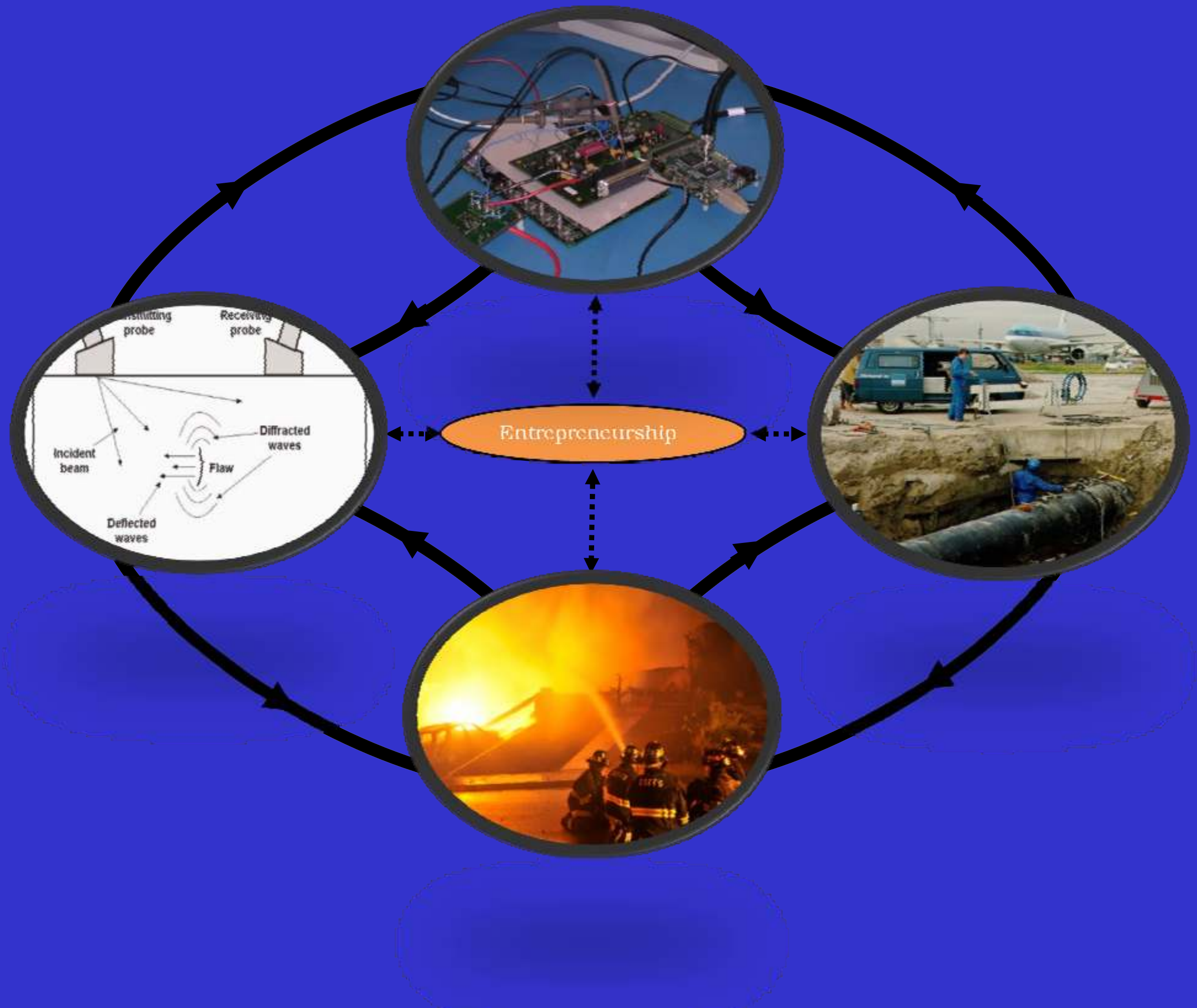
Innovation in Non Destructive Testing



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Innovation in Non Destructive Testing

Proefschrift

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Samenvatting

Innovatie is vandaag de dag geen activiteit meer die kan worden overgelaten aan een aparte afdeling of een kennisinstituut. Het is een kerncompetentie van succesvolle ondernemingen. Echter, in veel gevestigde ondernemingen is de snelheid van innovatie laag. De Niet Destructie Onderzoek sector is een voorbeeld van een sector waar de snelheid van innovatie zeer laag is. Gemiddeld duurt het 30 jaar om een nieuwe technologie van idee tot commercieel succes te brengen.

Niet Destructief Onderzoek (NDO) is een groep activiteiten die gebruikt wordt om de conditie van objecten te bepalen zonder deze te beschadigen. Veel van de technologie die gebruikt wordt in het NDO vind je ook in het ziekenhuis; voorbeelden zijn Röntgen foto's en ultrasone echo's. In het NDO worden deze technieken gebruikt voor het inspecteren van fabrieken, pijpleidingen, bruggen, vliegtuigen, enzovoorts.

Doelstelling

De doelstelling van dit proefschrift is om uit te vinden, waarom innovatie in het NDO zo langzaam verloopt, en tevens om voorstellen te doen om zowel het volume als de snelheid van innovatie aanzienlijk te vergroten. Voor bedrijven die actief zijn in het NDO is dit belangrijk. Zoals in iedere andere sector zullen bedrijven die niet innoveren vervangen worden door innovatieve alternatieven.

Selectie van een geschikt innovatie model

Als begin, zijn een aantal innovatie cases kritisch geanalyseerd, met behulp van het theoretisch kader van Roland Ortt. Deze evaluatie bevestigt dat NDO inderdaad de meest langzaam innoverende sector is, die tot dusverre is onderzocht. De bevindingen zijn gebruikt om een innovatiemodel te kiezen dat als leidraad kan dienen bij het innoveren van het innovatie systeem in het NDO. Drie veelbelovende modellen zijn diepgaand beoordeelt op basis van de eisen die voortkwamen uit het case onderzoek. Op zichzelf is het opmerkelijk dat zeer weinig innovatiemodellen voldoen aan deze eisen. Het Cyclisch Innovatie Model (CIM) van Guus Berkhout is uitgekozen omdat dit model als beste voldoet.

CIM is een relatief nieuw innovatiemodel dat innovatie ziet als een veelomvattend cyclisch proces. CIM onderscheid vier rollen in het innovatiesysteem: wetenschappelijk speurwerk, technologisch onderzoek, productontwikkeling en marktovergang. Deze rollen zijn verbonden door vier vooruit- en terugkoppel-relaties. Een vijfde rol, de ondernemer, stuurt en coördineert de activiteiten van de andere rollen in het innovatieproces.

Interviews met vertegenwoordigers van de NDO sector

In het onderzoek zijn interviews gehouden met vertegenwoordigers van de NDO sector, die samen alle rollen vervullen die beschreven worden door CIM. In het interviewproces is CIM niet alleen als (1) een model van rollen in het innovatieproces gebruikt, maar ook als (2) een model van de actoren in het innovatieproces, en als (3) een model van kennis in het innovatieproces. Doormiddel van deze brede benadering kunnen resultaten worden vergeleken op basis van de verschillende interpretaties van het model.

Fouten in het innovatiesysteem

De kernbevinding van het onderzoek is, dat innovatie nog steeds gezien wordt als een statisch en lineair proces, en dat resultaten worden overgedragen aan de volgende stap in het innovatie proces zonder nadere interactie. Verder worden NDO oplossingen gezocht op een te laag aggregatie niveau (iedere fabriek voor zich), op een te korte tijdschaal en worden alleen technische aspecten behandeld. De consequentie van deze vier systeemfouten is, dat innovatieve oplossingen niet volwassen zijn op het momenten dat ze aan de klant verkocht worden als een volwaardig product. Dit resulteert in vertraging en falen.

Systeem Fout	**Huidige innovatie mindset**	**Nieuwe innovatie mindset**
Innovatie als een statisch en lineair proces	Techniek moet in één keer goed	Meerdere iteraties en verbeteringen
Innovatie op het verkeerde aggregatie niveau	Op fabrieks- of projectniveau	Op industrie niveau
Innovatie op de verkeerde tijdschaal	Weken of maanden	Meerdere jaren
Innovatie als een geïsoleerd technisch proces	Nadruk op het vinden van defecten	Nadruk op: • Economische waarde • Veiligheid en risico-reductie • Sociale acceptatie van nieuwe technologie

Een andere bevinding is, dat er weinig vertrouwen is tussen de wetenschappelijke en de praktische NDO wereld. Ze hebben een scheidingsmuur opgetrokken en communiceren niet over de problemen die ze tegenkomen met betrekking tot nieuwe technologische kansen. Het resultaat is dat veel nieuwe technologieën nooit volwassen worden. Dit kan worden opgelost door het oprichten van innovatie teams die uit zowel wetenschappers als praktijk mensen bestaan.

Innovatie Strategie

In het Cyclisch Innovatie Model, is de eerste prioriteit van de sector, om een gedeelde visie over de toekomst te creëren, die rekening houdt met de macrotrends op wereldniveau in de industrie: (1) industriële objecten en infrastructuur worden ouder, (2) nieuwe materialen zoals composieten en ceramische materialen worden steeds belangrijker als constructiemateriaal, (3) veiligheid wordt een belangrijk onderdeel van de maatschappelijke verantwoordelijkheid van bedrijven. Daarnaast zal de sector zijn lineair-statische innovatie beeld moeten vervangen door een cyclisch-dynamisch innovatie model. Dit proefschrift doet een aantal praktische voorstellen om dit te bereiken.

De rol van dienstverleners

In de NDO wereld bevinden relatief kleine dienstverleners zich tussen zeer grote klanten (olie, gas en chemie concerns) aan de ene kant, en zeer grote leveranciers aan de andere kant (elektronica concerns). Om hun intellectueel eigendom te beschermen, hebben de dienstverleners een cultuur van geheimzinnigheid gecreëerd, en ontwikkelen ze zelf hun apparatuur. Deze geheimzinnigheid verhindert een effectief samenwerken in de sector, en laat belangrijk bronnen van innovatie, zoals apparatuurleveranciers, ongebruikt. Dienstverleners zullen moeten samenwerken, met een gedeelde visie. Ze zullen hun onderhandelmacht beter moeten benutten.

De rol van de overheid

Veel deelnemers in het NDO innovatie systeem weten niet goed wat de rol van de overheid is. De overheid heeft historisch veel innovaties gestuurd in reactie op ongelukken in de industrie, maar het kan niet van de overheid verwacht worden, dat zij het innovatiesysteem sturen en coördineren. Ondernemers zullen dit zelf moeten doen. De structuur van toezicht op het NDO laat toe dat iedereen voorstellen doet voor het veranderen van normen, maar de deelname in normcommissies is laag. Hierdoor worden kansen om te innoveren gemist.

De rol van de toezichthouder

De rol van de toezichthouder zal moeten worden versterkt. Als een resultaat van Europese harmonisering zijn een aantal overheidstaken geprivatiseerd. Deze taken worden nu uitgevoerd door certificeringsbedrijven, die optreden als aannemer van de industriële onderneming die ze inspecteren. Deze bedrijven zijn bezorgd over de kwaliteit van uitvoering van niet-destructief onderzoek, maar hebben weinig macht om op te treden, tenzij er een ongeluk gebeurt. Nieuwe NDO technieken worden veel strenger beoordeeld dan oude NDO technieken. Aangemelde Instanties en Aangewezen Keuringsinstellingen (de certificeringsbedrijven die toezicht uitoefenen) zullen nieuwe en oude NDO technieken gelijk moeten behandelen om innovatie een kans te geven. Dit zal alleen gebeuren als toezichthouders financieel onafhankelijk zijn.

Sociale en commerciële doelen van NDO

Tot slot is een belangrijke bevinding dat de NDO sector zich niet bewust is dat NDO wordt uitgevoerd ten bate van twee verschillende doelen. Aan de ene kant wordt NDO uitgevoerd ten bate van de publieke veiligheid (maatschappelijk doel), aan de andere kant wordt NDO uitgevoerd om de productiviteit van het te inspecteren object te optimaliseren (commercieel doel). Aangezien men ook niet beseft dat deze twee doelen vaak met elkaar in strijd zijn, is het zeer moeilijk de toegevoegde waarde van NDO, en het belang van innovatie in NDO, zichtbaar te maken. Het is moeilijk om bedrijven te laten investeren in een NDO onderzoek waarvan de toegevoegde waarde niet duidelijk is. De voorgestelde oplossing is, om het NDO een integraal onderdeel te laten zijn van de maatschappelijke verantwoordelijkheid van het bedrijf.

De resultaten van dit onderzoek zijn te generaliseren naar andere zwaar gereguleerde sectoren, zoals de financiële sector, waar publieke en private belangen regelmatig botsen.

