Crossing the valley of death: five underlying innovation processes

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Abstract

The aim of this paper is to elucidate the innovation processes of technology development across the Valley of Death. Hitherto, studies of the innovation process for this difficult early phase in technology development have implied a linear progression or have privileged the contribution of intermediaries channelling government-funded support. By making use of process theories, and pursing a novel action research methodology with all innovation actors involved in the Valley of Death transition, then a wider processual perspective is realised. This paper adopts a realist evaluation approach in order to integrate the findings from six different technology development projects. By these means, we suggest that crossing the Valley of Death implies the successful completion of five distinct innovation processes. We construct a conceptual framework constituted of the five innovation processes, and argue there is more than one pathway for crossing the Valley of Death. Finally, we offer practical implications for innovation management at this phase of technology development.

Keywords

Valley of Death;
process theory;
innovation dynamics;
action research;
realist evaluation

1. Introduction

It is widely accepted that the technology development Valley of Death is difficult to survive, but reasons why are not fully clarified and consensus on solutions is yet to be reached. The Valley of Death occurs during the early stages of innovation, at the transition between original scientific research and the commercialisation of associated technologies (Auerswald and Branscomb, 2003; Biemans and Huizingh, 2020; Frank et al., 1996; Markham, 2002). Management research has drawn attention to the difficulties in securing finance at this phase (Auerswald and Branscomb, 2003; Beard et al., 2009; Lefebvre et al., 2020), and how policy-makers have tried to bridge this gap (Bonnin Roca and O'Sullivan, 2020; Frank et al., 1996; Wessner, 2005). And yet, even where governments have increased the availability of financing and management support for the Valley of Death phase, the challenge of crossing it and securing first major commercialisation investment persists (EARTO, 2015; Rasmussen and Sørheim, 2012; U.K._Government, 2013).

Much is already known about innovation management between the tail end of scientific discovery and the front end of technology development. Research in this area is not always labelled as the "Valley of Death", and yet it is still relevant. For example, the extensive literature about university technology transfer (Bradley et al., 2013; Son et al., 2020), university-industry engagement (Perkmann et al., 2013) and Proof of Concept Centres (Hayter and Link, 2015b) has documented many innovation practices relevant for the Valley of Death (e.g. McAdam et al., 2010, 463). This management research on science commercialisation has resulted in a detailed understanding on the innovation processes subsequent to crossing of the Valley of Death (Siegel et al., 2004; Vohora et al., 2004), but also notes the considerable ambiguity about the earlier innovation processes (Djokovic and Souitaris, 2008, 243; McAdam et al., 2006).

Hitherto, research about the innovation processes during the Valley of Death has not reached consensus on why this phase is difficult to cross. Markham et al. (2010) argue that the innovation processes at the Valley of Death are different from other phases of technology development, and question whether innovation during this phase can be accomplished as a formal process. Osawa and Miyazaki have proposed a linear model for this phase (2006, 114), but this does not express the iterative processes widely suggested for the earliest phases of innovation (e.g. Siegel et al., 2004). More recently, Islam has developed an "integrated technology-push and market-pull" model (2017, 393) which suggests a crucial role for intermediary organisations. In contrast, other research has emphasised a dynamic interdependence between *all* innovation actors (Markham et al., 2010).

In this paper we report a detailed process study of six technology development projects that are crossing Valley of Death. Process research seeks to explain the flow of activity and events over time (Langley et al., 2013), and is thus relevant to an understanding of how technology development projects cross the Valley of Death. This is not simply a matter of identifying the antecedents that influence the process (Rasmussen, 2011), but rather requires the researcher to follow innovation actors and record how their work unfolds over time. The specific process methodology adopted was that of collaborative action research. Not only is this methodology suited for researching the dynamics of innovation systems (Ottosson and Bjork, 2004), but it allows the possibility of developing both management theory and practice (Eden and Huxham, 1996).

In this paper we make a number of contributions to the literature on the technology Valley of Death. First, we suggest that crossing the Valley of Death implies the successful completion of five distinct innovation processes. Drawing upon process theories of change (Van de Ven and Poole, 1995) we conceptualise why this phase of technology development remains difficult even when funding and innovation support is available. Secondly, we construct a conceptual framework for crossing the Valley of Death based upon the five innovation processes. Furthermore, we demonstrate that there is more than one pathway (the order of completing the five processes) across the Valley of Death. Finally, we use the conceptual framework to offer practical implications for innovation managers.

The paper is structured as follows. Section 2 discusses research covering innovation processes during the Valley of Death specifically, and more generally, in the early stages of technological development. This is followed by section 3 which describes the study's action research methodology. Section 4 summarises the findings from the six projects, and the way in which they were synthesised to build a conceptual framework for the innovation processes during the Valley of Death. Section 5 discusses the contribution for the research literature as well the implications for innovation management. Section 6 provides concluding remarks.

2. Literature Review

We begin with definitions of the Valley of Death and position this idea in relation to research concerned with the commercialisation of science; noting that the latter takes it starting point (i.e. defined commercial proposition) from when the Valley of Death has been successfully navigated. We then consider programmes created in response to government policies aimed at supporting technology projects through this vulnerable phase. Research on such support mechanisms privileges the perspective of the management of the programmes, and we respond to calls for process studies of innovation that take account of the activities of all innovation stakeholders. We end by arguing for the use of process theories in order to probe the innovation dynamics of crossing the Valley of Death.

2.1. The Valley of Death and why it is difficult to cross

The Valley of Death is a phase evident in the early stages of science-based innovation when a technology's continued development is hindered through a lack of funding and support. It has been characterised variously as occurring at: "the transition between invention and innovation" (Auerswald and Branscomb, 2003, 229); "the gap between the technical invention or market recognition of an idea and the efforts to commercialize it" (Markham, 2002, 31); and "an inability to advance from a technology's demonstration phase through the commercialisation phase" (Frank et al., 1996, 61). Whilst the terminology used may suggest different innovation processes are important, it is evident in each definition that this phase occurs at an inflection point in the technology's development. The foundational scientific research activity has not fully finished and the commercialisation of the technology is not completely underway: these two processes overlap and inform each other (Markham et al., 2010).

The transition of a technology across this valley might be expected to present a difficult management challenge. It is well-established that the early stages of science-based innovation are characterised by uncertainty in the understanding of both technology and markets (Van de Ven et al., 1999); and that the basis for investment decisions is never secure (Beard et al., 2009). The organisational complexity inherent to this development phase has been contrasted with the two better-organised innovation functions that surround it: research and commercialisation (Markham et al., 2010). The difference between these two functions is made more acute because they operate under different institutional logics. (Thornton and Ocasio, 2008). That is, the normative and cultural logics of science (research) and business (commercialisation) are different (Vallas and Kleinman, 2008); and the transition between these logics must be managed lest such differences become a barrier to the transfer of technological knowledge (Bjerregaard, 2010; Philpott et al., 2011). For example, different cultural and normative logics related to intellectual property are known to create conflicts in the disclosure of inventions and subsequent licensing of patents (Jensen et al., 2003) and on-going use of intellectual property by scientists in their research (Murray, 2010). Noting that the study of such tensions has dominated research of these early stages of innovation, Frishammar et al. (2011) argued for greater attention being paid to the problem of equivocality, i.e. the existence of multiple and conflicting perceptions of innovation partners.

2.2 Positioning the Valley of Death within science commercialisation

Much is known about the commercialisation of basic scientific research as it is an important theme in contemporary innovation (Calcagnini and Favaretto, 2016; Etzkowitz, 2008; Rasmussen et al., 2006) and a feature of national innovation policies (Grimaldi et al., 2011). Two broad categories of commercialisation have come to dominate research in this area: university entrepreneurship (Rothaermel et al., 2007) and university-industry knowledge transfer (D'este and Patel, 2007). Studies of innovation processes have been a key feature of this literature; and in particular the process of science commercialisation by means of university spin-out enterprises. In a detailed analysis of the development process for university spin-outs Vohora et al. (2004) identified the “critical junctures” at which complex problems must be solved in order for a science-based innovation to transition to the next phase. One such juncture is the transition between the “research phase” and the “opportunity-framing phase”. Whilst proposing that “there is a need to acquire the capability to synthesise scientific knowledge with an understanding of the market to which it may apply” (Vohora et al., 2004, 170), these authors do not elaborate on the process of this transition. Similarly in a well-cited model Siegel and co-workers propose a number of key stages and organisational support requirements for the technology transfer process that starts with university research (Siegel et al., 2004, 138). However, in keeping with many papers in this area their focus is on the configuration of support for innovation (cf. McAdam et al., 2006). The processes linking "scientific discovery" to the "evaluation of the invention for patenting" are not elaborated in their model.

