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## **Three dimensions of maturity required to achieve future state, technology enabled manufacturing supply chains**

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The particular challenges associated with supply chain application of emerging manufacturing technologies are increasingly recognised in industry, academia and government. The problem is often described in terms of Technology Readiness Levels (TRLs), with the particular challenge relating to the stages between proof of concept and initial adoption in the factory environment. In the UK the government has established the High Value Manufacturing Catapult, a network of manufacturing innovation centres brought together with the objective of addressing the so called ‘valley of death’ between traditional academic research and industrial needs across a broad spectrum of manufacturing process technology. This is achieved through demonstrating manufacturing technology at full scale, in factory representative environments in terms of equipment, process control and operation. This provision helps to address the key gap of full scale pre-production capability demonstration and can be seen to de-risk investment in new manufacturing technology. This paper argues that addressing this particular gap is entirely necessary but not sufficient to drive exploitation of the full potential that is available from the latest manufacturing technologies. A three dimensional maturity based framework is proposed which, in addition to considerations of technology demonstration, also allows the position of the target product application in its product lifecycle, and the readiness of the supply chain to receive the technology to be taken into account as success factors in the potential for industrialisation. Case study examples, both current and historical, are used to illustrate the need for such an approach in achieving future technology enabled supply chains. In combination this analysis introduces the basis of a more complete ‘long valley of death’ description which articulates the needs of research networks to establish a level of foundational capability ahead of specific client readiness

projects in order to maximise overall pace and achieve a level of agility of delivery which is consistent with future views on digitalisation of manufacture.

Keywords: Technology readiness level, manufacturing readiness level, supply chain, technology management, valley of death, maturity

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## **1. INTRODUCTION**

Product developers face a continual dilemma in specifying the componentry which drives the performance of their products between exploitation of latest technology and minimisation of supply chain risk. The drive to exploit latest technology is brought about by the need to achieve the best available design and manufacturing solutions to provide the most competitive products. Use of unknown or unproven technologies however carries risk both that the technology itself might not work, and that mature supply chains might not be established quickly enough to support demand and meet quality requirements. Likewise component manufacturers face a related dilemma between investment to meet apparent future product needs, and continued focus on running their operations to support the demand of today's customers and products.

The use of readiness based approaches to the de-risk technology reliant, complex product development is well understood and demonstrated. In general, readiness approaches are appealing to product developers on the basis that they provide a clear development route and means of assessing status in addressing future needs. They are most attractive in situations where the pace of introduction is sufficiently long term as to allow systematic technology planning, and where there is a need of at least a preparedness to develop technology as part of a committed product introduction programme. Hence they have been most widely applied to aerospace and defence applications. When used appropriately they can also aid component manufacturers in demonstrating a route to increased efficiency through the utilisation of new methods. The typical scenario is as outlined in Figure 1 which illustrates how multiple technology options might initially be down-selected into a relative few for which a business case and proof of concept can be implemented in a suitable timeframe. This scenario represents cases where TRL and derivative readiness approaches are generally employed to

help mitigate the risks of an unsuccessful or incomplete implementation. In these cases the so called ‘valley of death’ [1] or ‘missing middle’ as proposed by [2] both coincide with TRLs 4-6 and relate to scale-up of the technology from laboratory to industrial scale.

The applicability of the approach is much less clear, and the results therefore often far less effective, in addressing the more difficult scenario illustrated in Figure 2 which is triggered by a market failure of some kind. In this case it is argued that a ‘Long Valley of Death’ exists, which extends to stages prior to TRL/MCRL4 based on the need to address the primarily non-technological issues of supply chain partnership development, product alignment and the general appetite for change while technical propositions are being created in parallel. While these areas have been considered to some extent by earlier work which describes holistic and integrated approaches to readiness beyond TRL and MRL / MCRL, it will be argued here that there is a case for a ‘Foundation for Innovation’ approach which provides the basis of an assessment of the maturity of the underlying combined capability of a technology provider, target application, and associated supply chain as a precursor to large scale investment. Having a foundation for innovation would mean that the long term strategy which bridges the long valley of death is understood and largely in place.

Technology Readiness Levels (TRLs) first originated from NASA, and they were described as a “measurement system that aims to assess the maturity level of a particular technology” [3] or as “a discipline-independent, programmatic figure of merit (FOM) to allow more effective assessment of, and communication regarding the maturity of new technologies [4]. Technology Readiness Levels (TRLs) which originated from NASA [3] and Manufacturing Readiness Levels (MRLs) which developed by the US Department of Defence [5] are used extensively to articulate the ‘valley of death’ [1] between traditional university research and industrial implementation. The valley of death reference is meant to indicate a position in the technology implementation landscape where a disproportionate level of failure occurs. Both scales take their starting point from the NASA developed nine point TRL scale which describes technology maturation from the observation and reporting of basic principles (TRL1) to a fully operationally proven system (TRL9). In the case of the MRL scale a final stage of full rate production demonstrated and lean production practice

implementation (MRL10) has been added to reflect the need for a level of continuous improvement to achieve sustainment of the capability. Sustainment of capability is a major ongoing challenge in the case of manufacturing technologies on the basis that “factories have to adapt to ever new challenges, trends and paradigms in manufacturing to stay competitive”[6]. In this sense “sustainability in manufacturing means the targets and approach for measurement to meet the high level goals within a manufacturing company” [7]. The theme of sustainability in the context of mature manufacturing technology manifests itself in several different forms through the approach described here.

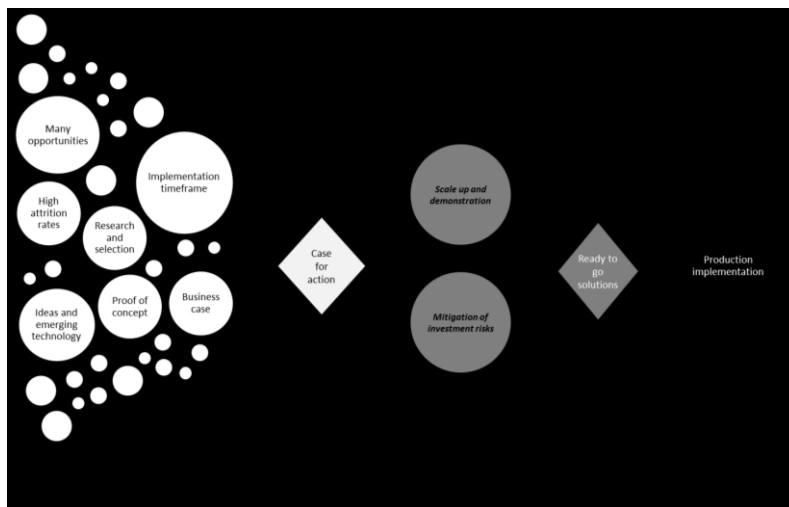


Figure 1. *The established ‘valley of death’ scenario*

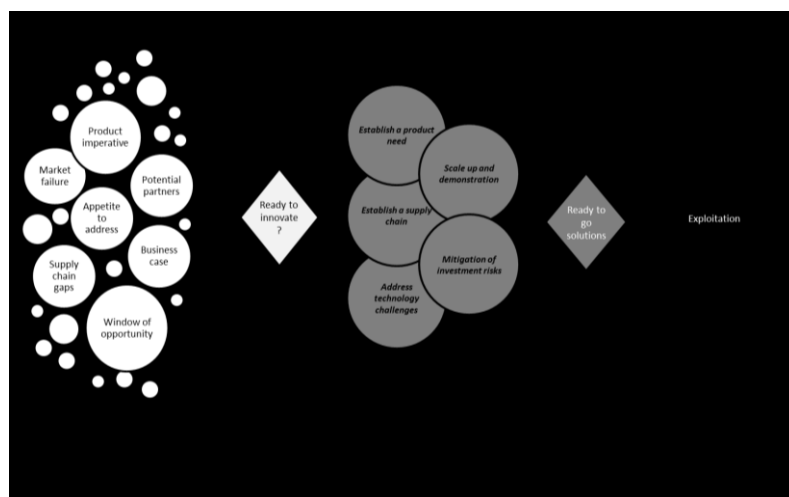


Figure 2. *Long Valley of Death scenario encountered when addressing systematic market failure*