Samenvattende tabel en voorgestelde maatregelen

Oorzaak van langzame innovatie	Oplossing voor snelle innovatie
Kleine dienstverleners gevangen tussen grote klanten en grote leveranciers	De sector moet een gedeelde visie creëren envan daaruit samenwerken binnen een gedeeld innovatie model
in combinatie met	
Cultuur van geheimzinnigheid bij dienstverleners	Dienstverleners moeten onderhandelmacht creeren en inzetten om te innoveren
Verkeerde interpretatie van de rol van:	
- Overheid	Van de overheid kan niet verwacht worden dat zij innovatie organiseert. In plaats daarvan moet de overheid effectief toezicht instellen en controleren, en ondernemerschap stimuleren
- Toezichthouder	Toezichthouders moeten financieel onafhankelijke zijn. Toezichthouders moeten oude en nieuwe NDO methoden gelijk behandelen om innovatie een kans te geven
- Ondernemer	Ondernemers moeten actief deelnemen in normcommissies om hun nieuwe producten geaccepteerd te krijgen
Wantrouwen tussen de wetenschappelijke en de practische NDO werelden veroorzaakt dat producten niet volwassen worden	Gemengde teams van praktijkmensen en wetenschappers moeten gevormd worden om nieuwe producten te introduceren en te verbeteren
Onvoldoende onderscheid tussen maatschappelijke en commerciële doelstellingen van NDO	NDO en inspectie moeten worden opgenomen in doelstellingen ten aanzien van Maatschappelijk Verantwoord Ondernemen

Executive summary

Today innovation is no longer an activity that is performed by a dedicated department in a company, or left to knowledge institutes. Being innovative is now a core competence of successful companies. In many established companies, however, the pace of innovation is low. The Non-Destructive Testing sector is an example of a sector where the pace of innovation is very slow.

Non-Destructive Testing (NDT) refers to the set of non-invasive activities used to determine the condition of objects or installations without causing any damage. Many of the technologies used in NDT are also used in medical diagnosis, for example X-Ray photos and ultrasonic echoes. In NDT, however, they are used on plants, pipelines, bridges, aeroplanes, etc. While the medical sector is struggling with the fact that innovation is slow, innovation in NDT is even slower. On average, it takes 30 years to bring a new technology from idea to a commercial success.

Objective

The objective of this thesis is to reveal why innovation in NDT is slow, and to propose how both the volume and the speed of innovation can be significantly improved. For companies who are active in NDT this is of increasing importance. Like any other sector, non-innovators will perish and be replaced by innovative competitors.

Selecting a suitable innovation model

First, we have critically analysed a number of innovation cases in NDT, using the framework developed by Roland Ortt. The evaluation confirms that NDT is indeed the slowest innovating sector that has been analyzed thus far. The findings were used to select an innovation model to assist in innovating the NDT innovation system. Three promising innovation models were extensively assessed on the basis of the requirements derived from the case research. In itself it is remarkable, that very few existing innovation models meet these requirements. The Cyclic Innovation Model (CIM) developed by Guus Berkhout was selected as it best fulfills the requirements.

CIM is a relatively new innovation model which views innovation as a comprehensive cyclic process. It identifies four roles in the innovation system: scientific exploration, technological research, product development and market transition. These roles are connected by four feed-forward and feedback relationships. A fifth role, the role of the entrepreneur, functions as a driver and coordinator in the innovation process.

Conducting interviews

Interviews were conducted with representatives from the NDT sector, together comprising all activities described by CIM. In the interview process, CIM was not only used as (1) a model of roles in the innovation process, but also as (2) a model of actors in the innovation process, and as (3) a model of knowledge in the innovation process. Following this broad approach, the results of the interviews were analyzed across the three interpretations of the model.

Innovation system errors

The key finding of the interviews is that actors in the innovation process still assume innovation to be a linear-static process, where results of one stage are handed over to the next without further interaction. Furthermore, new NDT solutions are looked for on a too low aggregation level (plant by plant basis), on a too short timescale and by addressing technical issues only. The consequence of these four system errors is that innovative solutions have not reached their potential when they are sold to the client as a finished product. The result is delay and failure.

System Errors	**Current Innovation Mindset**	**New Innovation Mindset**
Innovation at a wrong aggregation level	At plant or project level	At industry level
Innovation on a wrong time scale	Weeks or months	Several years
Innovation as a linear-static process	First time right technologies	Multiple iterations and improvements
Innovation as an isolated technological process	Focus on defect detection	Focus on: • Safety and risk reduction • Economic value • Social acceptance

Moreover, it was concluded that there is very little trust between the scientific and the practical NDT world. They erected a separation wall and are not communicating about the issues they encounter with new technological opportunities. The result is that many new technologies never reach maturity. This can be solved by building innovation teams that consist of both scientists and practitioners.

Innovation strategy

Following the Cyclic Innovation Model, the first priority of the sector is to formulate a shared vision of the future, taking into account the global macro-trends in industry: (1) industrial assets and infrastructure are aging, (2) new materials such as composites and ceramics are gradually becoming important construction materials and (3) safety will become an important component of corporate responsibility. In addition, in the daily practice the sector needs to replace its linear-static innovation concept by a cyclic-dynamic model. The thesis proposes several practical solutions for organising this.

Role of service companies

In the NDT sector relatively small service companies find themselves caught between large and powerful clients (oil, gas and chemical corporations) on the one hand and large and powerful suppliers on the other. As a result, innovative service companies protect their Intellectual Property (IP) by creating a culture of secrecy and by developing the equipment they use in-house. This secrecy hampers the necessary cooperation and leaves important resources, such as equipment suppliers, unused. Service providers will need to work with a shared vision and use more negotiation power to solve this problem.

Role of the government

Many participants in the NDT innovation system are confused about the role of the government. The government has historically initiated many innovations in response to industrial accidents, but it cannot be expected of the government to drive and coordinate the innovation system. Entrepreneurial companies should take up this role themselves. The regulatory structure in NDT allows for any participant in the innovation system to propose changes to codes and standards, but the participation in standard committees is low. The consequence is that opportunities to innovate are missed.

Role of the regulator

The role of the regulator will need to be strengthened. Under the new regulatory structure resulting from European harmonization, several regulatory government functions have been privatised. These functions are now being executed by certification companies, acting as contractors to asset operators. These companies have expressed concerns about the quality of the existing NDT practice, but lack the power to intervene unless an accident happens. New NDT techniques are judged by a much more demanding standard than old NDT techniques. Notified and appointed bodies (certification companies that execute regulations) will need to access new and old NDT techniques by the same quality standard. This will only be achieved if regulators are financially independent.

Fundamental issue

Finally, an important finding is that the sector does not realize that NDT is performed with two different objectives. On the one hand NDT is performed to safeguard the general public (social objective). However, on the other hand NDT is also performed to optimize the productivity of the asset being inspected (commercial objective). Since it is not always realized that these two objectives often compete, it is very difficult to express the value of NDT and the importance of NDT innovation. As a consequence, it is very hard to get companies to invest in something of which the added value is vague. The proposed solution to this problem is that NDT becomes an integral part of the Corporate Social Responsibility (CSR).

The results of this thesis can be easily generalized to other heavily regulated sectors, like the financial sector, where public and private interests continuously clash.

Summary table of proposed solutions

Cause of slow innovation	**Solution for fast innovation**
Small service providers are caught between large clients and suppliers *linked with* Culture of secrecy in service providers	Sector needs to create and work from a shared vision and a shared innovation model Service providers need to create and use negotiating power
Incorrect interpretation of the roles of: - Government - Regulator - Entrepreneur	Government should not be expected to organize innovation. Instead the government should create and monitor effective regulators and promote entrepreneurship Regulators need to be financially independent Regulators need assess old and new NDT equally to give innovation a chance Entrepreneurs need to actively participate in setting up new standards to get their products accepted
Mistrust between scientific and practical NDT worlds causing solutions to remain immature	Mixed teams of practitioners and scientist should be formed to launch and improve new innovative solutions
Insufficient distinction between NDT performed for social and commercial objectives	NDT and inspection needs to be included in the Corporate Social Responsibility (CSR)

Contents

1. Introduction: Innovation in Non-Destructive Testing

1.1. Framing the problem

Non-Destructive Testing (NDT) is defined as the set of activities that are used to assess the condition of an object or installation without destroying or damaging it. NDT is an important safety competence in almost every industry. In aviation NDT is used to ensure that planes are fit to fly. In oil and gas industry to make sure there are no leaks and the installations are safe. The electronics and semi conductor industry relies on NDT methods to provide feedback to the production processes. The nuclear industry relies heavily on NDT to guarantee safe operations.

Evaluation of several cases has shown that bringing a new inspection technology from invention to commercial success takes as much as 35 years on average (Scruby, 2007). Research by Ortt has shown that the mean time across other sectors is 20 years (Ortt and Schoormans, 2004). An illustrative example of the relative slowness of innovation in NDT is the history of one of the founding technologies of NDT, the radiography method, which uses X-rays or other radiation to make a picture of the inside of a structure.

X-rays were discovered in 1895 by Conrad Röntgen, who was a professor at the Würzburg University, when experimenting with a cathode-ray tube in his laboratory. He quickly realized the practical importance of his discovery and in the same year he made the first medical Radiograph of the hand of his wife Bertha (Wassink, 2006). The discovery of X-rays immediately caught the imagination of scientists and general public alike. Other research was dropped in favour of studying X-rays, and comic heroes soon had X-ray vision. Already in 1896 X-ray was being used by battle field surgeons to locate bullets in wounded soldiers. In 1905 Röntgen was awarded the Nobel Prize for his discovery.

The application of X-rays for industrial applications took much longer, as the early X-ray generators were not able to operate at energies high enough to penetrate steel. In 1922 a 200,000 volt generator provided the first effective tool. In 1931 General Electric developed a 1,000,000 volt generator and in the same year ASME permitted the use of X-ray radiography for the approval of fusion welded pressure vessels (Canonico, 2000). It should be noted however that technologies for reaching high voltages had been available in other areas much earlier in the 20th century.

The time it took for X-rays to be accepted for medical purposes was only a few years. For NDT this time was 36 years. There are several other examples where technology has been used for many years in neighbouring technology areas before it is employed in NDT. Several of these cases will be examined in this thesis.

There could be several reasons for the slow pace of innovation in NDT. It could be that new technologies are not needed, or that new technologies do not offer sufficient advantages. It could also be that new technologies are prohibitively expensive. The scientific literature on NDT however suggests differently. It was shown in numerous studies (PISC II (Nichols and Crutzen, 1988), PISC III (Bieth et al., 1998), RACH (RACH, 1999), NIL thin plate (Stelwagen, 1995) and CRIS (Burch and Hood, 2011)) that new NDT technologies are superior to the ones that are routinely applied today. Given that in the recent years several catastrophic accidents have happened that could have been avoided with (better) inspection technologies, one cannot say that there is no use for new technologies. Some examples of these accidents are the Prudhoe Bay oil spill (Krauss and Peters, 2006), The Mihama nuclear accident (Brooke, 2004) and the collapse of the Interstate 35W bridge over the Mississippi (Sander and Saulny, 2007). All of these accidents involved integrity issues which could have been found with NDT. New NDT technologies have also been shown to give significant cost reductions (Wassink et al., 2007).

The reason that is most often given for the lack of innovation in NDT is that an industry so intimately linked with safety has to be inherently conservative. Hastily replacing a tried and tested method with new technology is a risk. While true, this should not lead to stagnation and certainly not to the failure to implement technology that would improve safety. The structure that ensures conservatism is the use of codes and standards.

The relationship between safety, reliability and quality related problems and NDT solutions, is often not a simple `one problem to one solution` relationship. Over 50 different NDT technologies exist. These technologies are used to deal with issues related to almost every component, structure or equipment in use in industry. NDT has been organized mainly around the NDT technology used, instead of around the problem to be solved. This is a source of complexity for the innovation process.

Another source of complexity is the commercial arrangement in which NDT is performed, which in turn is also linked with the need for safety and conservatism.

In new construction NDT, the client is typically a construction or manufacturing company. In maintenance NDT, the client is the company operating the equipment. These two groups each again have their own standards, and their own regulatory environment. All of these regulations and standards are organized nationally. Even in the European Union, regardless of harmonization affords, countries still have their national system in place.

On a conceptual level, any kind of inspection creates a conflict of interest between the interests of the party demanding the inspection and the party being inspected. When the inspection finds a fault, the party being inspected will have to make repairs. Conversely, not finding a fault will have no consequences, whether there actually is a fault or not. If nothing breaks, and nothing is found, it is in many cases simply impossible to know if a fault exists or not. The solution to this problem is to have norms for when an inspection result is acceptable or not. Innovation in NDT will generally result in being able to find more flaws, which upsets the balance of interests between the demanding and inspected party. This creates parties that are interested in keeping things the same and parties that have an interest in innovation. This could be a contributing factor in innovation being slow.

In this thesis the innovation process in NDT will be studied in order to find out why innovation in NDT is slow. In the next section an introduction will be given to innovation management and management of technology. The final section will give an introduction to the model that will be used for the main investigation into innovation in NDT; the Cyclic Innovation Model (CIM). An overview of the NDT sector will be given in chapter 3.

1.2. Innovation management and management of technology

What is innovation considered to be? This thesis investigates the process and shows that there is a fundamental difference between technology management and innovation. This is particularly true for a service industry, like NDT.