More recently Rasmussen has addressed the absence of a conceptual framework to describe how the academic spin-out process originates (2011). In a longitudinal case study he notes that "strong technological research and the accumulation of knowledge over many years preceded all cases" (2011, 455). However, his detailed analysis gives no explanation of how such research knowledge is translated into a form that can allow the work of commercialisation to begin. Rather he suggests that further research is needed to understand the transition processes between academic and commercial settings. The Valley of Death exists at this very early point in technology development: the interface between the tail-end of scientific discovery, and the proposal of a credible commercial opportunity. These early stages pose distinctive challenges irrespective of the ultimate commercialisation path, and as a consequence national innovation policy has sought to provide targeted support for technology projects going through the Valley of Death (e.g. U.K._Government, 2013). The next sub-section considers the contribution of the research literature to our understanding of such support mechanisms.

2.3 Programmes to support early-stage technology development

Policy and investor initiatives to improve the success rate of the generation of propositions derived from basic research that are ready for initial commercial investment have emerged in recent years under the heading of "Proof of Concept" (PoC) projects (Rasmussen and Sørheim, 2012). Academic literature has positioned such schemes as a solution to fill the Valley of Death funding gap (Gulbranson and Audretsch, 2008). Silva et al. (2009) then presented case research examining different funding models in which the completion of PoC projects was described as involving "technology maturation". Best practices, relevant for Valley of Death technology development, emphasised clarity in: objectives, milestones, managing inventor expectation, investment decision criteria, and risks.

Research on the innovation support provided within PoC programmes related to the Valley of Death has hitherto been dominated by the perspective of the intermediaries facilitating those programmes (cf. Islam, 2017), and not that of individual technology development projects. For example, in a series of papers related to a government-funded programme in Northern

Ireland McAdam et al. (2010; 2009) argued that development in the absorptive capacity (Cohen and Levinthal, 1990) of the business incubator was crucial to the early stage development of technologies. The 2010 paper of these authors details the main support routines and practices associated with PoC projects, and also draws attention to the key role played by the project's lead university researcher. Whilst acknowledging the insights from this work we note that their process flow model (McAdam et al., 2010, 459) continues to show the main stages from the perspective of the management of the incubator. In a similar manner Islam's "Integrated technology-push and market pull model" (2017, 393) emphasises the role of intermediary organisations for emerging technologies crossing the Valley of Death. And yet, as noted by Frishammar et al. (2011) for early stage innovation projects in general, there is a need to take into account the existence of multiple and conflicting perceptions of different participants in the unfolding dynamics of these early stage innovation processes. The transition of university spin-outs to the next stage of development depends on having multiple participants with different competences (Fernandez-Alles et al., 2015). In the next sub-section we consider other innovation process literatures concerned with the earliest stages of technology development.

2.4 Innovation processes during the early stages of technology development

In their highly-cited paper Markham et al. (2010) position the Valley of Death in relation to the literature on the front end of product innovation. The Front End of Innovation (FEI) has been defined as starting with "the discovery of an opportunity or a raw idea for product innovation and ends when the 'Go' decision is made to develop a new product, so that the actual development can start and significant resources committed" (Eling and Herstatt, 2017). Although the term FEI is most usually associated with product innovation more generally (Cooper and Kleinschmidt, 1987), it covers the same technology development phase as the Valley of Death: between invention and innovation (Auerswald and Branscomb, 2003, 229). In a recent evaluation of the state-of-the-art of FEI research Eling and Herstatt (2017) draw attention to two process models (Khurana and Rosenthal, 1998; Reid and de Brentani, 2004). The first of these models is based upon case study research of new product development within firms, and the authors present a linear model of the FEI process (Khurana and Rosenthal, 1998) arguing for the importance of the business strategy in being able to frame key decisions. Whilst an overarching business strategy may not be present in all Valley of Death contexts, many of the individual innovation routines they describe are still relevant (e.g. opportunity identification/assessment/communication; idea generation; product definition; and project planning). In developing their own model, Reid and de Bretani argue (2004) that earlier accounts of the FEI process do not take sufficient account of discontinuous innovation, and they develop a process model that could be applied to the transition between research and commercialisation. This model revolves around decision making at three key interfaces in the innovation process that they label “boundary”, “gatekeeping” and “project”. The boundary interface operates between the external environment and key boundary-spanning individuals and is driven by the latter’s perception of information in the environment. The model appears relevant for Valley of Death contexts that involve innovation actors from different organisations. However, whilst different organisations are positioned in the model, the process is represented in linear terms (Reid and de Brentani, 2004).

Innovation processes that have a connection to the Valley of Death are frequently presented as linear models even as their authors acknowledge their iterative nature (cf. Ndonzuau et al., 2002), for example: science commercialisation models (e.g. Bradley et al., 2013); PoC models (e.g. McAdam et al., 2010); FEI models (e.g. Khurana and Rosenthal, 1998); and even a process model for the Valley of Death phase (Osawa and Miyazaki, 2006). And yet empirical studies of the development of new technologies reveal a process that is complex, characterised by uncertainty, and can entail setbacks, project iterations, and blind alleys (Van de Ven et al., 1999). Koen et al. (2001) do report a model for FEI that is explicitly iterative, but beyond a non-linear visual representation, the processual nature of the iteration is not explained in any detail.

As the foregoing review of literature has argued, there is no current explanation of the innovation processes for crossing the Valley of Death. Partial insights for making this transition may be gleaned from related literatures covering science commercialisation, proof-of-concept (PoC) programmes, and the front end of innovation (FEI). Beneficial innovation practices are advocated, and Frank et al (1996) hint that these may work well in contexts where a well-resourced firm is able to control the whole process. However, in the contemporary innovation landscape this condition does not hold with increased openness (cf. Huizingh, 2011) implying: multiple organisations, different institutional logics, non-linear, iterative processes. In the final sub-section of this review we bring these threads of innovation literature together and argue the case for a process study of innovation management during the Valley of Death.

2.5 Process theories and crossing the Valley of Death

Van de Ven and Poole argue (1995) that there are four basic theories that explain the processes of innovation and change: teleological, dialectic, life-cycle, and evolutionary. The teleological process model depicts innovation as proceeding through the purposeful enactment of a cycle of: goal formulation, implementation, evaluation, and modification of goals (ibid, p.515). The associated change process unfolds by means of purposeful social construction involving actors within an organisation, who have in mind some future end state (e.g. a new product) that they are seeking to attain. The dialectic process model also follows a constructed mode of change, but unlike the teleology theory, it relates to change involving multiple organisational entities (ibid, p.517). This process of change proceeds through a cycle that entails the confrontation of different viewpoints (i.e. thesis and antithesis), and their subsequent synthesis; which then becomes the thesis in the next cycle. The particular circumstance of change relevant to this theory is associated with a balance of power between different organisational entities or viewpoints.

The life-cycle process theory concerns modes of organisational change that are prescribed by some external constraint (e.g. regulation or institutional prescription), rather that constructed as in the two theories described above (ibid, p.513). Such steps may be defined by an overarching institutional framework. Organisational change in such situations is a process of "compliant adaptation" (ibid, p.520). The evolutionary process theory is also concerned with prescribed change, but in this case the underlying mechanism is one of environmental selection acting upon a number of organisational entities. The change process proceeds through an on-going cycle of variation, selection and retention that results, over time, in an accumulation of small changes.

In this paper we make use of Van de Ven and Poole's typology in order to characterise the innovation processes that operate at the Valley of Death phase. Our argument is that the involvement of multiple actors during this phase, possibly with conflicting motivations, together with the complexity of early-stage innovation processes, invites a consideration of multiple process perspectives. The overarching research question for this collaborative endeavour is: how can we explain the innovation processes of crossing the Valley of Death; by which the findings of scientific research are translated into investment-ready commercial propositions?