The readiness level concept has been extended to manufacturing processes in the form of Manufacturing Readiness Levels (MRLs), as originally defined by the US DoD and subsequently developed within the automotive sector [8] and elsewhere. In parallel Rolls-Royce developed its own system of Manufacturing Capability Readiness Levels (MCRLs) [9]. The addition of the word 'capability' is important in the MCRL system and was included on the basis that the effective delivery of manufacturing innovation depends on much more than just technology maturity. Operational, commercial, organisational, and integration issues also need to be addressed and are of equal importance. MRL based approaches also recognise these issues, and consequently both MRL and MCRL methods could be classified as somewhat holistic readiness methodologies. In the interests of consistency between manufacturing and technology readiness, the nine point Manufacturing Capability Readiness Level (MCRL) scale derived directly from TRLs [5] will be used as the primary measure of manufacturing maturity in this paper.

Several other more holistic views of both TRL and MCRL have been developed in recent years. Mankins [10] built on the TRL scale to develop a more general approach to risk and readiness assessment. In this work Mankins recognised that R&D management needs to address threefold goals of improving performance parameters of new technology, driving maturation, and reducing risks relating to the eventual uptake of the technology. In developing a more complete view of technology risk mitigation he proposed the need for additional parameters relating to 'R&D degree of difficulty' (R&D<sup>3</sup>) and 'Technology need value' (TNV), where five point scales are defined in each case. This much more complete view provides the basis to position TRLs within an overall R&D management context rather than is a simple maturity indicator. In defining Innovation Readiness Levels (IRLs) aimed primarily at incremental innovation Tao et al. [11] proposed a six point scale for product innovation. Most significantly Tao pays significant attention to a 'Chasm' phase which is deemed to exist when a technology first enters the market, and proposes market, organisational, partnership and risk factors which need to be considered at each of the six stages along with technology. Hicks et al. [12] developed a more general form of TRL focused product development through the definition of additional stages which relate to the enhancement of technology developed to TRL9, and through the

Product Readiness Levels (PRLs) which include consideration of marketing, manufacturing and ‘Other Functions’. Islam [13] attempted to combine thinking on IRLs with the established MRL scale to develop a five point Innovative Manufacturing Readiness Level (IMRL) scale which is proposed as particularly applicable to nano-manufacturing. Wang et al. [2] dealt with concurrent engineering and maturation via development of xRLs (Accelerated Readiness Levels) which bring together a combined or meta view of the total product readiness through combined consideration of separate MRL, TRL maturity status along with Business case Readiness Level (BcRL) and Ecosystem Readiness Levels (ERL) scales. All of these combined approaches have significant merit and effectively address Mankin’s [10] risk management question with different emphasis. They all however deal primarily with providing a total approach to maximising the likelihood of success of a project that is assumed to be committed or demanded for an end user. It is fair to say that the readiness assessment has a crucial role “within the systems engineering decision making process” - Tetlay & John, 2009 [14]. They are less effective in dealing with the uncertain starting point seen in cases of market failure or technology push, where the need to take action is clear, at least to some degree, but where the existence pre-requisites for success is difficult to assess.

## **2. CASE FOR ACTION**

All of these combined approaches described above have significant merit and effectively address Mankin’s [10] risk management question with different emphasis. They all however deal primarily with providing a total approach to maximising the likelihood of success of a project that is assumed to be committed or demanded for an end user. They are less effective in dealing with market failures where the need to take some specific action is clear, at least to some degree, but where the existence of capabilities and plans is insufficient to guarantee success. Equally they are not well suited to dealing with the provision of base technology capability which might be needed to serve a number of end use applications.

A consideration of the distinction between the terms ‘readiness’ and ‘maturity’, as outlined by Tetlay & John, [14] is of value in this context. The two terms can be described as follows:

- “Readiness refers to time. Specifically it means ready for operations at the present time” (Nuclear Decommissioning Authority [15]), or
- “Readiness, in the situation of a software environment (yet equally true for hardware), to be a measure of the suitability of a product for use within a larger system “in a particular context”, i.e., with respect to specific requirements. Depending on its application, a product deemed to be mature may possess different degrees of readiness” (Seablom & Lemmerman [16]).

On the other hand, maturity is defined as follows:

- “Maturity is therefore regarded as a part of readiness (...), the system must first be fully ‘mature’ before it can be ‘ready’ for use” (Tetlay & John [14])
- “Maturity is the verification within an iterative process of the system development lifecycle and occurs before (...) readiness” (ibid.)

Hence, both concepts seem to be context-specific and so the technology would have to be validated according to the requirements that were given at the beginning of the process, in order to check how ready the technology is at a given time. The idea of a separate maturity view, as part of a mechanism for assessing for addressing situations where foundational technology is being placed ‘on the shelf’, or where a market failure is being addressed seems to be inherently appealing in supporting a slightly different range of usage scenarios. It is however considered to be essential to distinguish three separate but essential ingredients of maturity which can be thought of as complementary success factors for manufacturing technology insertion.

### **2.1. The technology maturity dimension**

In the case of technology, and manufacturing technology in particular it is only meaningful to state that a technology is 'at' a particular state of readiness if that level is being applied to a specific technology application project, or there have been sufficient developments across a spectrum of applications such that it can be taken as the underlying maturity level for future projects. The fact that somebody somewhere has achieved a high level of maturity for similar technology under different circumstances of application is interesting in providing confidence about what might be possible, but



does not provide direct confidence in terms of maturity that can be replicated. It is likewise tempting to apply readiness terminology to situations where no new technology is being developed.

Manufacturing R&D facilities are often quite rightly employed to explore the resolution of production problems in mature manufacturing operations. This is perhaps one of the most effective ways of achieving economic and societal impact from them in the short to medium term timescale. There is however little value in applying readiness terminology in these situations on the basis that

- This implies a need to estimate the readiness of an operationally mature process, which is a philosophical exercise
- The application of readiness terminology distracts attention from that fact that other techniques and measures are far more appropriate and effective in directing operational improvement
- It provides a confused and unmanageable situation where technology insertion projects are measured and monitored based on the same expectations as continuous improvement, problem resolution, or attempts at achieving effective control of an embedded process.