Innovation is described in numerous textbooks (Burgelman et al., 2009, Tidd et al., 2005a, Trott, 2008, Tushman and Anderson, 2004, Howells, 2005) and in very extensive scientific literature. Despite these publications, innovation is still a notion that is hard to grasp. Almost every study on innovation starts with trying to define innovation. In these different definitions a number of issues stand out.

On one aspect there is agreement; innovation is about something new. Different scholars, however tend to focus either on the technology, process, business model, etc, that is new, or they focus on the objective of innovation which in most cases is increased economic performance and recently also includes issues such as sustainability or the general well-being of people.

When focusing on the technology it is realized that this does not need to be technical in the traditional sense but can also pertain to wider types of “technical” change, for example making new regulations or managing people differently. Schumpeter (1947) writes about new combinations when addressing this issue. On the other end of the spectrum innovation is associated with making profit, some going even so far as to say that any business that is able to make a surplus profit over its peers must be innovative in some way (Laestadius et al., 2005).

This section will first give a very short introduction of the way companies view innovation, and will then look at several overview articles on innovation to find out what the important dimensions are when considering innovation. These dimensions will be used later in the thesis as a basis for selecting a framework for the study of innovation in the NDT sector.

1.2.1. The corporate view on innovation

Booz and Company (Jaruzelski and Dehoff, 2010) annually publish a study on the 1000 most innovative companies in the world. Apart from offering some valuable insight into how these companies operate, the study also reveals a lot about the views companies have on innovation. There is a widespread believe that companies are more innovative when they spend more on R&D. In the very first part of the Booz paper, however, it is stated that there is no statistically significant relationship between financial performance and either total R&D spending or R&D as a percentage of revenue. Instead, the study finds that the most successful innovators follow a strategy for developing a product that their clients really need and want to pay for.

Related to the bias towards R&D as a decisive activity in innovation, many companies implement innovation management by using a linear stage-gate like model. The stage-gate model is based on the believe, that successful innovators use an approach where a lot of idea's for new products are gathered, and ideas that are most likely to result in a commercially successful product are selected for further development. This is executed in a number of stages, where at every stage a number of ideas are eliminated. The ideas that are considered to offer too little opportunity for profit are weeded out. The Booz and Company study uses the stage gate terminology to identify sequential activities (ideation, project selection, development and commercialization). Many companies use depictions of the stage gate "funnel" to describe their innovation process; some examples can be found in the 2006 special issue of the International Journal of innovation management (Berkhout et al., 2006) which was specifically dedicated to showing the innovation approaches of several leading companies.

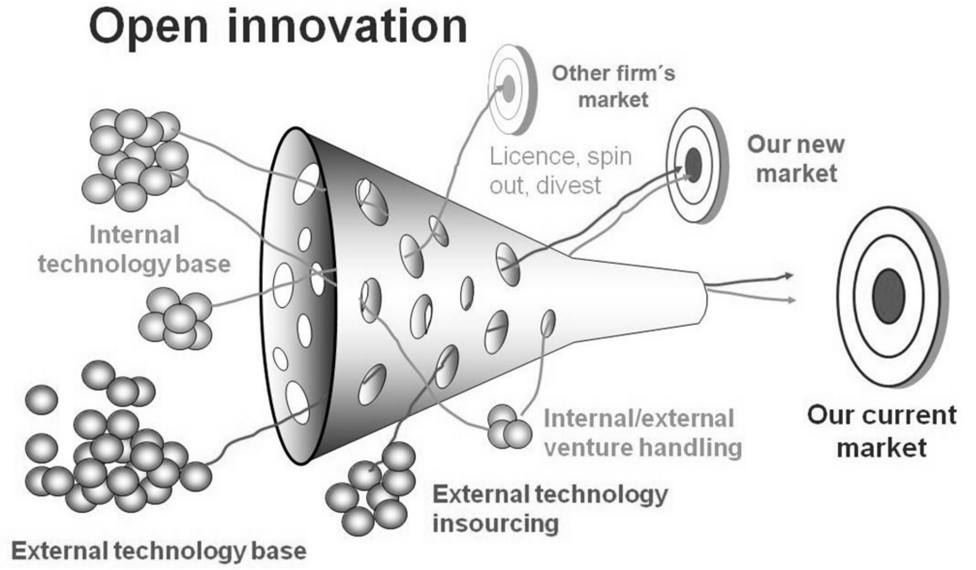


Figure 1: The innovation funnel as depicted by Chesbrough (2003). The traditional innovation funnel has been "opened" but is essentially still a linear stage-gate process

It is obvious that companies focus on short term profitability as a selection criterion for a new product they invest in. However, the focus on short term profitability as an outcome and R&D spending as an input almost inherently creates tension where the input does not necessarily result into the desired output.

It is therefore not surprising that e.g. Christensen (1997) finds that many companies that used to be innovators fail to continue to be so in the long run. Both Christensen and the Booz and Company study find that it is not the R&D capabilities that are lacking in these companies. It is the commercialization issues that companies are struggling with. The stage gate selection process does not compensate for this paradox.

As a result, today, business and management literature on innovation has produced a great number of books that offer solutions to the problems of linking the right technologies with the right user needs.

To give some examples; Christensen (1997) introduced the concept of disruptive innovation. Christensen started with the observation that many large companies fail to respond to the rise of new products that threaten their markets. He realized that this was not because these companies failed to analyze their existing markets, but because they were too focused on them and failed to notice new markets on the horizon. In examples, mainly coming from the disk drive industries, he shows that e.g. the disk drive manufacturers for mainframe computers did not think small desktop computer sized disk drives would be of any value to their clients, as these wanted bigger and more powerful models. As a consequence they failed to see the market for disk drives in smaller computers, and even lost the market for big computers as the smaller disk drives became powerful enough to fulfil the needs of existing clients. He calls these smaller disk drives a disruptive innovation, as they breakthrough and disrupt the pattern of incremental improvement in an industry.

The framework of disruptive innovation is further expanded to show how short term performance of new technologies is typically, at first, lower than established technologies. In a number of examples it is shown how visionary technologists who see the possibility of the new technology start their own business as they get frustrated by the lack of enthusiasm in established industries. These new companies typically service a less demanding customer group that has so far been ignored by industries, often because it is smaller and less profitable. The new client group then acts as a launching pad for the new technology to finally overtake the old ones, and beat the companies that first dismissed the new technology.

Chesborough (2003) popularised the concept of Open Innovation (see also Figure 1), which advises companies to open their funnel to idea's of others, not just at the ideation stage, but along all stages, and conversely for the company to offer those ideas that do not meet the profitability requirements, to others outside the company. In this way much more value is created from the same amount of R&D.

Von Hippel (1987) suggested more user involvement in development processes in order to make sure that products fulfil the needs of these users. This should also make commercialization more successful, as well as help the company select those ideas for development, that users are likely to want to buy. Today this approach is generally referred to as ‘crowd sourcing’.

Moore (2002) found that at various stages of product maturity, new user groups of the product will have different characteristics. He shows how companies can find out at what maturity stage their product is, what their clients are likely to look for in the product, and how to develop products that address these user group characteristics.

Each of these approaches constitutes another way of matching the needs of users with a suitable technology. It could be argued that these approaches try to repair the defects that have resulted from the old linear concepts of innovation, where it is assumed that innovation starts with spending on R&D and ends with successful commercialization. To explore alternative views, the current scientific views on innovation will now be explored.

1.2.2. The scientific view on innovation

Innovation has been studied by representatives of various academic fields such as economy, sociology, history and technology management. In this section the academic view on innovation will be summarized by reviewing a selection of papers which give an overview of the scientific issues involved in innovation. These studies reveal a number of key dimensions in innovation and management of technology.

Rossi (2008) divides innovation studies into two broad categories, the first studying the economic determinants of innovation, the second studying the historical, sociological and cognitive determinants.

On the economic side the paper elaborates on the difference between the views of neo-classical economists, who typically view technological progress as exogenous, and evolutionary and neo-Schumpeterian economist, who view technological progress as endogenous to the economic system. This raises the question: how does technological progress come about? Rossi explores the explanation given in the economic literature and concludes that neither technology push, nor market pull, nor the Schumpeterian notion that economic crises motivate people to innovate gives a full explanation.

On the sociological and historical side, the process of technological progress is further investigated by looking at the insights of authors Bijker and Hughes (Pinch et al., 1987) who study how technology is part of a social system. These authors propose that the purpose and use of new technology is primarily shaped by a process of interpretation by the social groups involved rather than being intentionally created by the inventor.

Rossi concludes that innovation can no longer be seen as a simple application of codified knowledge but has to be understood as a process of creating new, often tacit, knowledge. Reference is made to new approaches to study this knowledge generation process, such as actor-network theory and approaches that look at path dependencies such as studying technological regimes (Nelson and Winter, 1977) and trajectories (Dosi, 1982). The importance of cognitive proximity of innovation partners in national, regional or technological innovation systems is also noted.

Gopalakrishnan and Damanpour (1997) compare innovation studies from three distinct fields: economics, organizational sociology and technology management. In their paper they analyse these fields along three “dimensions of innovation”. These dimensions are listed in Table 1. In the paper it is shown that each of the research fields has preference for a position in each dimension. Economists tend to prefer a high level of analyses, and have a preference for technological radical innovation, while technologist and sociologist each can be sub-divided in multiple traditions.

Table 1: Three dimensions of innovation as used by Gopalakrishnan and Damanpour

Stage of innovation process	**Level of analyses**	**Type of innovation**
Generation of innovation Adaptation of innovation	Industry level Organization level Subunit level Innovation level	Process vs. product Radical vs. incremental Technical vs. administrative

Gopalakrishnan and Damanpour conclude that for practitioners in a corporate environment it is important to realize that in most innovation studies assumptions have been made about the timing and magnitude of innovations, meaning the stage the innovation process is at and whether the innovation is radical or incremental, and that innovation scholars should be more conscious about the differences between the distinct types.

Nieto (2003) follows a similar approach in his paper, taking into account the fields of sociology, history, technology, economics and industrial economics. Nieto first focuses on the level of analysis, finding 7 distinct levels (Table 2) for each of which he distinguished several research issues.

Table 2: levels of analysis of innovation as used by Nieto (2003)

Level of analysis	Units of analysis	Principle discipline
Macro level	Society	Sociology/ history
	Economic system	Economics
	Industry	Industrial economics
Micro level	Firm	Management
	R&D department	
	R&D project	
	Product	

Nieto finds that the most important determinant when looking at innovation studies is whether technology is viewed as static or dynamic, which he traces to the inclination of the research field to view technological progress to be exogenous or endogenous. There is however more to the difference between viewing innovation as dynamic or static, as a dynamic approach allows for viewing innovation as being path dependant. In this context he refers to concepts like technological trajectories (Nelson and Winter, 1977), technological paradigms (Dosi, 1982) and dominant designs (Utterback, 1996). Nieto concludes that the trend is to go toward resource based dynamic approaches.

The three articles studied in this paragraph show which dimensions are important for getting a complete overview of innovation. These dimensions are shown in Table 3. In two of the articles the level of aggregation at which innovation is studied plays an important role. In the papers this is treated as level of analysis, but for this thesis the term scale of aggregation will be used. The reason is that when a scale of aggregation has been chosen, it is still possible to choose the unit of analysis within it, although this will have an influence to the scope of analysis. Choosing the correct scale(s) of aggregation and units of analysis for studying innovation is an issue that is not yet resolved, and will be part of the investigation in this thesis.

The second dimension, which is mentioned in all three papers, is the trend to see innovation as a dynamic process. It is realized that innovation has vastly different characteristics over time, as it moves from an idea, through development of the idea, towards a marketable product. The consequence is that innovation has to be treated as a time dependant process. Part of this notion is also the occurrence in innovation processes of feedback behaviour. Innovation does not simply jump from one stage to another, but a back and forth exchange takes place, where products ideas and prototypes are tested by users and the result of the 'test' is fed back to the inventor.

The third dimension is related to the agents that are involved in the innovation process. In the three papers this is approached in different ways. Rossi mentions theories like action network theory, where the interaction between these agents plays an important role. Gopalakrishnan and Damanpour treat this as part of their investigation into different types of innovation e.g. radical versus incremental and technical versus administrative. Nieto mentions the importance of identifying who is involved in the innovation process where he treats resource based views of innovation. All of them concluded that both the participants and the structure of the innovation network are an import dimension of innovation.

Finally the importance of studying innovation not just as a diffusion of codified or technical knowledge is mentioned. Innovation also involves processes in which knowledge is continuously generated through processes like experimentation, learning by doing and user initiated innovation. A specific issue that touches both on the network and innovation system aspects of innovation and on the use and exchange of knowledge is whether small or large companies are more innovative. These dimensions will be further investigated in chapter 5 where a model for studying innovation in NDT is selected.