3. Methodology

3.1 Research context and sample

The empirical research was conducted at a university-based medical technology innovation centre (hereafter MTC) at which a government-funded programme was implemented with the goal of “de-risking new technology derived from basic research to help it progress to commercialisation” [MTC documentation]. The MTC positioned itself explicitly as "bridging the innovation Valley of Death...in order to develop technologies to a stage that is attractive to further investment" [MTC documentation]. Under the auspices of this overarching programme, individual technology development projects were provided with both financial support and innovation management advice to transition the Valley of Death phase. During the course of this research we engaged with six projects over a period of 18 months, and a descriptive summary of these projects is presented in Table 1.

Table 1 - Valley of Death projects – technology context and point of development at outset of management research

Project Code	**A**	**B**	**C**	**D**	**E**	**F**
Science domain	Physics	Immunology	Electronic Engineering	Rheumatology	Biology	Mechanical Engineering
Technology domain	Medical Imaging	Tissue Engineering	Medical sensors	Fracture repair	Assay	in-vivo diagnostic
Project team	scientist, commercial consultant, clinician	scientists, start-up company managers	scientist, new spin-out company sales manager	scientist, clinician	scientist, clinicians	scientists, clinicians
Development history	scientific proof of principle complete	Prior art developed by this team	scientific proof of principle complete	scientific proof of principle complete	scientific proof of principle complete	technology demonstrated in lab
IP protection at outset	patent filing in progress	process patent owned by project team	patent filing in progress	None	patent application made for underlying assay technology	sensing technology known for over 25 years.
Project goal	testing of prototype in a clinical environment	determine the biomechanical & biological compatibility of new material	improvement in reproducibility & robustness of technology in real world setting	develop process for use in operating theatres	production of assay kit to use in operating theatres	Solve technology challenges in a new application area. Develop prototype

3.2 Process research and an action research design

Whilst there is much interest in the innovation processes associated with the commercialisation of science, most management research of this subject has adopted a *variance* approach rather than a *processual* approach (Fini et al., 2018; Langley et al., 2013). Where variance approaches seek understanding based on the relationships between variables, process studies seek understanding based on flows of activity over time. In part, the lack of processual studies may be attributed to methodological challenges (McMullen and Dimov, 2013) that include access to suitable early-stage ventures for longitudinal studies. Notwithstanding these practical difficulties, calls for more processual studies of science commercialisation are advocated (e.g. Fini et al., 2018; McMullen and Dimov, 2013; Moroz and Hindle, 2012; Rasmussen, 2011). This paper responds to these calls, and in doing so adopts the typology of process theories advanced by Van de Ven and Poole (1995). This theorisation of process has been used previously in research encompassing the whole of science commercialisation (Rasmussen, 2011), but it is yet to be used in research focussed on the Valley of Death transition.

The management research reported in this paper had the dual aims of contributing to theory on Valley of Death processes and deriving practical implications for innovation management for such projects. Action research has been found to be a useful methodology in complex technology innovation settings in which there are dual goals of theoretical and practical contributions (Drejer and Gudmundsson, 2002; Terziovski and Morgan, 2006; Theodorakopoulos et al., 2012). The body of methods (Coghlan and Brydon-Miller, 2014) gathered under the heading of action research (AR) is methodologically diverse (Dick, 2015), and theoretically eclectic (Greenwood, 2015). The methodology is inherently processual in nature, proceeding through cycles of diagnosis, action, and evaluation. In addition, the collaborative mode common in action research emphasises the interaction between people with complementary knowledge and skills during the research process (Townsend, 2014). Therefore, an action research design was adopted that sought to elicit the insights from all innovation actors (cf. Ottosson and Bjork, 2004).

The action research reported here involved working with participants who operated at the programme-level of the MTC, as well as innovation actors associated with individual technology development projects. Participants who worked at the programme level included the Operations Director, Clinical Director, and three MTC Innovation Managers. The latter also acted as the organizational link to individual projects by being project managers who co-ordinated teams of scientists, clinicians, and commercial partners.

At any one time multiple projects, at different milestones of development and running to different timescales, operated under the whole MTC programme. This action research sought to engage with individual projects, but to also synthesise the findings from all projects into one process model for transitioning the Valley of Death. This synthesis and model building involved iterating between the programme and project levels within the MTC, and is shown schematically in Figure 1. This research design falls within the "participatory evaluation" (Greenwood and Levin, 2011, 184) tradition of action research. This approach to evaluation seeks to actively involve stakeholders in the planning and conduct of evaluations (Mathison, 2014), and serves the action research goal of contributing to the practical innovation management of Valley of Death projects as well as advancing academic knowledge (cf. Theodorakopoulos et al., 2012).

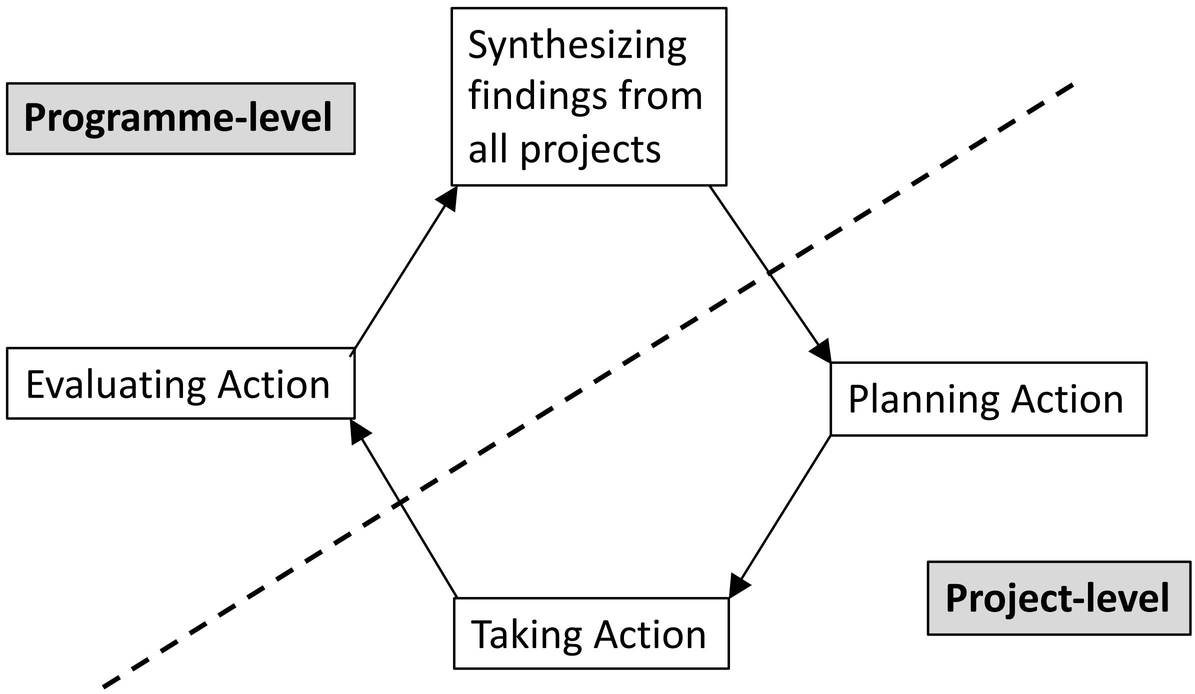

Figure 1 - Action research cycle showing iterations between programme-level and project-level within MTC

The research design in Figure 1 shows innovation actions (also termed 'interventions' in this paper) being planned and implemented within individual projects. Evidence for their impact was generated by individual project teams, and supplemented through observation and interviews with project-level participants. Data from all projects were evaluated by programme-level participants. The findings from all evaluations were synthesised in order to construct a single conceptual framework for the innovation processes during the Valley of Death. The action research cycle continued as emerging lessons were implemented by the innovation managers at the project-level.

3.3 Data collection and facilitation of action research process

Data collection operated at the level of both the MTC programme and individual projects. As part of the "pre-step" before entering into the action research it was first necessary to understand the original design intent of the MTC programme, and to "contract" with participants (Coughlan and Coghlan, 2002, 230). An understanding of the MTC programme itself was gained through interviews with the executive board and reading of documents prepared for their original funding proposal. Contracting with participants involved meeting with them to learn about their projects (Table 1). It was at this point that the dual objectives of explaining the innovation processes during the Valley of Death (academic goal), and collaborating on the refinement of innovation management of projects (practitioner goal) were first articulated.

During the action research cycles data related to "Planning Action" and "Taking Action" (Figure 1) were collected at the project-level through a mixture of interviews, participant observation of project meetings and from project reports. These data related to innovation management interventions: any discrete activity that sought to advance the Valley of Death project. For each such activity, notes were kept on who was involved, the actions taken and the observed outcomes. In summary, data generation at the project-level sought to describe innovation management interventions and what happened as a consequence of them.