Application of readiness can therefore be problematic and is only really appropriate to apply readiness terminology to situations of new technology insertion within committed, time bound programmes with a clear end application. Having said this, there remains a need for a maturity based assessment which can be used within the general context of the journey to generic capability in a particular field, and within an individual research network. This need is based on the many benefits to be had in articulating the gap between current state and aspirational target for capability within a field of technology. Such a measure needs to be able to articulate generic capability, and the ability to demonstrate highly competent execution of work in this area, as opposed to excellence in the performance of a single implementation project. The concept of underlying maturity is important on the basis of key problems with this view:

- Implementations of the technology can be somewhat specific to the application, either as a result of a high degree of design for manufacture integration, or standards within the target

industry. The effect of which would be that the technology requires an additional level of proving on other generic applications

- The technology demonstration may have involved an end user or other collaborating body acting as an integrator, combining the workpackage under consideration with others to provide demonstrable technology. Without access to the steps taken by the integrator, the ability to repeat the implementation may well be limited
- The technology may rely on intellectual property (either in the form of patented technology, or in the form of trade secrets or know how) owned by a third party, without which the technology cannot be readily exploited
- The scope for read-across from other applications is limited by differences in validation needs

## **2.2. The supply chain dimension**

The supply chain, in the context of the following discussion is ‘the network of organisations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer’ [17]. Here we are focused on manufacturing and manufacturing technologies, and in this sense we can be clear that supply chain activities involve the transformation of natural resources, raw materials, and components into a finished product that is delivered to the end customer [18].

Understanding whether preconditions are in place to address the Long Valley of Death requires a mechanism which can articulate the underlying maturity of supply chain, manufacturing technology and product maturity. Step change manufacturing technologies, or even adoption of global state of the art manufacturing technology to address the market failure of historic investment in technology, requires a capable, committed and sustainable supply chain which is scaled to reflect the total anticipated production requirement. This is perhaps the single most important success factor for large scale manufacturing technology insertion projects. Manufacturing Technology insertion projects which are sponsored by a receiving organisation who plan to implement the new technology within their own domestic facilities require competent technical execution. Supply Chain Management (SCM) “requires traditionally separate materials functions to report to an executive responsible for

coordinating the entire materials process, and also requires joint relationships with suppliers across multiple tiers” [19]. SCM is a concept, “whose primary objective is to integrate and manage the sourcing, flow, and control of materials using a total systems perspective across multiple functions and multiple tiers of suppliers.” Manufacturing technology projects, especially those which aim to insert technology which is missing from current supply chains needs to be consider in the context of SCM. Projects have a high chance of success however, assuming viable technology and a suitable level of organisational buy-in. Those who wish to push technology which addresses a market failure have a much more difficult job, and results in some alignment to Mankin’s [10] degree of difficulty. If it is assumed that some level of technology push activity needs to be prompted as a market intervention, then there is a need to understand the maturity of the target supply chain to receive any developed technology, as without such an understanding of maturity.

Recent developments in the digital manufacturing (Industrie 4.0) landscape relating to cyber physical systems, the internet of things and other related concepts will undoubtedly transform manufacturing supply chains in the years and decades to come. The exact nature of this change is yet to be understood and is inherently difficult to predict as it looks likely to emerge from the use of new business models which are enabled by technology rather than from the technology itself. This is clearly a vital consideration in the development of any mechanism or framework relating to manufacturing technology and supply chain development at the current point in time. The most predicable manifestation of this developing picture is that frameworks, structures and delivery mechanisms will need to be flexible and ready to quickly respond to emerging needs. This is an important driver of the need for reliable foundational capabilities which can operate as a platform for much more rapid readiness programmes in response to specific and rapidly emerging customer need.

### **2.3. The Product Dimension**

New product introductions, especially the introduction of highly innovative products often provide the best opportunity to catalyse the introduction of new manufacturing technology. It might well be argued that there is no particular need to include a product maturity dimension in and maturity framework, on the basis that readiness is directly aligned to key product technologies. The salient

point however is that the purpose of a maturity framework is not for use as a comprehensive numerical assessment tool, but as an approach for determining whether the pre requisites are in place to justify strategic efforts in addressing a manufacturing supply chain market failure. The maturity of the target product application(s) is clearly a key factor in making this determination and, unlike the first two proposed dimensions, it is not necessarily the case that the highest possible score is most conducive to successful uptake of technology.

### **3. ANALYSIS**

The need to consider maturity based on multiple dimensions is appealing as a mechanism which can allow clarity of understanding not simply whether there is a gap to full technology implementation, but also to pinpoint its specific nature. In this preliminary work the three dimensions introduced above will be demonstrated by consideration of case studies, which demonstrate why the three dimensions represent necessary success factors for implementation. The work described here should however be seen as a preliminary study which is yet to demonstrate that the three dimensions are sufficient to fully articulate maturity in all circumstances.

#### **3.1. Case Study 1 – Advanced Forming Research Centre – foundational capability planning**

The University of Strathclyde's Advanced Forming Research Centre (AFRC), has been operational for seven years during which time industrial, academic and government partners have worked together to establish a world leading research facility for the shaping of materials. The centre works closely with major industrial companies, and since 2011 it has been a part of the UK High Value Manufacturing (HVM) Catapult. The "interdisciplinary focus and combination of education with applied research have created a new model for performing science" [20]. The centre operates a membership model, whereby major industrial companies pay a significant annual subscription in return for collectively directing the Core Research Programme (CRP) which is entirely collaborative in nature. The collaborative nature of this approach [21] means that the CRP is typically aimed at developing underlying capability at a consortium level, with a view to exploitation and more rapid deployment through additional work. While the subsequent application work (typically company and application specific) can be advanced usefully via readiness approaches for the end customer application [14], this has not been effective at

the underlying capability level. The reason for this difficulty is inherent in the fact that capability is being developed for potential use by multiple end-users on multiple applications [16]. In this case readiness becomes a rather contentious issue with the obvious question ready for what exactly? Essentially the time-bound nature of readiness [15], becomes a major source of ambiguity. Different options are available, including the potential to simply assign the readiness based on the first customer application, or to position some kind of representative or typical readiness position. These options are in fact rather meaningless and can be seen to be misleading in providing a level of specific positioning without a particular target and associated specific requirements. Far more preferable and informative in this context is the concept of a more generalised description of foundational technology maturity. Such a maturity description provides the potential to be somewhat distinct from any specific end application, and therefore could be defined on the basis of the viability of exploitation by a broad customer base [14].

Figure 3(a) provides a basic technology based maturity measurement. It uses a five point scale, to chart the path between having no capability in a particular area of technology and what is termed to be an advanced technology. The use of a five point scale has been selected in the interests of distinctness from MCRL, and influenced to some extent by Mankins [10] R&D<sup>3</sup> and TNV concepts. Assessment against the scale is based on the use of elements (shown as the columns of Figure 3(a)) which provide a level of granularity to the maturity definition, and which could be re-defined based on specific situations. The elements have been selected based on experience within the AFRC and its partner organisations relating the typical technology related barriers to full implementation of new manufacturing methods. The elements relating to people / skills, equipment and process control are deemed to be core aspects of foundational technical capability. The Sustainability element relates to the long-term robustness of the provided capability and the ability to support application on an ongoing basis. This is deemed foundational to technology in research networks and is of key importance on the basis of their national strategic nature and their reliance on public funding mechanisms. The demonstration element is needed to provide a pragmatic assessment of whether the technology has been tested and achieved real and positive results.