Table 3: Analysis dimensions of the innovation process as found in the three overview articles described in this section

	Scale of aggregation	**Time dependant and feedback processes**	**Actor and network dependency**	**Knowledge generating processes**
Rossi	n.a.	Neo-classical vs. evolutionary economics	Trend towards actor network theories	From codified toward inclusion of tacit knowledge
Gopalakrishnan and Damanpour	4 levels (see table 1)	Treated as Timing of innovation	Treated as important to Type of innovation	n.a.
Nieto	7 levels (see table 2)	Dynamic vs. Static approaches	Trend towards resource based approaches	Inclusion of learning processes in innovation

1.3. The Cyclic Innovation Model (CIM)

The main investigation of this thesis uses the Cyclic Innovation Model (CIM) as a framework for studying innovation in NDT. In this section this model will be introduced. The justification for using CIM will be treated in Chapter 5, where CIM is compared to a number of other innovation frameworks.

The Cyclic Innovation Model was introduced by Berkhout in 1995 in the workshop “the knowledge market” at the Erasmus University. The model originated from the practical insights into innovation that were obtained in the Delphi Science-Industry Consortium (an innovation program on geo-energy that is financed by more than 30 international companies). Early versions have been presented at several international venues including symposia at the Royal Netherlands Academy of Arts and Science in 1996 and the OECD in 1997 (Berkhout, 2000).

Since then the model has been further developed when it was used for analysing the technology policy of Delft University of Technology, the Dutch water sector (Sommen et al., 2005), innovation in the chemical process industry (Kroon et al., 2008) and several other cases (Berkhout et al., 2006, Berkhout, 2007). Parallel to the writing of this thesis, Van den Noort is using CIM to study innovation in international economic development aid programs (van den Noort, 2011) and Boosten is used CIM to study innovation in the bio-mass sector (Boosten, forthcoming). The current status of CIM is captured in a forthcoming book (Berkhout, forthcoming).

CIM gives a descriptive and normative view on the system of innovation in the widest sense and distinguishes three levels that correspond with the different levels of decision making in organizations. The highest level, the level of leadership, addresses (a) the vision of the future of an organization, showing where the organization is heading for, (b) the strategy along the transition path, showing the roadmap how the ambitions in the vision can be reached, and (c) the operational framework, focusing on the processes needed to realize the goals in the roadmap. The second level, the level of entrepreneurship, provides the details of the process model, showing the cyclic interaction processes between science and business as well as technology and markets. Finally, the lowest level, the level of craftsmanship, identifies which capabilities in terms of people and organization, are required to make innovation a success. In chapter 5 we will argue that all requirements, discussed in section 1.2, are fulfilled in CIM. Actually, we will show that CIM offers more, because it makes innovation an integral part of 'new business development', meaning that it brings innovation at the level where it should be: the Board of Directors.

1.3.1. CIM: The level of leadership

One of the major challenges of innovation is to anticipate how the world is changing and to act appropriately according to those changes. The long time scales associated with fundamental science and breakthrough technological research and the mismatch of those long time scales with traditional project time scales in business, calls for a framework to guide their interaction.

Strategy and innovation are not often presented as an integrated process. The main reason for the reluctance to include innovation seems to be that technological research itself is unpredictable on a project level, and on short term. Methods that have been developed for predicting and managing this kind of uncertainty are for example scenario building and project front loading. These and other methods are listed by Van der Duin (2006) and Bosch-Rekveldt (2011). However, in the philosophy of CIM, this is old thinking. In innovation, science and technology are not longer autonomous activities but cyclically connected with product specifications and market information. Long term and short term ambitions influence each other and are part of the same system.

Figure 2 shows the leadership level of CIM. In order to include innovation as an integral part of strategy, it is necessary to use the time scales involved in innovation. Long term and short term ambitions are both used for strategy development. Leadership provides an image of the future on these time scales, which shows the ambitions to all stakeholders. Figure 2 shows that vision leads to an image of the future. Building such an image is the result of coupling global mega-trends to new business ambitions, taking internal strength into account. Berkhout and de Ridder (2008) formulate these mega-trends as ‘certainties of the future’.

The image of the future is accompanied by a transition strategy to come from the current state to the desired future. Given the uncertainties and risks associated with the transition path, this strategy will include a roadmap that may contain multiple short-term scenarios (transition scenarios) and requires a flexible organization. The actual implementation activities are described in the cyclic process model which is further clarified in the next paragraph.

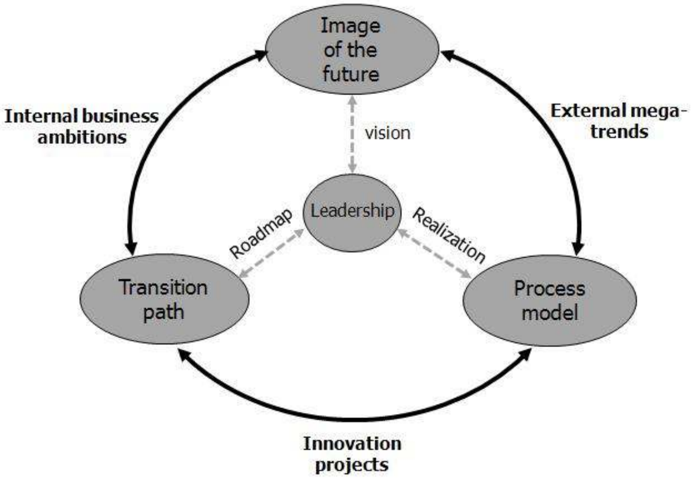


Figure 2: CIM at the leadership level (Berkhout, 2007)

1.3.2. CIM: the level of entrepreneurship

Figure 3 shows the cyclic process model of CIM, being referred to as the innovation circle. The 4 nodes of CIM represent an activity in the innovation process that is considered to be indispensable. The activity in each node is based on collecting a specific type of knowledge, and all four types of knowledge are cyclically connected.

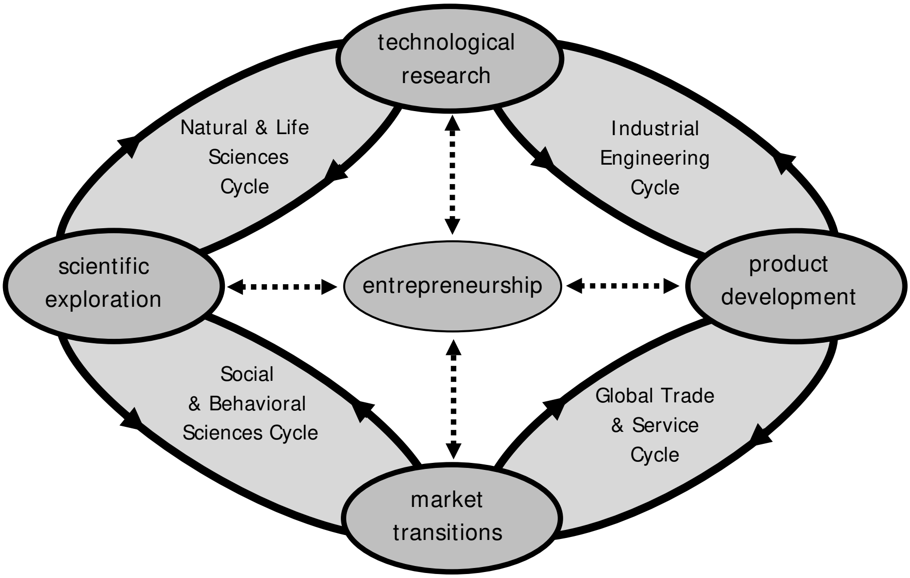


Figure 3: The innovation circle (Berkhout, 2007)

The activities in the scientific node focus on the “knowing why?” question, resulting in codified scientific models. The activities in the technological node focus on the “knowing how?” questions resulting in knowledge on how to design, make and control manmade products. Similarly, the activities in the product development node focus on the “knowing what?” question, and are concerned with the technical and social specifications for the development of tangible products. The activities in the market node focus on the “knowing who?” question and are concerned with potential users, their needs and their buying power.

1.3.3. CIM: The level of craftsmanship

The innovation circle shows that the four nodes are interconnected by feed-forward and feedback paths defining the activities in the four CIM cycles (see Figure 3). A creative and dynamic innovation environment is characterized by dynamic processes in the cycles, being executed by experts with strong cooperation skills.

It is important to realize that CIM does not describe a single product or technology or discipline. At every moment in time a multiple sets of specialized contributions will be needed in every node of CIM. Consider for example an engineer making a design of a car (the ‘what?’ question). The design will on the market side have to correspond to the product requirements of client groups (the ‘who?’ question). On the engineering side, the engineer will have to choose from a wide range of available concepts for his vehicle. For the engine this might be combustion, electric, hybrid or a multitude of additional options (the ‘how?’ question), for materials he has a similar set op options. Every node has multiple alternatives, moving anti-clockwise around the circle, and when the concepts and specifications are clear, combinations have to be made, moving clockwise along the circle. New technologies require many disciplines, new products require many technologies and new user needs require many products.

The cycles shown in Figure 3 have their own characteristic time scales and character. There is an opportunity for extending the framework of CIM in the area of identifying what makes up the nodes and cycles, how to determine characteristics for the applicable case, and how to draw conclusion. Two procedures have been proposed by Berkhout (2007). One uses the Cyclic Innovation Model to rank innovation based on the number of nodes and cycles engages, the other identifies flaws in the innovation system based on cycles being disconnected.

The Booz paper referred to in 1.2.1 distinguishes three possible innovation strategies that they found successful innovating companies to be following. The three strategies found are:

- **Need Seekers**, who directly and actively engage current and potential customers to shape new products and services based on superior end user understanding, and strive to be first to market with those new offerings
- **Market Readers**, who watch their customers and competitors carefully, focusing largely on creating value through incremental change and by capitalizing on proven market trends
- **Technology drivers**, who follow the direction suggested by their technological capabilities, leveraging their investments in research and development to drive both breakthrough innovation and incremental change, often seeking to solve unarticulated needs of their customers via technology

These three strategies each closely relate to one of the cycles of CIM. Need Seekers follow a process that is related to connecting the product and market node (lower right), Market Readers perform an activity and is related to connecting the scientific and market node (lower left), and technology drivers connect the technology to the product node (upper right). This would suggest there to be a fourth strategy (for example technology creators) which connects the science to the technology node (Berkhout, forthcoming). This innovation strategy can be found with start-up companies at universities which were not part of the Booz study.

1.3.4. System dynamics

Feedback is an essential feature of any dynamic system. For each cycle there will be a process bringing the results of the originating node to the next one, and a process feeding back requirements from the receiving node to the origination node.

The basic structure used for the transition cycles is not dissimilar to the double feedback loop often used in system dynamics. Extensive examples can be found with Senge (Senge, 2006). The most famous example of system dynamics is probably the report “The limits to growth” that was made for the club of Rome (Meadows et al., 1972).

One of the essential features expressed by these feedback cycles is that each cycle has its own characteristic time scale, ranging from 50 years of more for shifting the conceptual paradigm in the social and behavioural science cycle, to around a decade for developing a new technology in the natural and life sciences cycle, several years for designing a new product in the engineering cycle, and finally months for the introduction of the new product to the market.

Taking the interaction between the technology and product development node as an example, a new product will consist not of one, but of many different technologies. A company wanting to create a new product cannot expect to master every one of these technologies and will have to consider which it will take from its own knowledge pool, and which it will look for in the broader technological community. Christensen (Christensen et al., 2004) describes this process for the case of Research In Motion, which thoughtfully selected battery technology as the technology needing a breakthrough in order for its Blackberry product to be the big commercial success it has become.

The many to one relationship between each node has another characteristic. Since the many possibilities in each node will practically also be in competition the distribution of these possibilities will hold information about possible dominance of a certain resource e.g. the Microsoft Windows technology only having few and small competition, and thus giving system integrators little alternative to develop products using another operating system, even though for some client requirements Windows may not be appropriate at all. Life critical computer system for instance would much rather use an operating system that is more stable than one originally intended for ordinary business use.

1.4. Concluding remarks to the introduction chapter

This chapter started with an introduction of the subject that will be studied in this thesis: innovation in Non-Destructive Testing (NDT). Next, the chapter investigated the dominant corporate view on innovation and concluded that the main discourse on innovation in the corporate environment is dedicated to solving the issue of matching technologies produced by the R&D department with the needs of customers. It was also concluded that this linear view explains the bias towards R&D and R&D project management as the process to create innovation. Next the academic view on innovation was treated, resulting in four dimensions that are important for analyzing innovation. Finally the Cyclic Innovation Model (CIM) was introduced. A large difference between CIM and existing models is, that it has multiple levels corresponding to the levels of decision making in organization and has a strong emphasis on how to create the future.

In this thesis, the four dimensions (scale of aggregation, time dependant and feedback processes, actor and network dependency, knowledge generating processes) identified in section 1.2.2 will be used to analyse a number of cases of innovation in NDT. The conclusions related to the dimensions, and what values are important in each dimension will be used to select an innovation framework. In chapter 5 the choice of the most suitable innovation model for the NDT sector will be justified.