Once a month over the course of the action research study, the data generated from within projects were reviewed in a discussion facilitated by the authors. This evaluation stage of the action research cycle operated at the programme-level (cf Figure 1) of the MTC because the purpose of the evaluation was to combine the findings from multiple projects to derive generalisable conclusions. The reflections and learning resulting from these discussions were captured in fieldnotes. These discussions sometimes included suggestions for a specific management intervention for a particular project. These suggestions would be taken by the appropriate innovation manager for discussion with their project team, and represented inputs to the "Planning Action" phase of the next action research cycle.

3.4 Method of synthesis of findings from six Valley of Death projects

The analytical challenge in this research involves the synthesis of findings from six different technology development projects. The method used to achieve this synthesis was that of *realist evaluation* (Pawson, 2013) which is an established methodology for evaluating programmes comprising numerous separate projects (e.g. Pawson et al., 2005). It is a method of programme evaluation that seeks to uncover the reason why a particular intervention (e.g. an innovation management activity) leads to a beneficial outcome. Pawson et al. (2005) and Rogers (2008) have argued that realist evaluations are particularly suited to complex situations in which more than one social process may be operating. We believe that a realist synthesis of our research findings is warranted given the complexity of the innovation processes known to operate during the early stages of technology development.

The analytical routine starts with an initial theory (also known as a “programme theory”) about how the programme is intended to operate (Pawson et al., 2005). In this case that means a theory about how technology projects cross the Valley of Death. For this methodology theories are structured in a particular way that guides the search for data about individual projects. These theories are structured in terms of a “CIMO logic” statement (Denyer et al., 2008; Pawson, 2006). In other words, there are four elements to its structure: context (C), Intervention (I), Mechanism (M), and Outcome (O). In combination they express the logic underpinning the theory that we sought to develop about the innovation processes for crossing the Valley of Death, thus: for a particular innovation context (C), then implementing a particular action or intervention (I), will enable a process mechanism (M), to achieve an outcome (O). These four elements of the logic statement provide a set of generic headings that we used to organise data. From individual projects our data were ordered in terms of the specific context (e.g. project, participant, technology) and the intervention (i.e. innovation actions). We followed each of these interventions over time and recorded their outcome. The project data for context, intervention and outcome were discussed at the monthly programme-level reviews. These discussions culminated in expressions for the process mechanisms that explained how the interventions could realise the outcomes.

Over the 18 months of the study, we generated a list of CIMO logic statements for the innovation activities we were observing within projects. We consolidated this list by looking for similarities and differences in the process mechanisms, and grouped them in an analytical routine similar to the clustering of categories in the Gioia method (2013) for qualitative thematic analysis. This clustering routine was the means by which we synthesised the findings from six projects, and resulted in our identification of five innovation process mechanisms operating during the Valley of Death. This synthesis was consistent with the realist evaluation philosophy that a theory does not seek "generalization…in terms of the association between variables but in terms of the role and impact of generative mechanisms that play out in diffuse ways over time" (Denyer and Tranfield, 2009: 681). In the Results section that follows we present innovation processes operating during the Valley of Death that we elucidated through the evaluation of our data, and combine them in a conceptual framework.

4. Results

4.1. The Initial MTC "Programme Theory"

As part of the preparation to enter the action research field (Coughlan and Coghlan, 2002, 230), evidence was sought to understand the programme-level expectations of the MTC for the Valley of Death projects that they funded. Based upon MTC business plans as well as interviews with the Centre's executive board and management team, the MTC programme framed the transition across the Valley of Death as a series of "innovation challenges" that specific projects were required to resolve. The overarching development philosophy was expressed in the business plan as "*identifying and addressing barriers and risks to the successful delivery of an innovative product at the earliest possible stage in the research and innovation pipeline*". Stopping projects at an early stage was viewed by the MTC directors to be a significant departure from known academic practice which they expressed as one of perpetual exploration and problem-solving. Rather, the MTC sought "*innovation in the discovery process by operationalising a philosophy of early testing for failure*" [MTC

Chairman]. Their rationale was that "*killing projects early will accelerate innovation by focusing R&D on those activities that increase the probability of a successful regulatory and reimbursement outcome, thereby reducing the risk of costly late failures*" [MTC Director].

The MTC *programme* would operate by funding individual Valley of Death *projects* with the expectation that these projects would subject their technology concept to regular testing. The successful transition of the Valley of Death phase would be manifest by articulating a "credible commercial proposition" that attracted the next major investment. The MTC allocated one of their Innovation Managers to each project. These managers had experience both within industry, and also with other large government-funded Valley of Death programmes. Their role was to support the projects both with their own expertise, and to leverage that within the network of university researchers associated with the MTC. This network of expertise included health economics analysis, clinical trials design, improved diagnostics for enhanced patient targeting and complex simulation methodologies for improving short-term predictions of the long-term clinical outcomes. No prescriptions were made for the ultimate commercialisation trajectory that awaited specific projects once they had completed the Valley of Death phase. This could include various possible future commercialisation pathways including: IP creation and spin-out company formation in partnership with venture capital, collaborative projects with industrial firms, strategic partnerships with health technology translation agencies, collaborative projects with the local research and teaching hospital.

This information on the design of innovation support within the MTC was expressed as a "programme theory" (Pawson et al., 2005) for the subsequent *realist evaluation* of action research findings. Specifically, the MTC "programme theory" for managing projects was that the key innovation interventions were a series of tests designed to fail the technology. This was confirmed in discussions with MTC managers as a succinct summary of their technology development philosophy, and was evident in individual project plans. This approach towards the design of projects takes its inspiration from the innovation practitioner philosophy of "fail early" (Edmondson, 2011; Thomke and Rheinertsen, 2012). The process mechanism inherent to such designs is that of "falsification" (cf. Popper, 1959).

4.2. Valley of Death Projects

The first engagement with each of the projects was concerned with understanding of the nature of the technologies, their participants, the development history and Valley of Death project goal. In the following paragraphs we provide a brief summary of key innovation management interventions within the projects and their outcomes (project letters are listed in Table 1). In these summaries we seek to convey both the variety of concurrent innovation work and the way in which it was integrated in order to cross the Valley of Death.

Project A: Magnetic imaging device

The Valley of Death goal of project A was to develop a prototype magnetic imaging device to identify the cause of abnormal heartbeats and demonstrate its diagnostic efficacy in a clinical setting. The technology idea had originated with the lead scientist's own health check-up and discussion with a cardiac consultant. MTC programme funding allowed the construction of a lab-based instrument to collect performance data and model operation in other settings. An experienced industry consultant was co-opted to the project team to make connections with companies that might buy the technology, and to develop a business plan. A health economic analysis was initiated in order to compare the new technology with the existing clinical pathway. In the meantime lab-based work continued not only with improvements in the reproducibility of the instrument's reading, but in developing a user interface. Engagement with a cardiac clinician and the prospect of conducting a clinical trial brought together these different threads of activity in order to articulate a clinical value proposition encompassing: the technology, health diagnosis pathway, operability, interoperability, and device regulatory requirements. The trial proved successful, and provided the last piece of information to articulate a commercialisable proposition that succeeded in securing next round funding.

Project B: Medical tissue transplants

Project B was a follow on from the lead scientist's experience with a university spin-out company formed to commercialise tissue transplants. That experience suggested the same platform technology might address another clinical need for tissue repair in situ, but this required bespoke biocompatibility and stability testing. The MTC programme funded the optimisation of the tissue graft preparation, along with in-vivo & in-vitro testing of biocompatibility to confirm its safety using lab models. In parallel to lab work, a new supply-chain partnership with the Blood and Transplant Service of the UK's National Health Service brought a specific focus to one arena of clinical treatment, that in turn initiated specific regulatory work and clinical trials. The final product was successful in providing effective treatment and repair for chronic skin ulcers in patients that it had not been possible to heal through normal wound care treatment. In addition, the dataset that was compiled from the different threads of activity was used to articulate other commercialisable propositions that were successful in achieving private investment funding.