The applicability of this approach to a research provider rather than to an end user of technology becomes apparent by considering the nature of the five point scale. Here there is no inherent need to progress to the ultimate level 5 position for all technologies provided within the centre, especially in situations where the underlying need is simply to service other more core technologies available internally or through other organisations. In the case of the AFRC, certain metrology technologies could be easily seen as fitting into this category – i.e. where there is a need to establish credible technology offering to support the customer base directly, but where there is not necessarily a need to become world or even nationally leading. In other cases of core strategic technology, where there is a direct and unique alignment to the mission of the centre, the target end point would absolutely be level 5. Figure 3(b) outlines the basic mode of use of the approach in assessing the gap between a target level on the scale, and the actual achieved position for each of the elements of dimension 1. In the case shown a specific action plan would be drawn-up against the People, Demonstration and Process Control elements of capability so that the level 3 position could be achieved. This initial use of the technology dimension against a single area of technology in addressing specific gaps in maturity and approach is therefore an obvious mode of use. It is very consistent with typical usage of readiness approaches, but the focus on underlining generic applicability to potentially service a range of customers or end applications provides is differentiating.

		Technology dimension elements				
	Dimension 1 index	Sustainability	People/Skills	Equipment	Demonstration	Process Control
NO CAPABILITY	1	No understanding of what is needed to ensure on-going availability of the capability	No experience of the process	No definition of equipment needs	No experience of the capability	No understanding of process control
UNDERSTANDING OF PROCESS REQUIREMENTS	2	Requirements for maintaining and advancing the capability in line with strategy defined (including skills, people / continuity, equipment maintenance, replacement equipment, etc)	Required skills / expertise identified	Definition of specification in place	Defined set of demonstration requirements / acceptance criteria	Process variables defined
BASIC CAPABILITY AVAILABLE	3	Continuity plan for maintaining and advancing the capability in line with strategy defined (including skills, people / continuity, equipment maintenance, replacement equipment, funding source etc)	Lead Staff trained and have operational experience, training plan in place	Access to potentially suitable equipment	Process demonstrated on available equipment	Control strategy defined
DEMONSTRATED CAPABILITY AVAILABLE	4	Demonstration of the effectiveness of the plan for maintaining and advancing the capability in line with strategy defined	All staff operating the capability have demonstrated proof of competency	Suitable equipment available and demonstrated on similar application	Process used on at least one customer project, to the customer's satisfaction	Control strategy applied and tested
ADVANCED CAPABILITY AVAILABLE	5	Continual assessment and re-alignment of the plan for maintaining and advancing the capability in line with strategy defined	Expert team available to operated the capability	Equipment available, fully commissioned, and proven track record within the scope of use	Process used on sufficient customer projects within a defined scope of use that there is full confidence in use of the process to the customer's satisfaction	Process control strategies proven

(a) Dimension 1: Underlying Manufacturing Technology Capability

		Technology dimension elements				
	Dimension 1 index	Sustainability	People/Skills	Equipment	Demonstration	Process Control
NO CAPABILITY	1	No understanding of what is needed, available or going to be available	No evidence of the capability	No evidence of the capability	No evidence of the capability	No evidence of the capability
UNDERSTANDING OF PROCESS REQUIREMENTS	2	Requirements for advancing strategy of people / equipment maintenance	Requirements for advancing strategy of people / equipment maintenance	Requirements for advancing strategy of people / equipment maintenance	Defined set of demonstration requirements / acceptance criteria	Process variables defined
BASIC CAPABILITY AVAILABLE	3	Continuity of advancing strategy of people / equipment maintenance	Lead Staff trained and have operational experience, training plan in place	Available equipment	Process demonstrated on available equipment	Control strategy defined
DEMONSTRATED CAPABILITY AVAILABLE	4	Demonstrated readiness of the process in line with strategy defined	All staff operating the capability have demonstrated proof of competency	Suitable equipment available and demonstrated on similar application	Process used on at least one customer project, to the customer's satisfaction	Control strategy applied and tested
ADVANCED CAPABILITY AVAILABLE	5	Continual assessment and re-alignment of the plan for maintaining and advancing the capability in line with strategy defined	Expert team available to operated the capability	Equipment available, fully commissioned, and proven track record within the scope of use	Process used on sufficient customer projects within a defined scope of use that there is full confidence in use of the process to the customer's satisfaction	Process control strategies proven

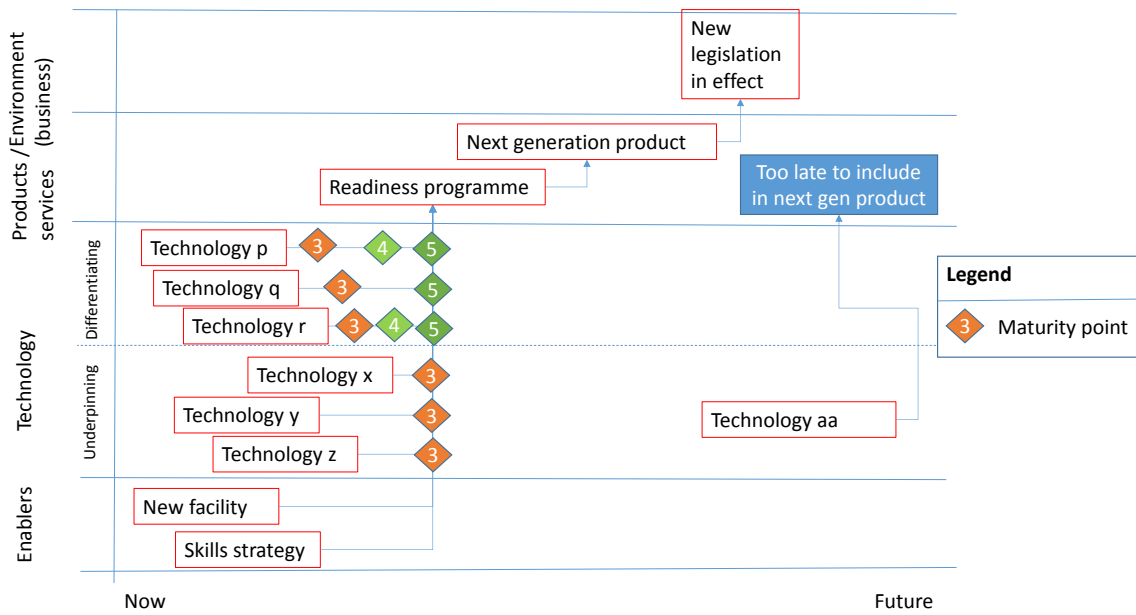
  

LEGEND	
	Demonstration level sort of minimum standard
	Demonstration level ahead of minimum standard
	Demonstration level aligned to minimum standard
	Minimum standard for customer application

(b) Applying Dimension 1 – understanding of the gap to a credible technology offering

Figure 3. *Technology Maturity – Dimension 1*

Figure 4 illustrates the more strategic use of the technology dimension in technology planning. Figure 4(a) shows a typical roadmap framework derived from the approach of Phaal et al. [22]. In this case the technology layer is divided into ‘underpinning’ and ‘differentiating’ layers. In these cases it is clear to see that the expectation is that differentiating technologies are expected to be driven to an advanced state of maturity in the research centre before readiness approaches are applied within a product programme. Underpinning technologies, potentially less core to making the product offering stand out in the market, are driven only to level 3, where a credible offering is in place at the research centre. The exact breakdown of target setting is a matter of risk management and will depend on the nature of the end application market, local decision making and the attitudes of immediate customers of the technology. The point is that a clear and consistent underlying technology maturity can be seen to provide insight into the timings of research capability and infrastructure ahead of readiness programmes in support of next generation products. Having understood the timing and priority of individual technology developments, the maturity measure can be further used in technology planning, as shown in Figure 4(b). Here it can be seen that at a detailed technology planning level specific actions (or the lack of them) can be used to develop technologies towards target end points – even though the target point may vary based on the nature of the technology within the strategic context, and based on opportunity.