2. Structure and methodology of the thesis

2.1. Research questions

As mentioned in the introduction (section 1.1), available information on innovation in NDT suggests that the innovation process in NDT, from invention to commercial success, takes much longer than innovation in sectors using comparable technology. The length of this process will be further explored in the cases described in chapter 4. Another observation from the introduction is that the NDT sector has many attributes that make the environment for innovation highly complex. This thesis takes these two observations as the starting point for the research:

1. It takes longer than in other sectors, even sectors with the same kind of technology
2. The environment in which Non-Destructive testing technology is operated is complex

The research starts from an operational point of view of an NDT service provider who wants to innovate in order to be more successful than his competitors. Being faster in implementing new technology is an advantage in this context. The research will endeavour to find out what it is about the NDT sector that causes it to innovate slower than sectors that use almost identical technology like medical diagnoses and geophysics. The main research questions are therefore:

- Why is innovation in NDT slow?
- What are the flaws in the innovation system, and how can they be repaired?

Knowing that the environment for innovation is complex, the approach of the research is to investigate how previous innovations were achieved, and to look at the interaction of actors in the innovation system. Both of these investigations have the objective to look at the influence of the structure of the sector on the innovation speed. It is anticipated that the relationships in the sector will have an influence on the speed of innovation. Another anticipated influence is that the NDT sector is influenced by the context of inspecting assets with a strong safety concern. These influences have been captured in the following additional questions:

- What is the technological issue to be solved? How did this issue become a subject for innovation
- Who are the actors in the innovation process? How do actors interact?
- How does each actor benefit from innovation?
- What is the role of Regulators, Codes & Standards?

On the academic side of the research, several frameworks out of innovation science will be evaluated for the purpose of studying innovation in an industrial sector, specifically the Non-Destructive Testing sector. This evaluation will be performed by assessing the frameworks against the dimensions of innovation processes presented in section 1.2.2. The frameworks evaluated are the Functions of Innovation Systems approach, the Social Construction of Technology Model and the Cyclic Innovation Model. In order to perform this evaluation it first needs to be determined what values in the dimensions of section 1.2.2 are important for the innovation processes in NDT. This is determined by case study research.

The underlying research questions for this academic part are:

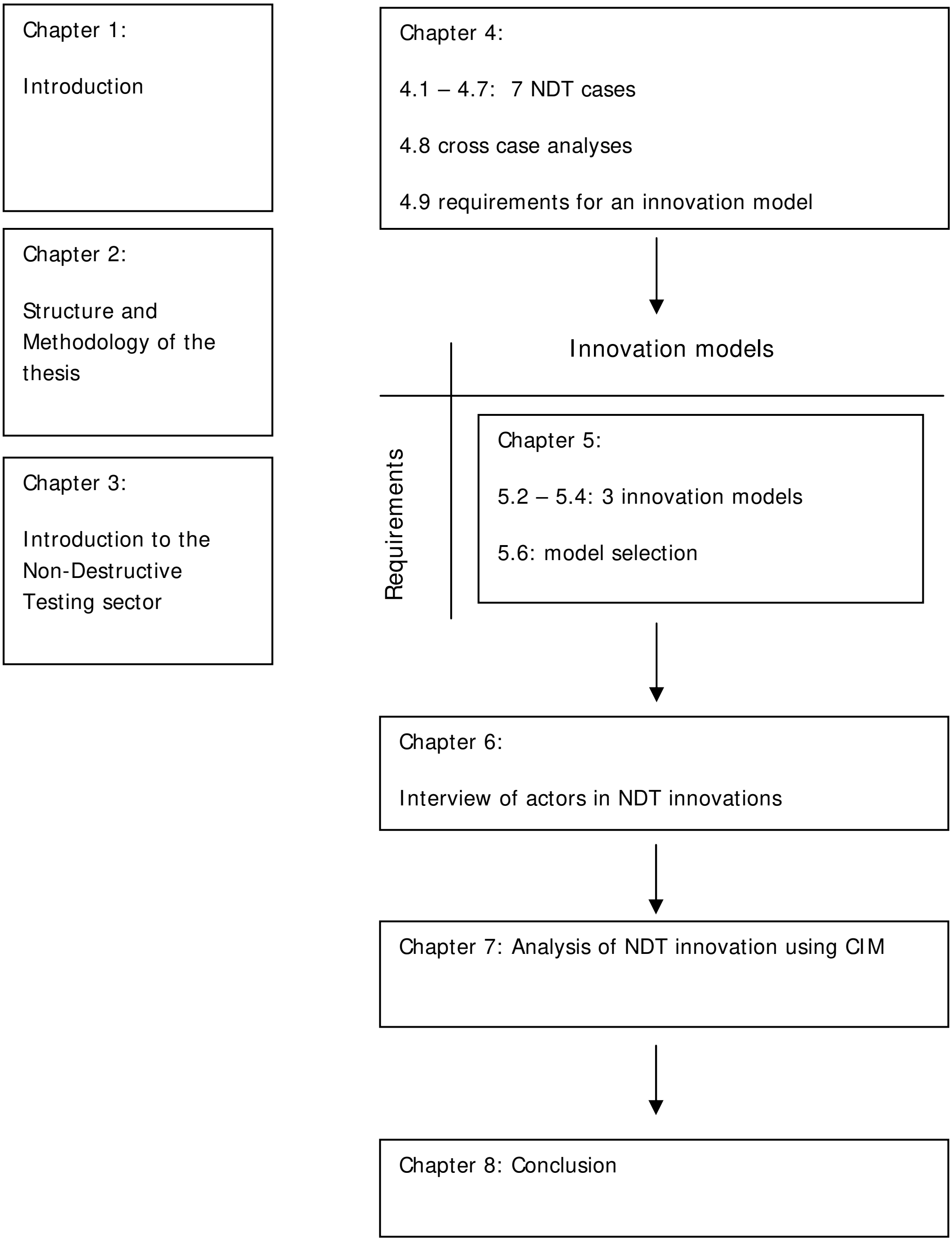
- What aspects need to be modelled for studying innovation in an industrial sector?
- Which innovation model best captures these aspects?

Finally the Cyclic Innovation Model will be used to analyse the Non-Destructive Testing sector. Some new methodology and tools will be developed to this end.

- How can the Cyclic Innovation Model be used to analyse the innovativeness of an industrial sector?

A schematic overview of the thesis can be found on the next page.

2.2. Structure of the Thesis



2.3. Methodology

The proposed research is methodologically divers and involved. Because the research involves the development of new research tools some methodological issue will be treated in the sections describing these research tools. There are some overall aspects of the methodology that are common to the whole thesis.

Easterby-Smith et al. (2002) order research methodologies along two axis. One axis is related to the relationship between the researcher and the subject, ranging from detached to involved. The other axis is related to how the researcher approaches the nature of reality. On one end is the positivist position that reality is fixed and observable, on the other end is the social constructionist view that reality is the result of socially embedded interpretations.

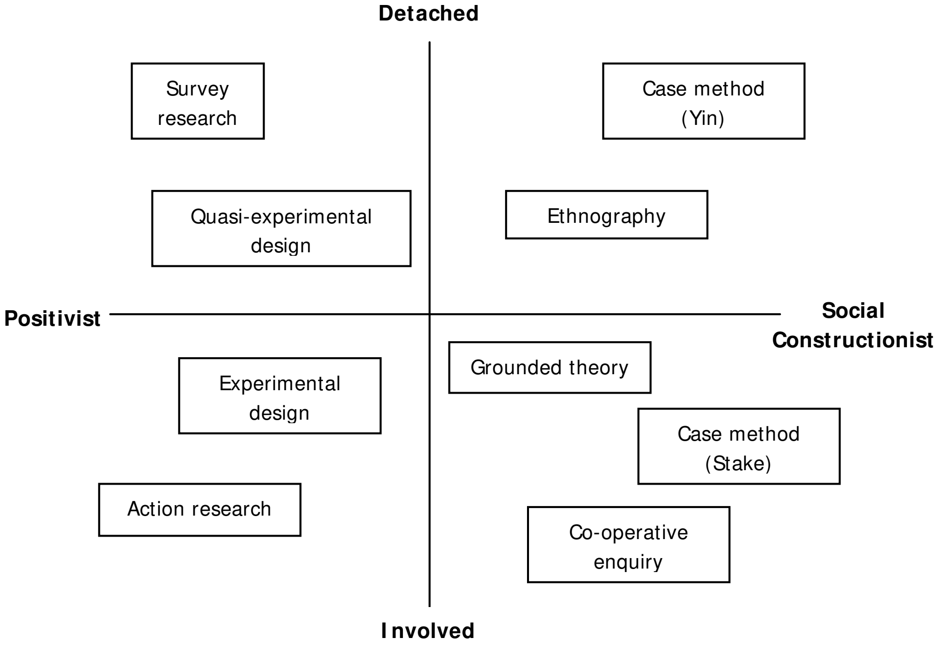


Figure 4: The methodological quadrants of Easterby-Smith

Regarding the first scale, ranging from Positivist to Social Constructionist[1], this research has some attributes of both sides. On the one hand it will be tried to

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[1] The use of the term Social Constructionist refers to Social Constructionist epistemology, dealing with the way scientific knowledge is arrived at. The term is taken from Easterby-Smith. In innovation science the same term is sometimes

make an objective analyses of innovativeness, on the other it is recognized that in innovation the social acceptance of technology is important and related to the subjective reception of the community involved. The practical side of the research more so than the theoretical one, will need to be sensible to the soft values involved in employing new technology. Non-Destructive Testing is an industry that is aimed at providing safety, and feeling safe is something that is personal and arises for every human being differently. Another reason why this research is not positivist, and may even be classed as post-modern, is the fact that power and politics are also acknowledged as important factors in the success and failure of new technology.

On the other axis (involved – detached) this research is clearly involved. The aim of the research is to be able to actively influence the innovativeness of an industry.

The positioning along these two axes discussed above, places this research in the lower right quadrant. Easterby-Smith has three research methodologies in this quadrant; grounded theory (Goulding, 2002, Locke, 2001), co-operative inquiry (Heron, 1996) and the case methods of Stakes (Stake, 1995). All of the methods were investigated and the methodological choices made are based on features of all three methods.

On the issue of validity an additional methodological notion will be used. Whereas the methods mentioned above mostly use saturation as the notion by which completeness of research is ensured, this research will also use triangulation between sources within the single method to be developed, and triangulation between methods when combining the results from multiple methods.

A final overall methodological issue is the relationship between theory and data. Although most of the methodology used is from explorative research, which traditionally places the collection of data before the formulation of theory, this research starts out with the Cyclic Innovation Model. It is however still felt that the nature of the research is primarily explorative. The research will start from the position that theory has so far failed to properly describe innovation, and will therefore treat CIM as a candidate theory rather than a hypothesis that needs to be tested.

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used to refer to the way an innovation (e.g. with Bijker) is arrived at, but this is not what is meant here.

2.4. Practical motivation for the research

When first talking to Applus RTD executives about this research two questions came up:

- How can we bring our new technology to the market faster and more effectively?
- How can we get higher in the value chain with our clients?

The first question revolves around technology. Applus RTD (formerly Röntgen Technische Dienst named after Röntgen, both the inventor of and the Dutch word for X-ray) employs around 40 different NDT technologies, including X-ray, various ultrasonic technologies, various electromagnetic technologies and various optical technologies. 80% of services however are fairly basic radiographic and ultrasonic services, e.g. weld radiography and ultrasonic wall thickness reading. Although the other technologies have been determined to be superior (PISC II (Nichols and Crutzen, 1988), PISC III (Bieth et al., 1998), RACH (RACH, 1999), NIL thin plate (Stelwagen, 1995) and CRIS (Burch and Hood, 2011)) they have very limited application. Furthermore it was determined that the typical time it takes for a technology to become accepted could be as much as 35 years (Scruby, 2007) which is very long for a commercial company. Still Applus RTD has been committed to innovation and has an in house R&D capability. At present a very large share of profit is coming from technologies such as Rotoscan and L-PIT, which have been pioneered in house. Rotoscan was patented in 1955, but took until the 1990's to become profitable.

The second question has to do with the value of NDT. Rephrased, the questions is how can we add more value to our clients using the same basic services, but interacting with the client in a way such that more effective use is being made of the inspection results. Appropriation of this value is another important issue. A different view of the value of the NDT services may also lead to a different appraisal of technologies.

In the background of this question is also the situation in the NDT service market. While the NDT technician is on one hand seen as a highly trained professional, and the market has reported labour shortage for many years, many branch office managers complain about price pressure and cut throat competition. It would be a big help to them to be able to present their service as something valuable.

2.5. Relevance

2.5.1. Scientific contribution of the research

Lack of innovation is considered a major issue to the performance of individual companies, industrial sectors and to the economy as a whole. Innovation, in combination with Entrepreneurship, has been mentioned as the single most important factor for remaining competitive for the western world and for getting out of the current economic crisis (Balkenende, 2008). Sources from the time of the last great crisis consider innovation to be the main source of wealth (Schumpeter and Opie, 1934) (Kuznets, 1930). The proposed research focuses on producing theory and methods for analyzing innovativeness on multiple levels. The research will be aimed at practical results. One of the objectives of the research is to impact the innovativeness of the industrial sector and companies under investigation.