Project C: Point-of-care diagnostic

The ultimate goal of the team behind project C was to develop a unique point of care diagnostic that uses an array of novel sensors to accurately and sensitively detect a host of biomarkers, enabling doctors to test for multiple conditions simultaneously. With funding from the MTC programme the project team initiated lab-based work that sought to resolve inconsistency in prototype performance. In parallel work a commercialisation consultant built relationships with supply-chain partners for clinical manufacture and distribution. A second consultant was engaged to develop quality assurance protocols and documentation. Prototype development continued and was successful in proving the technology with clinical samples – thereby establishing its clinical value proposition. The preparation of a patent application was the vehicle to integrate the different threads of activity. This resulted in a commercial proposition that succeeded in attracting venture capital funding.

Project D: Stem cell enrichment procedure

Project D sought to optimise an emerging surgical procedure for the rapid enrichment of large quantities of a patient's own stem cells, with a device that could be used in a surgical theatre. A regulatory pathway assessment was conducted that suggested a mechanical (rather than enzymatic) route to producing cells would be easier to accomplish. On this basis, the original collaboration between a surgeon and a clinical researcher was supplemented with expertise in mechanical grinding (of bone samples), and analytical biology (to test the potency of the acquired stem cells). A project plan of lab work was initiated in order to compare the efficacy of the new enrichment routine compared with an existing process. In parallel, work started on the preparation of a patent application. This preparatory work surfaced differences between project partners regarding the exact nature of the inventive step. These differences, allied to a lukewarm reception from commercial contacts led to the project being terminated.

Project E: Organ viability testing

The ultimate aim of project E was the development of assays to improve the utilisation of donated human cells, tissues and organs in clinical transplantation. Foundational scientific research had generated a diagnostic test, and the Valley of Death project goal was to beta-test, refine and document the design and production method for an assay kit in preparation for regulatory submission. A designer of analytical kit moulds was engaged and, following ethnographic observations of analytical testing in a donor centre, a series of prototypes was produced to refine the operability of the test. The interpretation of the analytical result was enhanced using automated visual image processing software. A quality assurance consultant was engaged to prepare the documentation for regulatory approval. Trials of the moulds and software were organised in partnership with the analytical lab of a large hospital. A patent application was filed at the end of the project, and together with results from trials of the diagnostic kit, the lead scientist secured follow-on funding for subsequent development.

Project F: Overactive bladder diagnostic

The Valley of Death goal of project F was to develop a pre-clinical prototype for the diagnosis of over-active bladder conditions. A lab-based model using pig bladder was built and translational research conducted in order to reduce the variability between tests. In a separate thread of technical work, improvements were completed in the visual output from the diagnostic test. A health economic analysis compared the use of this technology with that used in the existing clinical pathway. Attempts were made to build commercial partnerships with suitable clinical equipment manufacturers, but none were realised during this Valley of Death phase of the project. However, links were established with a large patient advocacy group, and this proved productive in the design of a patient pathway using this technology. By the end of the project funded by the MTC, a pre-clinical prototype had been built, and trials in a hospital research institute had demonstrated that the technology could differentiate clinical conditions pertinent to the diagnosis an overactive bladder.

4.3 Synthesis of action research findings

In this section we explain the results of the synthesis of data from the six projects (cf. section 3.4). As evident in the project summaries (section 4.2) a variety of different interventions were made during the action research study, and there were more processes in operation than the regular testing of the technology required by the MTC's initial programme theory. In total our analysis identified five process mechanisms. These are shown in Table 2 alongside an indicative list of innovation interventions that we observed.

Table 2 Summary of innovation process mechanisms and associated innovation interventions

Process Mechanism	Interventions (& project codes)
Refinement of the narrative for the technology concept	• Generate concept ideas within scientists research group (C, D, E & F) • Sensemaking upon previous commercialisation projects (B & E) • Sensemaking and speculation from reading of medical literature (A)
Technical evaluation of lab-scale models	• Generate data to pitch idea to financiers (B & C) • Assess robustness of lab model to different material inputs (B & C) • Develop range of lab exemplars of platform technology (C) • Produce lab model for existing surgical practice (A, D, E & F)
Refinement of understanding of how technology will be used.	• Engagement of expert clinical users (A, D & F) • Engagement with patient advocacy groups (F) • Production of quality assurance protocols (C & E) • Building supply-chain partnerships (B, C & F) • Developing user interface with technology (A, C & F) • Positioning with respect to established healthcare pathways (A, B, D, E & F)
Comparative value assessment	• Health economics analysis (A & F) • Timing approach to venture capital (C) • Negotiating contribution vs returns of innovation intermediaries (B, C, D & E)
Integration of innovator actor inputs	• Development of IP strategy (B, C & E) • Resolving commercial/scientific language disputes (D) • Clinical trials design (A, E & F) • Identifying gaps in technical & market competence (B & C)

To describe more fully the innovation processes related to these interventions and mechanisms, we considered the *contexts* in which they were observed, along with their *outcomes*. We found that the process mechanisms could be grouped into three contexts of project activity as shown in Table 3

Table 3 Groupings of *Context* and *Outcome* in which process mechanisms were observed.

Process Mechanism	Context (innovation actors in brackets)	Outcome
Refinement of the narrative for the technology concept	Extension of medical research (involving scientists, engineers and analysts)	Validated process or product
Technical evaluation of lab-scale models		
Refinement of understanding of how technology will be used.	Appreciation of user value (industrialists, clinicians, health economists)	Initial valuation of technology
Comparative value assessment		
Integration of innovator actor inputs	Crafting of investment-ready proposition (all above, plus MTC Project managers)	Application for commercial investment

The analysis summarised in Table 3 suggests that the innovation processes for crossing the Valley of Death in the MTC programme operate within three key contexts: "extension of medical research" and "appreciation of user value", the learning from which is then integrated by crafting an investment-ready proposition. Extending medical research encompassed interventions to refine the narrative of the technology concept, along with the testing of laboratory models of the technology. These two processes were led by scientists and engineers, and resulted in the creation of a validated technology concept. The appreciation of user value proceeds via interventions to improve the understanding of how the technology is used, along with a quantitative assessment of its value. The dominant participants in these two processes were industrialists, clinicians and health economists, and the outcome was an initial valuation of the technology.

Once Valley of Death projects were initiated the order of the interventions did not follow a set pattern but rather depended on the contingencies of the project. Interventions associated with the first four process mechanisms (in Table 3) might operate concurrently and learning from one would eventually inform the others. For example, in project F the prototypes of the diagnostic kits were designed, tested & refined based on the scientist inventor's own laboratory routines. In parallel, ethnographic observations were conducted in the laboratories of a prospective user to understand how the new diagnostic kits might eventually be used.

Once the findings of these user observations were analysed, then they informed the next iteration of the prototype diagnostic kit.

The interactions between these four innovation processes would continue until a point when next-stage funding became a requirement, and the learning from all aspects of the projects was integrated. A number of particular interventions enabled the crafting of investment-ready propositions (Table 2). At its simplest this involved completing the application documents for a government financing scheme for emerging technologies. In the case of project A the detailed design of a clinical trial provided the means of integrating different threads of the project, and in other projects the completion of a patent application fulfilled the same function. This particular Valley of Death innovation process was the one in which all innovation actors took part and could be accompanied by heated discussion on the relative importance of different contributions. Differences in opinion about the proposition might prompt further work in one of the other four innovation processes. However, in the case of project D the differences between project participants that surfaced at this point could not be resolved and the project was terminated.

The final stage in our analysis was to combine the foregoing analysis into a single conceptual framework (Figure 2). The framework should be read from top to bottom. The majority of Valley of Death project activity occurs at the top of the diagram, which is a combination of the contexts “Extension of medical research” and “Appreciation of user value”. The four related innovation processes are placed within these contexts, with double-headed arrows representing how one process could inform another. The learning from all this innovation activity is integrated by means of the fifth and final innovation process in order to generate investment-ready propositions.