(a) Application within a typical roadmapping framework

Element	HISTORY -2 years		Current year		+1 year		+2 years		+5 years		Ultimate aspiration	
	Maturity	Indicators	Maturity	Indicators	Maturity	Indicators	Maturity	Indicators	Maturity	Indicators	Maturity	Indicators
	<b>TECHNOLOGY THEME</b>											
Core technology area 1	1	Some simple approaches to shape definition	2	Some simple customer case studies supported by modelling	3	Potential implementation of published approach	4	AFRC approach developed and tested	4	Multiple customer case studies	5	UK technology leadership
Core technology area 2	1	Some simple approaches to shape definition	2	Some simple customer case studies supported by modelling	3	Potential implementation of software vendor approach	4	AFRC approach developed and tested	4	Multiple customer case studies	5	UK technology leadership
Core technology area 3	2	Definition exclusively provided by customers, General CAD capability (software + people)	3	Some examples of in-house tooling definition	3	Parts using AFRC developed geometry	4	Multiple customer case studies	5	Multiple customer case studies	5	Global leading offering
Core technology area 4	2	Use of modelling to evaluate customer tooling	2	Use of modelling to evaluate customer tooling	2	Collaborative programmes needed	2	Collaborative programmes needed	2	Collaborative programmes needed	3	Ability to support customer cases studies and internal R&D
Support technology area A	2	Some guidance provided to customers on alternative materias	2	Some guidance provided to customers on alternative materias	2	Assessment of an alternative MoM	3	Materials and process route list, supported by material properties	4	Capability underpinned with materials selector database	3	Die materials selector database
Support Technology area B	1	No activity	1	No activity	1	No activity	2	Initial tooling definition based on inserts	3	Initial customer case studies	3	Ability to support customer cases studies and internal R&D
Support Technology area C	1	Manual shape improvement	1	Manual shape improvement	1	Manual shape improvement	2	Initial die definitions (preforms) based on optimised shape	3	Initial customer case studies	3	Ability to support customer cases studies and internal R&D

(b) Application within a in technology planning

Figure 4. *Technology Maturity – Use of dimension 1 in technology roadmapping*

### 3.2. Case Study 2 – UK Automotive metals supply chain

Despite some recent resurgence in UK (Original Equipment Manufacturer) OEM performance especially in the automotive sector, the adverse long term trend in overall market share for the metals supply chain looks likely to continue, irrespective of acceleration of technology development. For



example in the period from 1994-2009 the UK fabricated metal products and for basic metal processes activities fell by 10% and 38% respectively in terms of real value added, this despite an overall growth of more than 50% in aircraft, automotive, rail and motorcycle value add in the same period [23]. While the industry [24] and government previously identified a £3 billion opportunity to increase UK Tier 1-supply chain value, realising this opportunity has been proved to be a major challenge. Perceptions among OEMs and major Tier 1 suppliers of competitive and technological capability among UK suppliers is believed to be a primary reason for this. The low levels of year-on-year investment in research, development and innovation compared with other industrial nations supports this view. There is an urgent need to take action in this area on the basis of some important and time bound drivers:

- Major OEMs in a number of sectors, notably automotive are developing next generation products based on major changes in propulsion and transmission systems required to achieve future environmental standards [25], [26]. The effect of this is that established supply chains are being re-evaluated and new ones developed in support of new product launches [27].
- Overseas initiated movements such as Industry 4.0 are being established at a scale and pace that could provide large barriers to entry for companies and national industries who have not delivered innovation at the same pace [ibid.]
- From a more positive perspective the UK manufacturing R&D network has successfully completed a phase of growth with the establishment and early success of the High Value Manufacturing Catapult including the AFRC [ibid.]

Despite the many difficulties that surround innovation in the UK metals industry, The Automotive Council have identified that realistic opportunity exists to increase local sourcing (Tier 2s, Tier 3s) to the UK Tier-1 community by at least £2 billion annually that is additional to the £3 billion Tier 1 opportunity already identified [ibid.].

All of this illustrates that consideration of the maturity of the supply chain in its capacity to receive new manufacturing technologies, and respond to the demands and opportunities presented by new product developments is essential both in exploiting the benefits of new processing technology, and in

addressing national industry needs [27], [28]. It typifies the Long Valley of Death at a total supply chain level through a current market failure. In this situation the critical success factor has little to do with the readiness of technology to meet a particular product need, or even the underlying maturity of that technology in supporting a broad potential customer base, it is about the fundamental existence (or viability) of a supply chain which can address the needs of the market [29]. Digitalisation of manufacturing and the creation of new and more globalised supply chain service models may well be seen to mitigate national security of supply issues in situations of this type, but do not in themselves obviate the need for physical supply, at least at a global level. Essentially resolution of market failure of this type requires intervention on a number of fronts, none of which have much chance of success without the basic conditions being in place to establish a physical supply chain [27].

Figure 5 outlines a basic framework of supply chain maturity. As with the technology dimension (Figure 4) its most obvious mode of use is in plotting the current state of maturity versus each of the elements of maturity to understand and quantify the gap to achievement of a viable supply chain position. As with the Technology dimension the elements have been developed based on practical experience of the barriers to implementation of manufacturing technology which relate to supply chain. The elements relating to raw material, equipment and consumables are deemed to be core physical elements of the supply chain which need to be understood. The Quality Standards element in this case relates to the standards that need to be developed and achieved in order to embed technology in a potentially regulated environment. Sustainability is addressed both from the perspective of robustness of the developing supply chain, and in terms of the use of scarce resources. For many process technologies which impact product integrity this aspect of supply chain definition is a vital and often overlooked step. Perhaps the most important success factor in any supply chain implementation is whether or not leaders in target supply chain organisations are keen to change their business model through insertion of the technology under question. This is an obvious consideration but, based on a level of experience is often overlooked.

Supply chains, especially in established sectors like the UK metals supply chain for the automotive industry, are however potentially complex with substantial elements of legacy and reliance on global

as well as national markets. This makes action planning difficult. While it is potentially viable determine gaps in supply chain maturity and use the maturity framework to define the case for corporate or government level intervention at a theoretical level, making a real change requires decision making and a level of focused effort. A pragmatic approach can however be readily offered through the maturity framework concept. Essentially it is feasible to assess whether supply chain challenges are addressable – in which case there is a case to be made in addressing a grand challenge, or non-addressable in which there is a need to accept a genuine long term market failure. Figure 6 illustrates this approach and concept through two different scenarios, one of which is difficult to address based on issues of systematic under investment and lack of access to natural resources, and one of which subject to a lack of standards and appetite to invest based on limited engagement. Only the specifics of the different situations provide the real view about which scenario can be deemed to be addressable, but it is clear that in each of the two situations there are different issues which need to be addressed. The second situation outlined in Figure 6(b) requires procedural and engagement action which could conceivably be addressed as part of a major call to action on either a corporate end-user or a government basis.