The research will contribute to understanding why innovation is difficult to achieve in some industries. Scientifically the research will result in extension of the CIM model with theory that is novel in using innovation processes and knowledge as the core units of analyses for studying innovation.

2.5.2. Practical contribution of the research

Non-Destructive Testing (NDT) touches nearly every industry. Without it refineries, chemical and nuclear plants could not operate safely, aircraft could not fly safely and many production processes could not run effectively.

Through this link with so many industries, innovation in NDT could make a contribution to safety and productivity in these industries. Studying and improving the innovativeness of the NDT sector is thus relevant to society.

Next to the economic impact of the NDT sector itself, the results will have possibilities to be generalized towards other activities where economic activities and safety interact. The research is novel in that it not only looks at the technical and probabilistic issues concerned but also looks at the interaction with social processes and the emotional experience of new technology in a safety related area.

A second area where results could be generalized is in those services that have been recently outsourced by large corporations. At the moment of outsourcing, these services are often considered to be technological stable, and a readily available commodity. This research will provide insights into how those companies providing these services could innovate, and capture some of the rewards of innovation despite the price pressure coming from being considered a commodity.

Particularly to the oil and gas industry, NDT shares many characteristics with other technical services. These technical service are often grouped under the heading Asset Management (AM) or Asset Integrity Management Services. These services are now commonly performed in a risk based approach, and the performance of services is expressed in a reduction of risk and in their impact on the life cycle cost (LCC) of the asset. Figure 5 shows an overview of the Asset Management Services for a typical oil and gas asset, like a refinery or offshore production platform, showing the risk assessment methods used, the risk control instruments and the actual technical services. Results from this research are expected to also be valid for these other services.

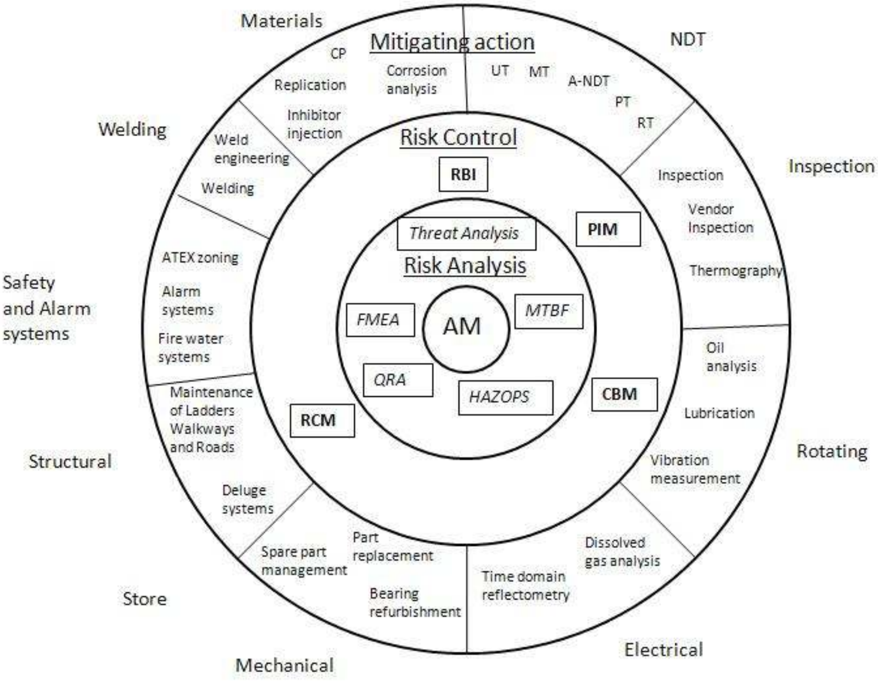

Figure 5: Asset Management (AM) broken down into the technical services typically used to reduce risk and optimize Life Cycle Cost of a plant

2.5.3. Bias towards the process industries

As a consequence of the research being performed from the perspective of a service company, the research presented in this thesis has a bias towards situations where NDT is performed by a service company. As both the level of outsourcing to service companies and the way sectors are regulated are not equal in each client sector this has an impact on the applicability of the research results.

Applus RTD is mainly active in oil refineries, transmission pipelines, chemical plants, offshore oil and gas exploration, fossil fuel power generation plants and associated construction and maintenance companies. The research results in this thesis are representative for NDT performed for these industrial sectors. These are also the sectors where NDT is most often performed as an outsourced service. Some differences may apply compared to other sectors where NDT is performed.

3. The Non-Destructive Testing Industry

Non-Destructive Testing (NDT) is defined as the set of activities one can use to assess the condition of an object or installation without destroying or damaging it. In this work it is also the set of services that are performed in order to practically perform these activities in a commercial setting, although care will be taken to use “NDT services” when this is meant.

Frost & Sullivan (2006) estimate the NDT equipment market to be around 1 Billion in total value worldwide in 2006. Commonly NDT services using this equipment are very labour intensive. Financial reporting of Applus RTD over the period 2003 to 2006 shows a contribution of 2.5% to 4% of equipment to the hourly rates. NDT companies that publish information on their results show similar figures in their annual report (MISTRAS, 2009, TEAM, 2009). Using 5% cost contribution of equipment to services as a conservative estimate, this would make the size of the NDT service market 20 Billion worldwide. This is still a small market.

The economic footprint of NDT is however much bigger than this. Dijkstra (1998) used an estimate of 20% for the share of NDT service in the total cost of making NDT inspections in a refinery or chemical plant. The other 80% go into work preparation, safety measures and other overhead. Particularly, scaffolding, insulation removal and surface preparation (cleaning) of the object are often more expensive than the inspection itself.

Another way to illustrate the extent of the economic footprint is to consider the risk involved, which the Non-Destructive tests are mitigating. Although serious accidents, like the leak in the coolant system of the Mihama nuclear plant in 2004 in Japan, are not common, they do happen, and with huge consequences. Four workers died in the named accident, and eight were exposed to radiation. The cause was corrosion of a steam pipe that could have been inspected with NDT. The risk (probability multiplied by the impact of something happening) mitigated with NDT is many times bigger than the industry itself. NACE international estimates the cost of corrosion in the USA alone at $276 Billion annually (Koch et al., 2002). This is only one of the risks for which NDT is employed.

The NDT service industry is made up of a few bigger and many small companies. This is illustrated by the information in Figure 6 which shows the companies active in the German NDT service market. Although most markets show more concentration than the German one, NDT companies with between 20 and 100 employees serving their regional call-out market are very common in most countries. In markets like France, Germany and Italy there are 100s of small local NDT service providers

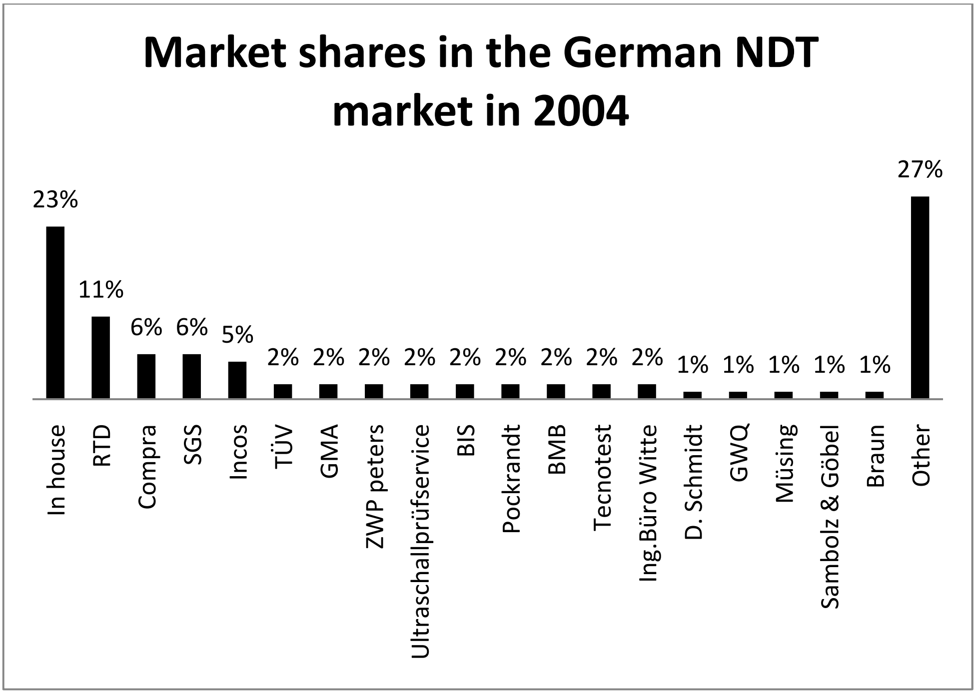

Figure 6: Market shares in the German NDT market in 2004. Sources: RTD competitor analyses, DGZfP Websites, Deutsche Akkreditierungsrat

3.1. Classification of Non-Destructive Testing

3.1.1. Classification by measurement technology

Non destructive testing is usually segmented by measuring technology. Professional literature, equipment marketing, professional training and often also departmental organization are segmented according to this division. The division is into methods, denoting the basic measurement principle, and techniques, individual ways in which the method is applied. In this sense people often talk about the big 4 NDT methods, being Radiographic Testing (RT, x-ray), Ultrasonic Testing (UT), Dye Penetrant Testing (PT) and Magnetic Particle Testing (MT). All of these methods include multiple techniques.

The division of methods in techniques is not without issues. Magnetic Flux Leakage for example, could be classed in different methods depending on an approach from historical development (Magnetic), physics (Electromagnetic) or main applications (Eddy Current). Phased Array as another example, is fundamentally an equipment technology with which all ultrasonic and eddy-current techniques could be performed, and not itself a technique. Even so, Phased Array is understood to be a technique inside the ultrasonic method by most NDT practitioners.

One of the most important NDT methods, Visual Inspection is sometimes omitted from technology lists, as very little technology is needed to see something. With the advent of digital cameras and infra-red systems this is however quickly changing. NDT has many emerging technologies. Depending on the type of division more than 50 techniques can be distinguished. The interactive knowledge base of HOIS (Burch, 2009) list 59 separate techniques (Table 4).

Virtually the same technologies are used for medical diagnostics under other names. Geophysical survey methods used for finding oil and mineral deposits is another neighbouring technology area.

3.1.2. Classification by client industry

NDT can be segmented in a number of different ways. One of the most obvious ways is by client industry. Depending on the economic and social importance of the sector, and on the amount of safety considerations associated with it, more NDT will be used. A refinery in a developed country will employ a lot more NDT than one in a developing country. Nuclear industry has long been a big source of new technology for NDT due to the availability of funds to improve safety. As mentioned, every major industrial sector uses NDT in some shape or form.

Table 4 NDT techniques as listed in the HOIS interactive knowledgebase

Method (basic physical principle)	**Techniques (specific application of the physical principle)**
Radiography	Compton backscatter Computed Radiography Gamma film radiography Gamma ray real time radiography Neutron backscatter radiography Neutron radiography Tangential Radiography X-ray film radiography X-ray real time radiography X-ray tomography
Ultrasound	Automated Pulse-Echo CHIME Corrosion Mapping C-scan imaging EMATs Flexible Arrays Long range guided waves Manual Pulse echo Manual Pulse-Echo Medium Range Guided Waves Medium Range Pulse-echo M-skip Phased Arrays Self Tandem Surface Waves Tandem Thickness Gauge ToFD
Magnetic	Magnetic Flux Leakage Magnetic Particle Inspection Magnetic Stress Measurement Remote Pipeline Inspection Magnetic Squid Magnetic Flux Leakage
Electromagnetic	Microwaves

Method (basic physical principle)	**Techniques (specific application of the physical principle)**
Eddy Current	AC Potential Drop ACFM Conventional Eddy Current EMA Array Eddy Current Low Frequency Eddy Current Pulsed Eddy Current Remote Field Eddy Current Saturation Low Frequency Eddy Current
Penetrant Inspection	Automated Penetrant Inspection Manual Penetrant Inspection
Acoustic	Acoustic Emission Impact Testing
Thermography	Passive Thermography Transient Thermography
Visual Inspection	Closed Circuit TV Visual Inspection Endoscopy Visual Inspection General and Close Visual Inspection
Optical	Holography Interferometry Profilometry Shearography Triangulation Vibration Interferometry
Leak Detection	Acoustic Leak Detection Laser Dye Leak Detection