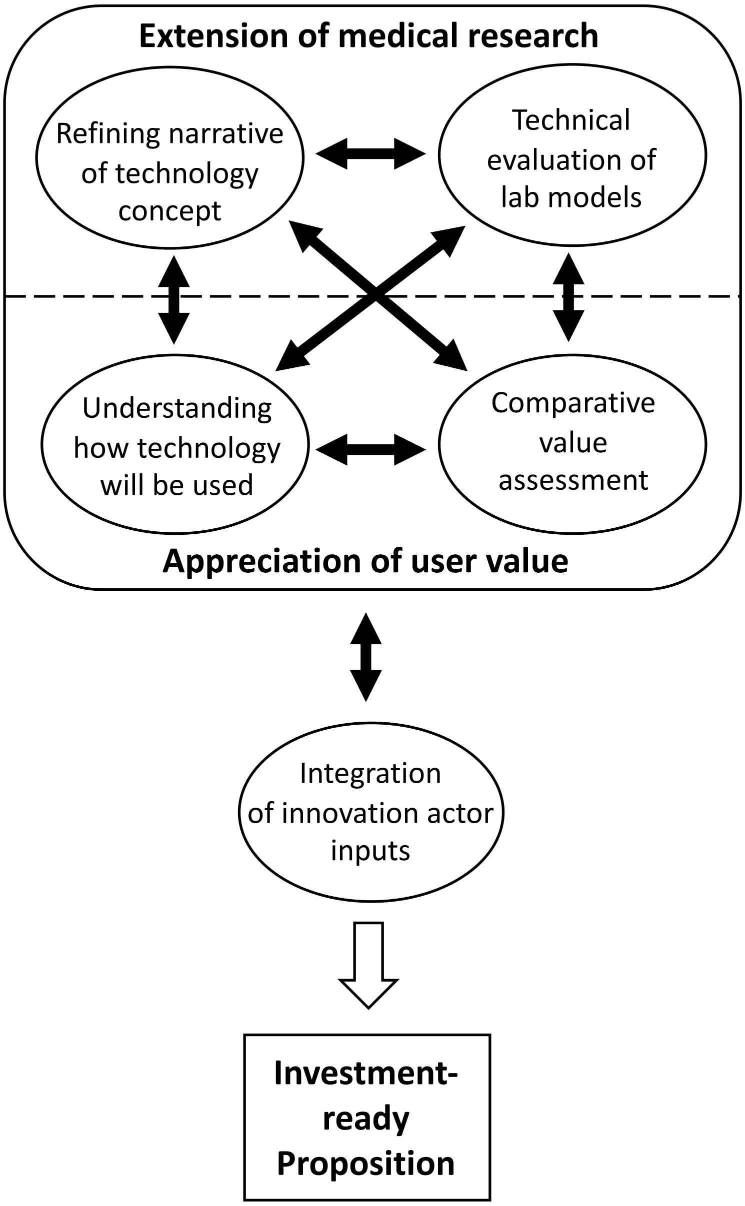

Figure 2 Conceptual framework of innovation process mechanisms during the Valley of Death.

5. Discussion

The aim of this research was to explain the innovation processes for crossing the Valley of Death, and in this section we articulate two contributions to the literature. We build upon these contributions to develop implications for innovation managers. The section closes with a consideration of the limitations of our study, and opportunities for future research.

5.1. Contribution to research literature on technology Valley of Death

The paper's first contribution is to suggest that crossing the Valley of Death implies the successful completion of five distinct innovation processes, and this extends current explanations of why the Valley of Death is difficult to cross. It is well-established that transitioning a project across the Valley of Death is difficult because of the relative lack of resources and expertise (Markham et al., 2010), and problems of securing finance in the absence of a defined technology and clear market position (Auerswald and Branscomb, 2003). To these difficulties with managing the transition, this paper's first contribution adds the processual complexity of this phase. Furthermore, we draw upon Van de Ven and Poole's typology of process theories of development and change (1995) to conceptualise this complexity not only in terms of the number of innovation processes, but also the way in which the processes enact change. Our argument is that we have found evidence during the Valley of Death phase for all four "motors of change" theorised by these authors (Van de Ven and Poole, 1995, 520).

The teleological motor of change (Van de Ven and Poole, 1995, 517) explains how innovation unfolds by means of purposeful social construction involving actors who have in mind some goal (e.g. a new product). It is evident in two ways during the Valley of Death phase: firstly in the construction within the scientist's peer-group of a narrative for the technological concept; and secondly in the refinement of understanding on the part of commercial partners of how the technology will actually be used. The life-cycle motor of change (ibid, p. 513) concerns innovation that progresses through a defined sequence of steps. Within our study such steps were evident in the routines to test and evaluate lab-based models of the technology. The evolutionary motor of change (ibid, p. 517) operates when some consideration existing in an innovator's wider operating environment informs decisions about developments to a Valley of Death project. This process driver is evident when one recognises that competition for investment funding is not only with other technologies addressing the same user needs: it is also from a diverse population of candidate projects that might offer the investor superior returns. Finally the dialectic motor of change (ibid, p.517) is concerned with innovation that proceeds through a cycle that entails the confrontation of different viewpoints, and their subsequent synthesis. This theory comes into play when there is a need to consolidate the learning from projects as different positions (such as those of the scientist, industrialist, and potentially the government programme funder) are brought into confrontation, and require resolution. Therefore, the complexity is not simply a matter of five different innovation processes operating concurrently: though that is complicated indeed. Rather, it is also that these five innovation processes are enabled by four fundamentally different motors of change.

The paper's second contribution is to develop a conceptual framework (Figure 2) composed of five innovation processes. This framework expresses the iterative dynamics of innovation management during the Valley of Death. The important point is that there are a variety of pathways for crossing the Valley of Death, i.e. innovation management activities do not unfold in a defined order. During our engagement with six Valley of Death projects we did not discern a common pattern or order in which the five innovation processes took place.

The iterative nature of this framework (Figure 2) stands in contrast to the linear Valley of Death process model of Osawa and Miyazaki (2006). The variety of process theories operating concurrently between all innovation actors that we make explicit also extends Islam's Valley of Death process model (2017, 393). Islam's model suggests a dominant role for key intermediaries (such as government-funded programmes, business incubators and technology brokers) who orchestrate two innovation mechanisms: technology-push and market-pull. Whilst not denying the role played by such intermediaries, we argue that the innovation processes during the Valley of Death are too complex to be orchestrated by a single intermediary. In our study, the MTC could be described as an intermediary in the terms discussed by Islam, but the suggestion that they alone are crucial to crossing the Valley of Death (2017, 389) is not consistent with our observations, nor conceptualisation of innovation processes. Intermediaries are but one innovation actor important for crossing the Valley of Death, and the integration of the five process mechanisms (Figure 2) might be led by different actors on different occasions.

5.2. Implications for innovation managers

The processual complexity we have elucidated has implications for the management of projects crossing the Valley of Death. One important consideration is that the imposition of an overarching normative process structure designed around an innovation intermediary (cf. Islam, 2017) is not a complete solution to the challenges of completing this technology development phase. The different processual theories evident and discussed above imply that change is not amenable to prescriptive processes and the completion of defined series of organisational tasks that such prescriptions might imply. Rather, this research suggests that innovation actors should be conscious that different process mechanisms are operating and seek to manage the uncertainties that they represent. On the basis of the innovation process mechanisms elucidated in our analysis, the MTC programme managers created a risk-assessment tool to aid innovation actors managing a Valley of Death project.

The purpose of the tool was not to define a series of innovation activities, but rather to bring to their constant attention the innovation risks associated with crossing the Valley of Death. There are five areas of innovation risk (one associated with each of the processual mechanisms) that managers are asked to reflect upon during the design and execution of their projects. These areas cover uncertainty in matters of: the technology concept, technology performance, commercial and clinical risk, impact risk, and the future commercialisation pathway (Table 4). The risk assessment tool poses a number of questions which lead innovation actors to generate information.

Table 4 Summary of categories of innovation risk

Innovation process mechanism	Risk category	Risk Assessment questions
Refinement of narrative for the technology concept	Technology concept	• Is the validity of the underlying science confirmed? • What concept development activities are completed? • What foreground intellectual property protection arrangements are in place?
Technical evaluation of lab-scale models	Technology performance	• What performance attributes must be achieved to prove the technology concept? • What level of formal technical or clinical risk has been completed?
Refinement of understanding of how technology will be used.	Clinical & commercial uncertainty	• To what degree is the clinical value proposition for translation of the medical technology concept understood? • To what degree is the business model for effective translation of the medical technology concept understood? • Can the medical technology concept be validated or "proven" within the scope of Proof of Concept project funding? • To what degree is the commercial landscape for the opportunity of the technology concept understood?
Comparative value assessment	Potential Impact	• How much change would the health service need to undergo if it were to adopt the technology? • Have you involved clinicians or other healthcare professionals in the development of the medical technology concept? • When do you expect your medical technology product might reach its initial market? • How long might it reasonably take for the medical technology concept to reach full market potential?
Integration of innovator actor inputs	Post-Valley of Death commercialisation strategy	• Are the necessary skills available to take the technology through to exploitation after Valley of Death phase? • Do you have exploitation partners identified to provide a route-to-market? • If the regulatory pathway is known, please specify the expected classification? • Are the reimbursement and market access scenarios understood for the technology concept?