Supply chain elements								
	Dimension 2 index	Raw Material	Equipment	Tooling and consumables	Sustainability of supply	Sustainability of resources	Willingness	Standards, Quality and Systems
NO SUPPLY CHAIN	1	No viable source for even small quantities of material OR no understanding of production implications	No viable source of equipment. OR no understanding of requirements	No viable source of tooling or consumables OR no understanding of requirements	No understanding of what is needed to ensure on-going supply		Supplier attitudes to the technology proposition are unknown or hostile	No clarity on requirements
UNDERSTANDING OF PROCESS REQUIREMENTS	2	Raw material supply chain available to support small scale process development AND understanding of production implications	Equipment supply chain available to support small scale process development AND understanding of production implications	Tooling and consumables supply chain available to support small scale process development AND understanding of production implications	Requirements for maintaining and advancing the supply chain are defined and understood	Key resources which are	Suppliers have been approached and enough are known to support the technology proposition to confirm feasibility	Areas where standards, specifications and systems are needed are defined and agreed
VIAIBLE SUPPLY CHAIN IN PLACE	3	Material supply chain available to support large scale process development and small volume initial production	Equipment supply chain available to support large scale process development and small volume initial production	Tooling and consumables supply chain available to support large scale process development and small volume initial production	Minimum standards defined and implemented to ensure sustainable supply	Supply chain design model addresses issues of resource scarcity, non-sustainable logistics and through life support	Suppliers (material, equipment, and consumables) are supporting the technology to a level which enables production	Standards, specifications and systems are developed and being applied
DEMONSTRATED SUPPLY CHAIN IN PLACE	4	Material supply chain in place which can support some of the market potential	Equipment supply chain in place which can support some of the market potential	Tooling and consumables supply chain in place which can support some of the market potential	Demonstration of the effectiveness of the minimum standards	Demonstrated supply chain design model which addresses issues of resource scarcity, non-sustainable logistics and through life	Suppliers (material, equipment and consumables) are supporting the technology in production	Standards, specifications and systems are demonstrated as effective
ADVANCED SUPPLY CHAIN IN PLACE	5	Material supply chain in place to support full market potential	Equipment supply chain in place to support full market potential	Tooling and consumables supply chain in place to support full market potential	Continual assessment and re-alignment of the minimum standards	Continual assessment and re-alignment of improvements in resource sustainability	Suppliers (material, equipment and consumables) are supporting the technology in production, and proactively planning for the future	Standards, specifications and systems are sufficient to drive world class performance

Figure 5. *Supply Chain Maturity – Dimension 2*

Dimension 2 Index	Supply chain elements							Standards, Quality and Systems
	Raw Material	Equipment	Tooling and consumables	Sustainability of supply	Sustainability of resources	Willingness		
1	No material supply chain in place to support full market potential	No equipment supply chain in place to support full market potential	No tooling and consumables supply chain in place to support full market potential	No sustainability of supply chain in place to support full market potential	No sustainability of resources in place to support full market potential	No willingness in place to support full market potential	No standards, quality and systems in place to support full market potential	
2	Material supply chain in place to support some of the market potential	Equipment supply chain in place to support some of the market potential	Tooling and consumables supply chain in place to support some of the market potential	Sustainability of supply chain in place to support some of the market potential	Sustainability of resources in place to support some of the market potential	Willingness in place to support some of the market potential	Standards, quality and systems in place to support some of the market potential	
3	Material supply chain in place to support some of the market potential	Equipment supply chain in place to support some of the market potential	Tooling and consumables supply chain in place to support some of the market potential	Sustainability of supply chain in place to support some of the market potential	Sustainability of resources in place to support some of the market potential	Willingness in place to support some of the market potential	Standards, quality and systems in place to support some of the market potential	
4	Material supply chain in place to support some of the market potential	Equipment supply chain in place to support some of the market potential	Tooling and consumables supply chain in place to support some of the market potential	Sustainability of supply chain in place to support some of the market potential	Sustainability of resources in place to support some of the market potential	Willingness in place to support some of the market potential	Standards, quality and systems in place to support some of the market potential	
5	Material supply chain in place to support full market potential	Equipment supply chain in place to support full market potential	Tooling and consumables supply chain in place to support full market potential	Sustainability of supply chain in place to support full market potential	Sustainability of resources in place to support full market potential	Willingness in place to support full market potential	Standards, quality and systems in place to support full market potential	

(a) Failing supply chain – major systemic and infrastructural gaps

(b) Failing supply chain – regulatory and supplier engagement gaps

Figure 6. Use of Dimension 2 in distinguishing between addressable and non-addressable supply chain gaps

### 3.3. Case Study 3 – Super Plastic Forming

Superplasticity is a phenomenon of certain metallic alloys, whose fine grain structure allows very large plastic elongations to be achieved under controlled conditions of temperature and strain rate [30]. Superplastic forming (SPF) exploits this phenomenon to allow large scale deformation of sheet metal components in a single operation, typically through the use of gas pressure. SPF is an important technique for some high cost aerospace applications and specialist automotive components, but is energy intensive and typically requires expensive equipment and tooling. For these reasons it is often considered a niche technology. Most significantly in the current context, many of the product applications of SPF are somewhat mature, and arguably reaching the end of their product lifecycle. This means that all of the early stage barriers to end product application of the technology have been addressed for these established markets. Many future applications are however subject to competition from other techniques which allow the design and manufacture of stiff, lightweight, geometrically complex structures such as composites and additive manufacture [31]. Without consideration of the how SPF positions itself on future generations of product in the light of competition, it will have a limited long term future.

This illustrates the importance of end-product maturity in any consideration of a successful route to

market for a manufacturing technology [32]. Manufacturing technologies as a fundamental mechanism for achieving product and component characteristics [33], [34], are inherently always a step away from the end use, and must therefore be considered to be subservient to the underlying maturity of the end application. Typical approaches to technology and manufacturing readiness assume an ongoing upward trajectory, with additional development and application driving increased readiness [14]. The approach is not well suited to situations where the end application changes or ceases to exist. On this basis, as the need for a dimension of maturity relating product maturity is considered, it becomes clear that need is different than in the cases two dimensions already considered. For both technology and supply chain maturity there is an underlying assumption that increased levels of assessed maturity are inherently a good thing. In the case of product maturity this is not necessarily the case, as the benefit of targeting a technological solution to a product at the end of its lifecycle seems to be inherently less than applying the same benefit during the early to mid-stage of product maturity. That said, targeting manufacturing technology towards purely emerging product needs could be seen as a rather risky strategy unless it was part of some form of portfolio planning.

Figure 7 shows a maturity structure on the same basis as Dimensions 1 and 2 but applied to product maturity. Again the elements have been developed based on practical experience of the barriers to implementation of manufacturing technology which relate to product in this case. Here the elements relating to market intelligence, product concept and financial viability are deemed to be the basic elements of a business case for development. The Intellectual Property and Legislative issues easy to overlook, especially when the detailed combination of process as applied to product are considered. Perhaps the most important success factor in the case of product is the extent and nature of Customer Pull. The Customer Pull elements is perhaps the central driver behind inclusion of the Product dimensions.

