purposes

### Fundamental research

**Scope**: A programme of PhDs that will investigate how typical defects in critical infrastructure can be recreated in at least two industries and used for safety assessments. This work should target the application to other industries that may not yet be looking at this application.

**Duration**: up to 5 years

**Outcome**: Procedures and guidance issued on how to use additive manufacturing to recreate defects for safety cases.

## 4D printing

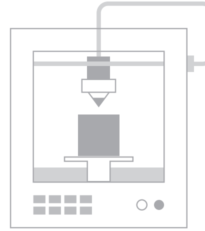
### Prize competition

**Scope**: A prize fund will be established to reward the first organisation that reaches the point of commercialising 4D printing technology in an application that has a significant and quantifiable enhancement to safety within the critical infrastructure on which society depends.

**Duration**: Until awarded

**Outcome**: Technology developed and a fund that can support further commercialisation.

2016 2017 2021 2023



# Appendix 4: Safety enhancements enabled by additive manufacturing / 3D printing (continued)

## Design optimisation

### Exemplar fund

**Scope**: An initiative to demonstrate how design can be simplified using additive manufacturing to create an inherently safer system.

**Duration**: up to 2 years

**Outcome**: A workshop and series of published case studies showing how simplified design enabled by additive manufacturing can reduce inherent risk.

## Smart materials

### Scene setting workshop

**Scope**: Joint workshop with at least one major additive manufacturing organisation to understand state-of-the-art of how additive manufacturing is creating smart materials and a view on what is possible but not yet tried.

**Duration**: 6 months

**Outcome**: Published review summarising the topics raised in the workshop with recommendations on white space.

Programme?

Programme?

Programme?

Programme?

Programme?

### Scene setting workshop

**Scope**: Joint workshop with at least one major additive manufacturing organisation to understand state-of-the-art of how additive manufacturing is creating smart materials and a view on what is possible but not yet tried.

**Duration**: 6 months

**Outcome**: Published review summarising the topics raised in the workshop with recommendations on white space.

**Outcome**: Demonstrators showing how smart materials can enhance safety of life and property.

2016 2017 Timeline (not to scale) 2018 2019 2020 2021 2022 2023