5.3 Limitations and suggestions for future research

A potential limitation of our analysis based upon the realist evaluation of unstructured interviews, is that it does not enable a quantitative justification of the relative importance of different innovation process mechanisms. Despite this possible objection the open questioning of participants placed no constraints (e.g. through a strong theoretical framing) on their reflections, and this helped us construct the meanings that innovator actors attributed to the Valley of Death challenges that they faced. Future research might generate more quantitative information in order to understand the relationships between variables associated with each of the five innovation process mechanisms. Limitations were also presented by the choice of projects being contingent upon those actually operating within the MTC at the time of our research. The six case studies allowed a good degree of variability in aspects such as science and technology domains, and development history (see Table 1). However, it might be noted that four of the six case projects involved different types of diagnostic technology. Whilst the conceptual contribution and practical implications of this research are not expected to be limited to health technology innovation, the importance of context for innovation management is well-established (Tidd, 2001), and so further process research covering the Valley of Death phase might usefully study other technology domains. We also note that only one of the six projects failed to meet their Valley of Death project target. Future research that explicitly concentrated upon reasons for failure would insightful. Our research setting was that of a government-funded programme to develop new technologies originating in universities. Much of the extant research related to the earliest stages of technology development is in a similar setting (e.g. Hayter and Link, 2015a; Islam, 2017; McAdam et al., 2009). While this has resulted in useful knowledge, new insights might be revealed through longitudinal studies of crossing the Valley of Death in large, established companies (see Dean et al., 2020, for a cross-sectional study of the Valley of Death in large companies).

Other opportunities for future research follow from our use of action research. Whilst this methodology has its advocates within the innovation research community (e.g. Guertler et al., 2019), the number of published studies remains small. Not only are action research methodologies generative for theorising how innovation unfolds in practice, they can also produce implications for practice that have greater credibility by virtue of the involvement of practitioners in their development. Therefore, future research concerning the Valley of Death and not limited to the subject of innovation process, but focusing on topics such as the required skills or financing, might adopt action research designs (Coghlan and Brydon-Miller, 2014).

6. Conclusions

Innovation during the Valley of Death is characterised by uncertainty concerning both what a new technology will do, as well as the future market demand for it. In such circumstances we might expect the management of innovation to be a complex endeavour prone to failure. In this paper we have argued that this management challenge is not solely a consequence of these uncertainties, but also a processual complexity hitherto not elucidated. Not only does crossing the Valley of Death imply the completion of five distinct innovation processes, but additionally, these processes unfold through four different motors of change. This processual variety explains why this phase of technology development remains difficult even with the existence of finance and management support from expert intermediaries. We hope our deconstruction of innovation processes during the Valley of Death will prompt further detailed studies of how this earliest phase of technology development unfolds.

References

Auerswald, P., Branscomb, L.M., 2003. Valleys of death and Darwinian seas: Financing the invention to innovation transition in the United States. Journal of Technology Transfer 28, 227-239.

Beard, T.R., Ford, G.S., Koutsky, T.M., Spiwak, L.J., 2009. A Valley of Death in the innovation sequence: an economic investigation. Research Evaluation 18, 343-356.

Biemans, W.G., Huizingh, K.R.E., 2020. Rethinking the valley of death; An ecosystem perspective on the commercialization of new technologies. Technovation forthcoming.

Bjerregaard, T., 2010. Industry and academia in convergence: Micro-institutional dimensions of R&D collaboration. Technovation 30, 100-108.

Bonnin Roca, J., O'Sullivan, E., 2020. The role of regulators in mitigating uncertainty within the valley of death. Technovation forthcoming.

Bradley, S.R., Hayter, C.S., Link, A.N., 2013. Models and Methods of University Technology Transfer, Department of Economics Working paper. University of North Carolina, Greensboro.

Calcagnini, G., Favaretto, I., 2016. Models of university technology transfer: analyses and policies. Journal of Technology Transfer 41, 655-660.

Coghlan, D., Brydon-Miller, M., 2014. The SAGE Encyclopedia of Action Research. Sage Publications Ltd, London.

Cohen, W.M., Levinthal, D.A., 1990. Absorptive Capacity - A new perspective on learning and innovation. Administrative Science Quarterly 35, 128-152.

Cooper, R.G., Kleinschmidt, E.J., 1987. New products: What separates winners from losers? Journal of Product Innovation Management 4, 169-184.

Coughlan, P., Coghlan, D., 2002. Action research for operations management. International Journal of Operations & Production Management 22, 220-240.

D'este, P., Patel, P., 2007. University-industry linkages in the UK: What are the factors underlying the variety of interactions with industry? Research Policy 36, 1295-1313.

Dean, T., Zhang, H., Xiao, Y., 2020. The role of complexity in the valley of death and radical innovation performance. Technovation forthcoming.

Denyer, D., Tranfield, D., van Aken, J.E., 2008. Developing design propositions through research synthesis. Organization Studies 29, 393-413.

Dick, B., 2015. Reflections on the SAGE Encyclopedia of Action Research and what it says about action research and its methodologies. Action Research 13, 431-444.

Djokovic, D., Souitaris, V., 2008. Spinouts from Academic Institutions: a lietarture review with suggestions for future research. Journal of Technology Transfer 33, 225-247.

Drejer, A., Gudmundsson, A., 2002. Towards multiple product development. Technovation 22, 733-745.

EARTO, 2015. The European Innovation Council - A New Framework for EU Innovation Policy.

Eden, C., Huxham, C., 1996. Action Research for Management Research. British Journal of Management 7, 75-86.

Edmondson, A.C., 2011. Strategies for Learning from Failure. Harvard Business Review 89, 48-55.

Eling, K., Herstatt, C., 2017. Managing the Front End of Innovation-Less Fuzzy, Yet Still Not Fully Understood. Journal of Product Innovation Management 34, 864-874.

Etzkowitz, H., 2008. The Triple Helix: University-Industry-Government Innovation in Action. Routledge.

Fernandez-Alles, M., Camelo-Ordaz, C., Franco-Leal, N., 2015. Key resources and actors for the evolution of academic spin-offs. Journal of Technology Transfer 40, 976-1002.

Fini, R., Rasmussen, E., Siegel, D., Wiklund, J., 2018. Rethinking the commercialization of public science: from entrepreneurial outcomes to societal impacts. Academy of Management Perspectives 32, 4-20.

Frank, C., Sink, C., Mynatt, L., Rogers, R., Rappazzo, A., 1996. Surviving the "Valley of Death": a comparative analysis. Journal of Technology Transfer 21, 61-69.

Frishammar, J., Floren, H., Wincent, J., 2011. Beyond Managing Uncertainty: Insights From Studying Equivocality in the Fuzzy Front End of Product and Process Innovation Projects. Ieee Transactions on Engineering Management 58, 551-563.

Gioia, D.A., Corley, K.G., Hamilton, A.L., 2013. Seeking Qualitative Rigor in Inductive Research: Notes on the Gioia Methodology. Organizational Research Methods 16, 15-31.

Greenwood, D.J., 2015. An analysis of the theory/concept entries in the SAGE Encyclopedia of Action Research: What we can learn about action research in general from the encyclopedia. Action Research 13, 198-213.

Greenwood, D.J., Levin, M., 2011. Introduction to Action Research: Social Research for Social Change. SAG Publications Inc., Thousand Oaks.

Grimaldi, R., Kenney, M., Siegel, D.S., Wright, M., 2011. 30 years after Bayh-Dole: Reassessing academic entrepreneurship. Research Policy 40, 1045-1057.

Guertler, M., Sick, N., Kriz, A., 2019. A Discipline-Spanning Overview of Action Research and Its Implications for Technology and Innovation Management. Technology Innovation Management Review 9, 48-65.

Gulbranson, C.A., Audretsch, D.B., 2008. Proof of concept centers: accelerating the commercialization of university innovation. Journal of Technology Transfer 33, 249-258.

Hayter, C.S., Link, A.N., 2015a. On the economic impact of university proof of concept centers. Journal of Technology Transfer 40, 178-183.

Hayter, C.S., Link, A.N., 2015b. University Proof of Concept Centers. Issues in Science and Technology 31, 32-35.