		Product dimension elements					
	Dimension 3 index	Market intelligence	Product concept	Financial viability	Customer pull	Intellectual property	Legislative requirements
NO TECHNOLOGY PROPOSITION	1	No awareness of the potential market for the technology	Technology is scientifically interesting without obvious commercial outlets	No assessment of development cost or potential revenue from the technology	No commercial entities aware of or supportive of the technology	No awareness of background intellectual property; no consideration of potential foreground IP	No consideration given to legislation relating to the technology
UNDERSTANDING OF TECHNOLOGY OPPORTUNITY	2	Market potential of the technology is understood and supports ongoing investigation	Product applications are defined and under development	Cost and benefit drivers related to the technology are understood and support further investigation	Potential customers are aware of the technology and offering low level support	Background IP is understood with mitigation plan for any issues; areas for foreground IP are identified	Legal obstacles which need to be navigated are known with plans to address
BASIC TECHNOLOGY EXISTS	3	Defined market is being pursued for the technology	First-off products have been developed for commercial use with the technology	Business case for the technology has been developed and supported investment	Early adopters of the technology are in place and active	Background IP issues addressed; foreground IP protected	The technology has been implemented in a legally compliant manner on lead applications
DEMONSTRATED TECHNOLOGY AVAILABLE	4	Technology is supported by an active market with clear growth potential	Products based on the technology are successful in the market place, with clear growth potential	Application costs for routine use of the technology are understood	Technology is widely considered to be essential with a high level of demand to implement	IP management issues addressed; potential for product / service differentiation	Legal framework for use of the technology is well understood
DIFFERENTIATING TECHNOLOGY OFFERING	5	Market growth is only restricted by the pace of technology development	Second or third generation products based on the technology are available in the marketplace	Application costs for implementation on next generation products can be readily obtained	Technology is a basic requirement or pre-requisite for all relevant businesses	Product or process IP provides product or service differentiation	

Figure 7. *Supply Chain Maturity – Dimension 3*

Returning specifically to SPF, the problem can be readily identified. The technology is well understood including its costs of implementation and use. The product application of the technology meets level 5 expectations. This knowledge is sufficient to firmly position the processing technology in its established niche. The problem is that it is competition with technologies, in this composite materials, threatens the existence of the niche, and certainly threatens the conditions which drive onward innovation. Without a level of forward innovation the technology development need to drive future market growth cannot be achieved. There is a need in this situation to drive alternative product applications as the mechanism to move the technology forward. Alternative uses of the technology, for example as a means of cost effective prototype or low volume production forces an alternative set of considerations provide this possibility but represent technology push rather than market pull. The technology challenge here would relate to establishing flexible tooling concepts which are cost effective at low volume. The use of the product maturity dimension on helping to articulate this combined challenge is illustrated in Figure 8.

		Product dimension elements					
	Dimension 3 Index	Market intelligence	Product concept	Financial viability	Customer pull	Intellectual property	Legislative requirements
NO TECHNOLOGY PROPOSITION	1	No market intelligence	No clear product concept	No clear financial viability	No clear customer pull	No clear intellectual property	No clear legislative requirements
UNDERSTANDING OF TECHNOLOGY OPPORTUNITY	2	Market potential of the technology is understood and supports ongoing investigation	Product concept is understood and supports further investigation	Cost and benefit drivers related to the technology are understood and support further investigation	Potential customers are aware of the technology and offering low level support	Background IP is understood with mitigation plan for any issues; areas for foreground IP are identified	Legal requirements are understood
BASIC TECHNOLOGY EXISTS	3	Defined market is being pursued for the technology	First-off products have been developed for commercial use with the technology	Business case for the technology has been developed and supported investment	Early adopters of the technology are in place and active	Background IP issues addressed; foreground IP protected	The technology has been implemented in a legally compliant manner on lead applications
DEMONSTRATED TECHNOLOGY AVAILABLE	4						
DIFFERENTIATING TECHNOLOGY OFFERING	5	Market intelligence is available	Second or third generation products based on the technology are available in the marketplace	A business case for the technology is available	Technology is a basic requirement or prerequisite for all relevant businesses	Product or process IP provides product or service differentiation	Legislative requirements are well understood

LEGEND	
↓	Demonstration level sort of minimum standard (use in prototyping)
↑	Demonstration level ahead of minimum standard (traditional aerospace part manufacture)
■	Demonstration level aligned to minimum standard

Figure 8. *SPF product maturity challenges*

So in this case the proposition is about taking an already mature, and arguably sunset technology, and repositioning it as a flexible, and adaptable process. Clearly in this situation there are threats for other competing technology, most notably digitisation of manufacturing generally as well as specific manufacturing techniques including composite material and additive manufacture. In this case it becomes essential to consider the availability of suitable end product applications as a critical success factor in any specific aspect of technology development, and create the case for developing the technology further (assuming this is genuinely believed to be a valid approach with a future). In this case the product dimension of the maturity framework makes this issue of target product maturity very clear, and also signposts the potential importance of a revised version of the process as a prototyping method. The approach also assists those involved in the strategic development of this very sophisticated and capable technique to recognise the need to address the technology gaps that currently make widespread application early stage product development problematic. In particular it helps clarify the route to achieving the basic building blocks required for new applications, which may require development of some of the underpinning aspects of flexible processing on established products in order to help make the case for the future uses. Finally it identifies the challenge of aligning this technology potential to the next generation of products to support their development.

#### 4. DISCUSSION

The valley of death concept has been essential to the success in the UK of raising awareness of high value manufacturing issues, especially in the UK where it has driven the establishment of the HVM Catapult network, including the AFRC. It has helped decision makers understand the need to connect fundamental research with industrial innovation. It does however describe a particular situation and a particular aspect of providing the solution. The more generalised 'long valley of death' concept outlined in Figure 2 is more complete, and outlines a broader range of issues and necessary aspects of routes to resolving it. In particular a broader consideration of the long valley of death model and the issues it raises forces consideration not just of readiness, but of maturity, and that in turn drives the view expressed here that there are multiple dimensions of maturity, three of which are described here.

There is some value in taking the long valley of death concept and the three proposed dimensions of maturity and describing a unified view. Figure 9 achieves this in very simple terms by reducing the long valley of death challenge to the transition between conception of technology to its use in production. The combination of the three dimensions of maturity can be seen to combine to form a Foundation for Innovation (FFI). Given that this work is focused on manufacturing there is a subtle but important difference between the roles of the three dimensions of maturity within the foundation for innovation. The technology and supply chain dimensions should be seen as pillars of the FFI. There needs to be a level of balance between the maturity states of the two, and there needs to be a strong and consistent basis for development in each case. The product dimension needs to be considered differently. As already discussed, addressing the product dimension is not simply about achieving the highest possible level of product maturity. It is meant to drive consideration of the anticipated end use of a manufacturing technology in the context of where that end-use application is in its lifecycle. In many cases the target point will be towards the midpoint of the maturity range. This means that the product dimension plays a number of different, but essential, roles in the FFI:

- It distinguishes between technology push and market pull in the context of the use of a manufacturing technology



- It provides a means of understanding the length of the journey from conception to production, and the pace that needs to be achieved
- It provides the imperative to deliver foundational capability within a definable timeframe in order to avoid missing key implementation opportunities
- It drives strategic decision making on whether to extend the scope of technology on current programmes in order to get them into a good position for future applications, in this way it can provide the basis for a consistent strategic thread between development programmes

Based on this the Product dimension is seen as the spanning device which fundamentally drives the connection between manufacturing technology conception and production. As has previously been stated, manufacturing technologies and, and always will be subservient to products and product service offerings as an manufacturing technology without an end use has little or no value.