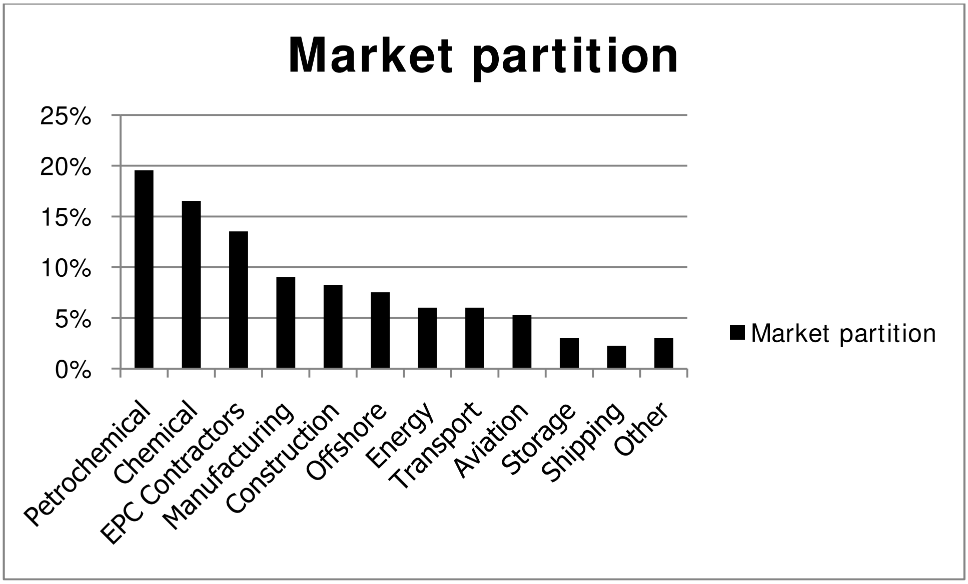

Figure 7: Market partition of the NDT service market by industrial sector. Sources: RTD market analysis and Mistras group (2009). Please note that this only lists NDT services performed by contractors and not NDT service performed as an in house activity (e.g. in the automotive industry and steel industry)

3.1.3. Classification by position in the supply chain

A third way to segment the sector is by position in the supply chain. This position has a big impact on the innovativeness due to the big difference in the power attributed to these positions. Most major industrial corporations started out having an in house quality or inspection department doing NDT. In many cases this has now been outsourced or made autonomous. Another source of NDT activity are government organizations charged with inspection. Lastly, the performance of quality control is often made a responsibility of the company doing the construction of an economic asset e.g. a process plant or a ship. Each of these configurations has a different power structure. It is very different to inspect the same structure as a government superintendent, or as a contractor of the construction company. In some cases this will show in the inspection results. It definitely has an impact on the ability to innovate.

Table 5: NDT can be classified in a number of ways. The table below shows four different classifications, based on principal function, technology, industry and position in the supply chain.

Principal functions of NDT	**Main NDT technologies**	**Industrial Area's NDT is applied in**	**Position in supply chain**
Compliance testing Safety inspection Production control Quality inspection	Visual X-ray and Gamma Ray Radiography Ultrasonic Magnetic Particle Dye penetrant Magnetic Flux Leakage Eddy Current (around many others)	Oil and Gas Chemical Power generation Nuclear Aerospace Automotive Steel Construction Rail and infrastructure Defence Water …	In house service Service provider to asset owner Sub contractor to engineering or construction contractor Government appointed supervisor

Technological thinking in the NDT industry is dominated by single techniques. Even when discussing single NDT techniques it is possible to distinguish two levels of technology. There is the inspection tool, and the application of this tool. Codes and standards clearly make this distinction, in having a separate code for the inspection equipment, and for the inspection process. For the purpose of illustration, one could say that building a car is different from driving it. Different skills are needed for building and driving. However, to know something about the car you drive certainly helps to drive it faster or safer, and to know about driving when building one helps to make a faster or safer car.

Knowing how to drive a car however still won't let you drive from A to B without additional knowledge about the road systems, traffic rules and where B actually is. In addition a car is not the only way to go from A to B, there are also planes and trains. Translated back to NDT, designing an inspection solution needs considerable knowledge about the actual problem, including metallurgy, corrosion processes, mechanical loading of the component, and what process the component is being used for. Additionally many different NDT techniques exist, and selecting the right one is not trivial.

Finally, design of NDT equipment cannot be done without underlying fundamental knowledge about measurement physics, and other fundamental scientific knowledge about electronics, mechanics, industrial design and a large number of other technical disciplines. In previous papers the relationship between these four areas of knowledge was presented as a hierarchy as shown in Figure 8.

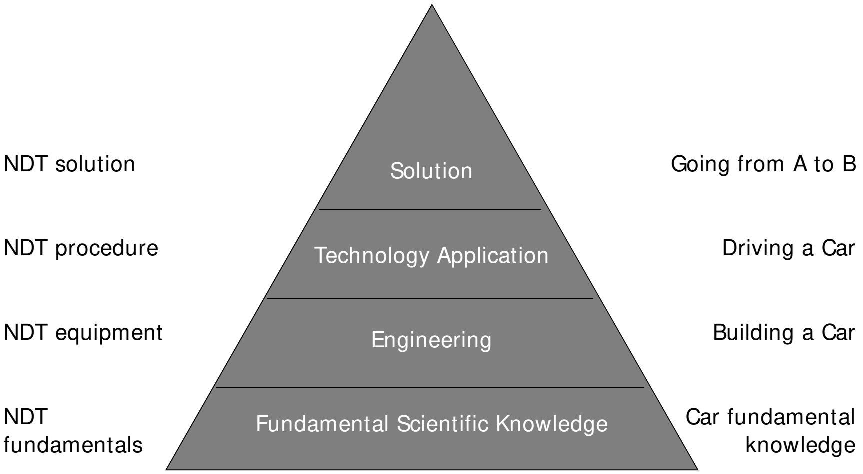

Figure 8: Hierarchy of NDT technology

3.2. Codes and standards in NDT

Although some inspection can be performed without conforming to a standard, it is essential for an NDT technology to be codified at some point. NDT uses a hierarchy of terms for inspection technologies. An NDT method is defined as a group of NDT techniques employing the same physical principles. An NDT technique is defined as a specific implementation of the physical principle. E.g. ultrasonic wall thickness reading is technique inside the ultrasonic method. In general a full NDT technique needs a number of standards. The EN structure has a standard for the NDT method, a standard for the NDT technique and a standard for the NDT equipment. Additionally there will be standardized procedures for applying the technique, and for the certification of the personnel performing the technique. Finally there will standards for the object being inspected, that may also have details about the NDT techniques being used, and a set of acceptance criteria which tells when a measurement has to be interpreted as reportable (and acceptable or rejected), or when it can be ignored. In total this results in 7 documents for a singular NDT application. Recently a large number of new NDT techniques has been developed, or is under development. It is perceived to be inevitable that the codification of these technologies is lagging behind on their development.

A well know division is to distinguish NDT in the new construction phase and NDT in the maintenance phase. In the new construction phase NDT is typically performed as quality check on the construction work, testing workmanship. Maintenance NDT is performed to detect threats to the integrity of the object. Both phases have very different requirements for the kind of defects to be found and for the extent of coverage to be reached. Defects resulting from poor workmanship are typically much smaller than defects that would cause catastrophic failure, and are therefore often only inspected for by taking samples.

In the maintenance situation, although a defect generally has to have a significant size and extend to be a danger to safety, they absolutely need to be found, requiring 100% inspection coverage. In practice most NDT practices are derived from new construction NDT. Both situations require different use of inspection technology, and different codes and standards.

3.2.1. The origin of the code and standard system

In the second half of the 18th century, industrialization had proceeded to the point that agreements were needed in industry to enable engineers to work together. Practices for making engineering drawings had to be agreed on, and some parts had to be specified to be interchangeable. The resulting Standards enable that someone can buy a bolt on one side of the country and buy the nut on the other side, and still have them fit together. Standards can be written by a government department, national and international standardization organizations like DIN and ISO and engineering societies like ASME and IEC. Some companies also independently write standards. From the oil and gas industry, the DEP (Design and Engineering Practice) specifications of Shell are an influential example.

An important driver for the importance of standards was that many countries saw a sharp increase in the number of steam boiler explosions in the 1880s. Governments of industrialized countries demanded of industry to improve its safety record. As a response standards for the manufacturing and testing of boilers and pressure vessels were developed. In the USA this task fell to the American Society of Mechanical Engineers (ASME) which developed the Boiler and Pressure Vessel

Code, today still the largest engineering standard. In Germany industry founded industry associations for inspection of pressure vessel which became the TÜV network of companies. In the Netherlands, this task was given to a government department (Dienst voor het Stoomwezen) which by now has been privatized and is part of Lloyds Register.

The difference between a code and a standard is, that adherence to a standard is voluntary, while a code has been adopted by a government body and has the force of law. In the European context another word used for standards is Norm, which is the name for standards in many European languages, and can refer to both legally binding and voluntary standards.

Currently another driver for standards development is that many insurance companies base their premiums on adherence to codes and standards.

3.2.2. The USA codes and standards system

In the USA most standards are written by engineering societies. For Non-Destructive Testing important engineering societies are the American Society of Mechanical Engineers (ASME) and API (American Petroleum institute) which write the standards for many of the products tested, the American Society for Testing and Materials (ASTM) which specifies many of the tests performed, and the American Society for Non-Destructive Testing (ASNT) which also specifies test, and regulates the personnel certification in the USA.

All of these standards organizations are affiliated with the American National Standards Institute (ANSI) which specifies the procedures for development of standards. American standards are developed in a consensus process. The committee meetings of a standards organization, which is comprised of engineers with knowledge and expertise in the particular field, have to be open to public and must have representatives from all interested parties. Any comment on technical documentation must be considered in the approval process, and any individual may appeal an action of the committee.

Many of the products tested with Non-Destructive Testing are covered by codes (standards with power of law). To be able to officially manufacture pressure vessel to the ASME Boiler and Pressure Vessel code, a company has to be audited by a National Board inspector. National Board inspectors have to be employees of an ASME accredited AIA (Authorized Inspection Agency), and follow courses at ASME. The inspector will be commissioned by the Nation Board of Boiler and Pressure Vessel Inspectors, which in most American states is the official government representative. This inspector will also verify the competence and certificates of the NDT personnel.

3.2.3. National European standards systems

In Europe almost every sovereign country has its own standards system, which is now in the process of being harmonized. The organization of these systems is different in every country and for every industry. To give some examples; the standards for pressure vessel were written by government institutes in England, while they were written by industry committees in Germany and the Netherlands. In the nuclear industry, almost all standards are government controlled.

The enforcement of standards is again something that is organized different in every country. For Pressure Vessels, in Germany this is performed by industry associations (TÜV), while in the Netherlands (Stoomwezen) and England (HSE) it was performed by government agencies. Under European harmonization, government inspection organizations have now been disbanded or privatized.

3.2.4. Harmonized standards

In 2001 the Vienna agreement came into effect, in which technical cooperation between ISO and CEN (the European Committee for Standardization) is agreed. This agreement offers a route for European standards to become worldwide standards, although this is not automatic. Combined with the harmonization of standards in the common European market, this means that in the future many more standards will have a worldwide scope. For Non-Destructive Testing, the ISO 9712 is an extension of EN 473, which specifies the personnel qualification for NDT. Another example is ISO 13847 “Petroleum and natural gas industries -- Pipeline transportation systems -- Welding of pipelines”, in which also the NDT at pipeline construction is specified.

3.3. Literature on innovation in NDT

The amount of literature on innovation in NDT is very limited. Although a lot of people write about innovation in NDT, in most cases this is to present a new product offering. Three papers were found that were trying to predict the future based on technology trends.

Cawley (2001) starts with an overview of what NDT is, and describes new technological directions. One of the main propositions of this article is that these new technologies will especially be used to find problems that cannot be found with current NDT technologies.

Kröning (Kroening et al., 2004) starts with signalling a direction technology as a whole has taken toward smaller scale, i.e. micro and nano technologies. He then shows that several technologies can be used to detect flaws at this scale, and shows how being able to detect a flaw in a semiconductor manufacturing process will help this process improve dramatically. This same feedback of improved observation/detection by NDT being the driver towards higher production quality was also found by Bouma (Bouma et al., 2002).

Scruby (2007) emphasizes the long time between research and application of a new NDT technology. He finds that the delay mainly happens in a period of disillusionment with the new technology which he attributes to commercialization beyond the technological foundation. He also shows that the technologies are developed in a dynamic relationship with the client industries. He shows several cases in which there was an alternating pattern of technology push and client pull.

No other papers were found that look at the innovation process in NDT. However, from the literature described above, and from the body of literature on NDT in general, it is clear that there is a dynamic relationship between the development of NDT technology and the development of technology in the industries that the NDT service entities are serving. Bouma (Bouma et al., 2002) for instance describes how first the developments in welding technology required more accurate NDT, and then the more accurate NDT drove an improvement in quality in welding in general.

An interesting development in this sense is the development of probabilistic risk assessment methods that are used to ensure plant integrity in petrochemical industry. These methods can only be used if sufficient quality data is available, and on the other hand, higher quality data does not add much value if it cannot be used in an integrity assessment setting developed to take advantage of it. A relationship between data quality and integrity quality is present in API standard 581 (API, 1996).

Another example of this kind of a dynamic relationship is the development of fracture mechanics methods for the evaluation of pipeline designs and the development of ultrasonic inspection methods described by Dijkstra and De Raad (2006) .

Concluding, the literature found on innovation in NDT confirms that innovation in NDT is perceived to be difficult and slow. Many authors observe an interaction process between the NDT technology and the client industries technology.