Huizingh, E., 2011. Open innovation: State of the art and future perspectives. Technovation 31, 2-9.

Islam, N., 2017. Crossing the Valley of Death-An Integrated Framework and a Value Chain for Emerging Technologies. Ieee Transactions on Engineering Management 64, 389-399.

Jensen, R.A., Thursby, J.G., Thursby, M.C., 2003. Disclosure and licensing of University inventions: 'The best we can do with the s**t we get to work with'. International Journal of Industrial Organization 21, 1271-1300.

Khurana, A., Rosenthal, S.R., 1998. Towards holistic "front ends" in new product development. Journal of Product Innovation Management 15, 57-74.

Koen, P., Ajamian, G., Burkart, R., Clamen, A., Davidson, J., D'Amore, R., Elkins, C., Herald, K., Incorvia, M., Johnson, A., Karol, R., Seibert, R., Slavejkov, A., Wagner, K., 2001. Providing clarity and a common language to the "Fuzzy Front End". Research-Technology Management 44, 46-55.

Langley, A., Smallman, C., Tsoukas, H., Van de Ven, A.H., 2013. Process studies of change in organization and management: unveiling temporality, activity, and flow. Academy of Management Journal 56, 1-13.

Lefebvre, V., Certhoux, G., Lefebvre, M.R., 2020. Sustaining trust to cross the valley of death: A retrospective study of business angels' investment and reinvestment decisions. Technovation forthcoming.

Markham, S.K., 2002. Moving Technology from Lab to Market. Research Technology Management 45, 31-42.

Markham, S.K., Ward, S.J., Aiman-Smith, L., Kingon, A.I., 2010. The Valley of Death as Context for Role Theory in Product Innovation. Journal of Product Innovation Management 27, 402-417.

Mathison, S., 2014. Participatory Evaluation, in: Coghlan, D., Brydon-Miller, M. (Eds.), The SAGE Encyclopedia of Action Research. SAGE Publications Ltd, London.

McAdam, M., Galbraith, B., McAdam, R., Humphreys, P., 2006. Business processes and networks in university incubators: A review and research agendas. Technology Analysis & Strategic Management 18, 451-472.

McAdam, M., McAdam, R., Galbraith, B., Miller, K.D., 2010. An exploratory study of Principal Investigator roles in UK university proof of concept processes: an absorptive capacity perspective. R & D Management 40, 455-473.

McAdam, R., McAdam, M., Brown, V., 2009. Proof of concept processes in UK university technology transfer: an absorptive capacity perspective. R & D Management 39, 192-210.

McMullen, J.S., Dimov, D., 2013. Time and the Entrepreneurial Journey: The Problems and Promise of Studying Entrepreneurship as a Process. Journal of Management Studies 50, 1481-1512.

Moroz, P.W., Hindle, K., 2012. Entrepreneurship as a Process: Toward Harmonizing Multiple Perspectives. Entrepreneurship Theory and Practice 36, 781-818.

Murray, F., 2010. The Oncomouse That Roard: Hybrid Exchange Straties as a Source of Distinction at the Boundary of Overlapping Institutions. American Journal of Sociology 116, 341-388.

Ndonzuau, F.N., Pirnay, F., Surlemont, B., 2002. A stage model of academic spin-off creation. Technovation 22, 281-289.

Osawa, Y., Miyazaki, K., 2006. An empiricalanalysis of the valley of death: Large-scale R&D project performance in a Japanese diversified company. Asian Journal of Technology Innovation 14, 93-116.

Ottosson, S., Bjork, E., 2004. Research on dynamic systems - some considerations. Technovation 24, 863-869.

Pawson, P., 2013. The Science of Evaluation: A Realist Manifesto. . SAGE Publications Ltd, London.

Pawson, R., 2006. Evidence-based Policy: A realist perspective. Sage Publications Ltd, London.

Pawson, R., Greenhalgh, T., Harvey, G., Walshe, K., 2005. Realist review--a new method of systematic review designed for complex policy interventions. Journal of health services research & policy 10 Suppl 1, 21-34.

Perkmann, M., Tartari, V., McKelvey, M., Autio, E., Brostrom, A., D'Este, P., Fini, R., Geuna, A., Grimaldi, R., Hughes, A., Krabel, S., Kitson, M., Llerena, P., Lissoni, F., Salter, A., Sobrero, M., 2013. Academic engagement and commercialisation: A review of the literature on university-industry relations. Research Policy 42, 423-442.

Philpott, K., Dooley, L., O'Reilly, C., Lupton, G., 2011. The entrepreneurial university: Examining the underlying academic tensions. Technovation 31, 161-170.

Popper, K.R., 1959. The Logic of Scientific Discovery. Harper Torchbooks, New York.

Rasmussen, E., 2011. Understanding Academic Entrepreneurship: exploring the emergence of university spin-off ventures using process theories. International Small Business Journal 29, 448-471.

Rasmussen, E., Moen, O., Gulbrandsen, M., 2006. Initiatives to promote commercialization of university knowledge. Technovation 26, 518-533.

Rasmussen, E., Sørheim, R., 2012. How governments seek to bridge the financing gap for university spin-offs: proof-of-concept, pre-seed and seed funding. Technology Analysis & Strategic Management 24, 663-678.

Reid, S.E., de Brentani, U., 2004. The Fuzzy Front End of New Product Development for Discontinuous Innovations: A theoretical model. Journal of Product Innovation Management 21, 170-184.

Rogers, P.J., 2008. Using Programme Theory to Evaluate Complicated and Complex Aspects of Interventions. Evaluation 14, 29-48.

Rothaermel, F.T., Agung, S.D., Jiang, L., 2007. University entrepreneurship: a taxonomy of the literature. Industrial and Corporate Change 16, 691-791.

Siegel, D.S., Waldman, D., Atwater, L.E., Link, A., 2004. Toward a model of the effective transfer of scientific knowledge from acadicians to practitioners: qualitative evidence from the commercialisation of university technologies. Journal of Engineering and Technology Management 21, 115-142.

Silva, R., Allen, D., Traystman, R., 2009. Early-stage Biomedical Research; Proof of Concept Program Objectives, Decision Making and Preliminary Performance at the University of Colorado. Medical Innovation & Business 1, 52-66.

Son, H., Chung, Y., Yoon, S., 2020. How can university technology holding companies bridge the valley of death? Evidence from Korea. Technovation forthcoming.

Terziovski, M., Morgan, J.P., 2006. Management practices and strategies to accelerate the innovation cycle in the biotechnology industry. Technovation 26, 545-552.

Theodorakopoulos, N., Sanchez Preciado, D.J., Bennett, D., 2012. Transferring technology from university to rural industry within a developing economy context: The case for nurturing communities of practice. Technovation 32, 550-559.

Thomke, S., Rheinertsen, D., 2012. Six Myths of Product Development. Harvard Business Review 90, 85-94.

Thornton, P.H., Ocasio, W., 2008. Institutional Logics, in: Greenwood, R., Oliver, C., Sahlin, K., Suddaby, R. (Eds.), The SAGE Handbook of Organizational Institutionalism. Sage Publications Ltd, London, pp. 99-129.

Tidd, J., 2001. Innovation management in context: environment, organization and performance. International Journal of Management Reviews 3, 169-183.

Townsend, A., 2014. Collaborative Action Research, in: Coghlan, D., Brydon-Miller, M. (Eds.), The SAGE Encyclopedia of Action Research. Sage Publications Ltd, London.

U.K._Government, 2013. Bridging the valley of death: improving the commercialisation of research, in: House_of_Commons_Science_and_Technology_Committee (Ed.). The Stationary Office Limited, UK.

Vallas, S.P., Kleinman, D.L., 2008. Contradiction, convergence and the knowledge economy: the confluence of academic and commercial biotechnology. Socio-Economic Review 6, 282-311.

Van de Ven, A.H., Polley, D., Garud, R., Venkataraman, S., 1999. The Innovation Journey. Oxford University Press, Oxford :.

Van de Ven, A.H., Poole, M.S., 1995. Explaining Development and Change in Organizations. Academy of Management Review 20, 510-540.

Vohora, A., Wright, M., Lockett, A., 2004. Critical Junctures in the Development of University High-tech Spinout Companies. Research Policy 33, 147-175.

Wessner, C.W., 2005. Driving innovations across the valley of death. Research-Technology Management 48, 9-12.