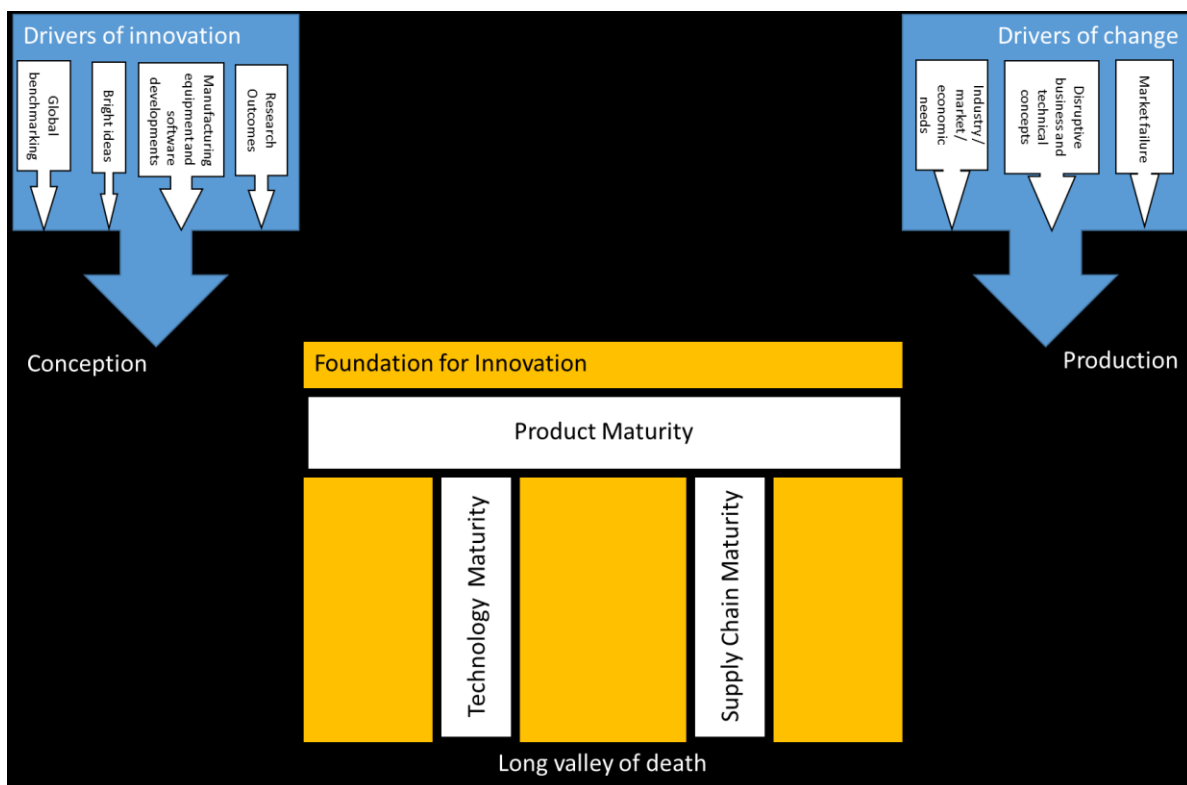


Figure 9. *Valley of Death 2.0, bridged by a Foundation for Innovation*

The three dimensions are not necessarily exhaustive. A key limitation of the specifics of the three dimensions that have been developed and their underlying elements is that it may have been unduly

influenced by the origin of this work from the context of metal forming and forging research provision. Sustainability in the context of business and commercial robustness rather than environmental sustainability is included at the element level of two of the three dimensions. Under particular circumstances it is quite possible that a fourth sustainability dimension, which would probably operate as a foundational pillar, might be added. This has been omitted in the current work as it is assumed to be implicit in some of the other considerations. Likewise it is easy to see how digital manufacturing considerations might be deemed to be of sufficient importance to represent a dimension in its own right, again depending on the specific context and emphasis that is needed. That said the three dimensions shown here are deemed to be somewhat generic and even if additional dimensions might be considered under certain particular circumstances, the three presented here are would be retained and would be central to the foundational maturity assessment.

Within a network of research and innovation providers such as the HVM Catapult, articulating the FFI and achieving a viable and known position against it provides the basis completion of client based readiness task and projects with substantially enhanced pace. In this sense it is seen as a key enabling mechanism to digitalisation manufacturing. If digital manufacturing is going to achieve one thing it will be to make supply chains and product development more agile. This could mean that the pace of change in manufacturing will accelerate beyond recognition, as has already been the case in digital communications. For this to happen, and for this working landscape to allow and facilitate the progressive developments of new manufacturing technologies it is essential that research providers can respond to emerging customer demands on an agile basis. For many long running streams of technology innovation this means establishing a foundation for innovation, on which readiness projects can be built and executed much more rapidly than in today's environment. These linkages digital manufacturing and Industrie 4.0 have provided the motivation to describe the model in Figure 9 as the valley of Death 2.0. This is meant to suggest a linkage and relevance of this foundational approach to the digital manufacturing landscape.

## **5. FURTHER WORK**

This preliminary investigation has demonstrated the need to articulate maturity rather than readiness in dealing with the underlying state of technical development offerings from research networks. It also demonstrates that technology, supply chain, and product dimensions of maturity are necessary to address different circumstances and situations. The concept of foundational and spanning dimensions of maturity seems to be helpful as a mode of use for the combined framework. This however requires validation through practical validation activity. A further phase of work will be undertaken to develop the FFI framework further and to address the issue of how many and which dimensions are sufficient to address the issue on a generic basis and on a broader range of circumstances.

## **6. CONCLUSIONS**

1. The 'valley of death' illustration of the gap between basis research and development, and production implementation has been critical to achieving a focus on close to market manufacturing R&D, especially in the UK
2. That model is however somewhat limited to particular cases and situations. In particular it does not support decision making at the level of widespread market failure, or on how to progress technology development which might be targeted and multiple end uses.
3. A development of the Valley of Death model, termed the 'Long Valley of Death' is proposed to more fully articulate the total problem.
4. Since the original work on which defined TRLs there has been a significant body of work which has resulted in quite systematic and in some cases extensive methodologies for managing technology insertion risks both generally and for manufacturing technology.
5. These approaches are mainly designed for the management of risk during live or committed project activity, and are not as well focused on situations of generic market failure, or on establishing foundational capability for general use.
6. A gap is believed to exist in the provision of manufacturing technology management tools and techniques that can assess the extent to which pre-requisites for successful large scale innovation led investment programmes.

7. The use of maturity as a generic, non-time bound indicator of development status is preferred to readiness in the development of this foundational
- 8.
- 9.
10. The three dimensional Foundation for Innovation (FFI) approach is proposed as a technique which can help articulate whether the basic ingredients are in place for rapid readiness development and with a level of pace and agility that is consistent with digital manufacturing aspirations
11. Further work will be needed to validate the FFI framework and to determine whether the three proposed dimensions are not only necessary, but that sufficient dimensions can be articulated such that the framework is sufficient to provide a robust and generic framework for foundational manufacturing innovation.

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