4. Cases of Technological Innovation in NDT

A number of cases of the introduction of new technology in the NDT industry will be presented. These cases have been taken from practical experience in Applus RTD. As both the technologies and histories of these cases were known to the researcher prior to the investigation presented in this thesis, these case can be considered as prior information to the research. The method of collection of the case information will be briefly described in this section. In the next paragraphs the cases will be described as a history of a technological solution to an industrial problem.

Table 6: The innovation cases in this chapter. Technologies were introduced by a number of different companies. The involvement of Applus RTD is described in the cases descriptions.

	Case	**Description**	**Stage of the technology**
1	MFL Floorscanner	Inspection of the bottom of storage tanks with the magnetic flux leakage technology	Introduced in 1980s. Technology widely used, but challenged by newer technologies
2	Rotoscan Automated Ultrasonic Testing	Inspection of pipeline girth welds with multiple ultrasonic probes and mechanized scanners	Basic technology patented in 1950s, introduced in the 1970s, breakthrough in the 1990s, now an established technology
3	RTD-INCOTEST Pulsed Eddy Current testing	Inspection of thermally insulted components with a pulsed magnetic field	Introduced in the 1990s. Gradually increasing applications, but no commercial breakthrough
4	Time of flight diffraction	Inspection of welds using a new method of imaging and interpreting ultrasonic signals	Introduced in the UK in 1970s. Gradually increasing application. Different acceptance by country
5	Guided Waves piping inspection	Inspection of inaccessible piping with ultrasonic waves that travels along the length of a pipe	Introduced in the 1990s. Gradually increasing application.
6	Computed radiography	Transition of x-ray and gamma imaging from film based to digital systems	Developed for medical applications. Introduced in NDT in the 1990s. Breakthrough happened in some areas.
7	Phased Array	Transition of ultrasonic inspection from single element transducers to multi element phased array transducers	Patented in the 1950s. Introduced in 1980s. Breakthrough happened in some sectors.

Each case will be treated in a number of steps:

- Description of the measurement technology
- History of the technology before invention
- Case history of invention, and subsequent developments
- Tabulation of events from the case listing type of activity, and the reference from which the data was gathered (will go into appendix in thesis)

Material for the cases was collected from scientific and trade literature as well as reports from joint industry collaborations. The R&D archive of Applus RTD was an important source. After the case descriptions were written, they were discussed with several people who were involved with the research for corrections and additions. For all cases both sources inside and outside of Applus RTD were used. These contact yielded a lot of new information, particularly on those issue that are generally not documented in literature, for instance why research was started. For example, discussions with Brian Spies, the inventor of RTD-INCOTEST, pointed to a strong link to corrosion issues experienced at ARCO.

4.1. Magnetic Flux Leakage (MFL) inspection for storage tank floors

4.1.1. Description of the technology

Magnetic flux leakage (MFL) is a magnetic method of Non-Destructive Testing that is used to detect corrosion and pitting in steel structures, most commonly pipelines and storage tanks. The basic principle is that a powerful magnet is used to magnetize the steel. At areas where there is corrosion or missing metal, the magnetic field "leaks" from the steel. In an MFL tool, a magnetic detector is placed between the poles of the magnet to detect the leakage field. The NDT technician interprets the recording of the leakage field to identify damaged areas and hopefully to estimate the amount of metal loss.

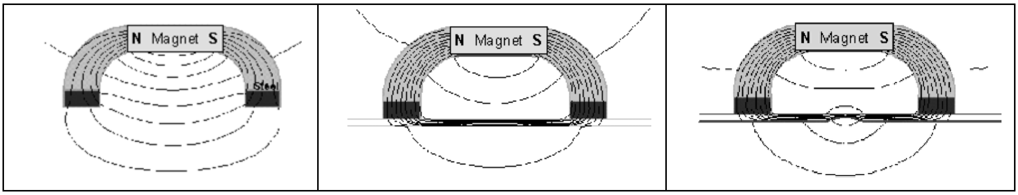

Figure 9: Field lines of the magnetic field. Left: just the magnet, Middle: magnet with an undamaged plate, Right: magnet with a damage plate.

Figure 10: Left: Prototype Floorscanner of APS inside a storage tank. Right: The Mk1a Floorscanner as it was built for commercial use

4.1.2. Technological history

From an historical point of view, the magnetic flux leakage method can be seen as an extension of the magnetic particle inspection (MPI) method (Larson, 2001). The earliest known use of magnetism to inspect an object took place as early as 1868. Cannon barrels were checked for defects by magnetizing the barrel then sliding a magnetic compass along the barrel's length. These early inspectors were able to locate flaws in the barrels by monitoring the needle of the compass. This was a form of Non-Destructive Testing but the term was not commonly used until sometime after World War I.

In 1917, William Hoke realized that magnetic particles (colored metal shavings) could be used with magnetism as a means of locating defects. Hoke discovered that a surface or subsurface flaw in a magnetized material caused the magnetic field to distort and extend beyond the part. This discovery was brought to his attention in the machine shop. He noticed that the metallic grindings from hard steel parts (held by a magnetic chuck while being ground) formed patterns on the face of the parts which corresponded to the cracks in the surface. Applying a fine ferromagnetic powder to the parts caused a build up of powder over flaws and formed a visible indication. Real industrial application was made by Victor de Forest and Foster Doane after 1929. They formed a company with the name Magnaflux in 1934, famous world-wide until today.

The magnetic flux leakage can be detected in several other ways as well, for example with a sniffer coil, or a Hall Effect sensor. The first reference of the technique as magnetic flux leakage is related to pipeline inspection. Shell Research had patented an eddy current based prototype of a system that could be sent through a pipeline for the inspection of corrosion of the pipe wall in 1963. A license to this technology was sold to Tuboscope who changed the technology to MFL, in line with their existing tool for inspection of drill pipes. Commercial operation was started in 1964.

4.1.3. Case History

In 1982 the European Seveso directive was passed (EEC, 1982). This directive calls for the owner of a storage tank to take actions to prevent spills and pollution. These owners were now obliged to collect data for safe operation of their installations, and have mitigation and emergency plans. This meant that the industry now had to look for an effective way to inspect for corrosion on storage tank floors. Corrosion of storage tank bottoms had been known to be an integrity issue for some time, but no effective solution for testing the tank bottom for flaws had been found (ref. interview 1 of this thesis).

Against this background, BP international and UK DTI (department of trade and industry) funded a program at AEA (Atomic Energy Authority) Harwell lab to find a solution to storage tank bottom corrosion in 1983 (Saunderson, 1988). As a first step the dimensions of the defect to be found were determined. The result was that the detection target was set to be a 120deg conical hole penetrating 3mm into the plate, on the side opposite to the side being scanned. This shape is still today used as the calibration and reference standard at Applus RTD.

Several technologies were tried, against a set of requirements. Standard Eddy Current testing did not penetrate deep enough, and low frequency eddy current made measurements to slow. The project team finally arrived at a technique where the plate was magnetized with a DC magnet field. The technique was called MFE, magnetic flux exclusion. It is unknown if the research team was aware of the existence of MFL technology in the pigging industry. The project team reports that they arrived at MFE by going to the low frequency limit of eddy-current testing.

Successful results motivated the partners to finance further development of the method into practical NDT equipment. RTD Pantatron was invited to participate based on their reputation as an inspection company with wide manufacturing and inspection service experience. RTD Pantatron was granted a license to offer a tank-floor inspection service using the Harwell/BP MFE system. RTD Pantatron started operating the system in 1988.

The United States had several incidents involving storage tanks around this time. Cornell and Baker (2002) list 3 incidents in 1987 and 1988 that were a specific driver for the development of the API 653 standard (API, 1991). This code constituted a specific regulation to inspect the storage tank bottom, as a failure of the bottom had been the cause of one of these incidents. Many oil companies around the world and a number of states and nations use the API code as a mandatory regulation. The result was that there was now a market that had to buy an inspection solution.

Around this time both the Harwell laboratory and the RTD Pantatron went through a period of change. The Harwell laboratory was commercialized and thereafter named APS (AEA petroleum services), and RTD closed down Pantatron. APS and the RTD R&D department in Rotterdam agreed on further developing the system, and did so in a joint research program. This program started in 1989 and yielded the Mk1a Floorscanner, of which 24 were built. In this project a lot of attention was paid to making the system user friendly, e.g. being transportable through a 20 inch man hole into the tank, rugged enough for this kind of handling, having consistent procedures, and fool proof for field personnel.

Based on the success of the cooperation, a new project was started to extend the system to thicker floor plates. A European research grand was received for this project. APS development and later also produced the Mk2 scanner based on this research. This scanner was never adopted by RTD as many of the user friendliness features were undone by addition of new features by APS (Rundberg, 2009).

The Mk1a system was a big success in the market, as it was a first viable way to inspect storage tank floors. Several RTD crews travelled Europe to apply the technology at very good rates, compared to normal NDT services. Also a number of units were sold or leased to other companies.

In the middle of the 1990s several competitor systems came to the market. Rosen NDT borrowed sensor technology from their pigging systems to build a competitor system. MFE enterprises was founded in 1994 by Bill Duke and Dave Amos, who had brought the MFE technology from the UK to the USA. Silverwing in the UK, previously a trading company, started development their own versions of the Floorscanner in 1992, in cooperation with Swansea University.

The limitations of the MFL system motivated RTD to look for technology to inspect thicker tank floors, in particular for storage tanks in Japan which have far thicker floor to withstand earthquakes. This led to the development of the SLOFEC tankfloor system with Kontrolltechnik in 1996-1998. Subsequently the MFL technology was not maintained and the MFL floorscanners are slowly being phased out. A small number of Mk1a floorscanners are still in use today. Interestingly many operators have expressed that the Mk1a floorscanner was the best ever built from a user friendliness point of view.

4.1.4. Case analyses table

Date	Actor Institution	Countries involved	Event	Type of activity	Reference
1982	European Economic Community	EEC countries	Seveso directive	Legislation	Seveso-I (EEC, 1982)
1983	AEA BP	UK	Research project	Fundamental Research	(Saunderson, 1988)
1988	API	USA	Tank incidents	Industrial incident	(Cornell and Baker, 2002)
1989	AEA RTD	UK	Floorscanner project	Equipment development	RTD report X-2086.1994 (Dijkstra and Raad, 1994)
1991	API	USA	API 653 standard	Standardization	API 653 (API, 1991)
1991	Sonomatic RTD	UK Netherlands	Initial service offering	Service offering	(Rundberg, 2009)
1992	AEA RTD	Netherlands UK	EU Research project	Applied research	RTD report X-2086.1994 (Dijkstra and Raad, 1994)
1994	Silverwing MFE-enterprises	UK USA	Competitors come to the market	Service offering	MFE website (Duke, 2006), (Romero Ramirez, 2008)
1998	RTD Kontroll-technik	Netherlands, Germany	Next generation research	Equipment development	Firsthand author experience

4.2. Rotoscan® Automated Ultrasonic Testing of pipeline girthwelds

4.2.1. Description of the technology

Inspection of welds with ultrasound is based on the idea that the propagation of sound of sufficiently high frequency can be approximated as a beam shining through the material, and reflecting back from flaws, not unlike shining the beam of a flashlight on an object in the dark. (Cases where this approximation does not hold will be treated in later sections, most notable section 4.4 on Time of Flight Diffraction). The ultrasonic probe traditionally generates a fixed beam shape that is characterized by the frequency of the sound, the shape of the beam and the angle at which it exits the probe on the targeted material.

Welds are typically inspected with an angle beam probe from the sides of the weld. The width of the sound beam is typically small compared to the thickness of the material, having the consequence that the probe has to be moved to and from the weld in order to cover the whole weld volume.

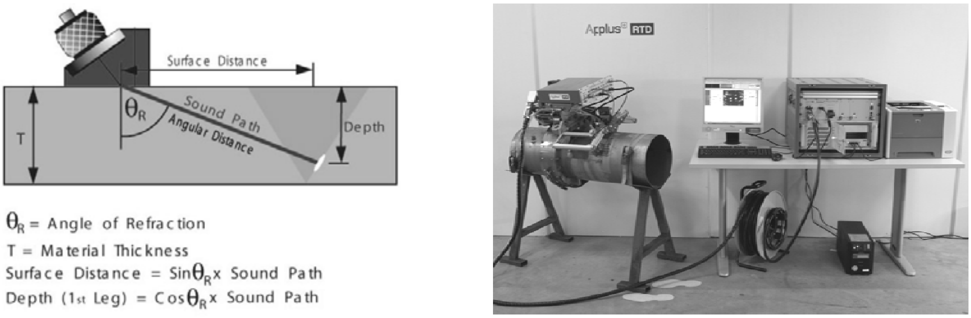

Figure 11: Left: a diagram of ultrasonic weld inspection with an angle beam probe. Right: Rotoscan equipment built in 2008

Pipeline Automated Ultrasonic Testing (AUT) equipment, like the RTD Rotoscan uses multiple probes, or a Phased Array probe with an adjustable beam, to cover the thickness of the material and furthermore consist of a guide band, a manipulator to move the probes along the band, and the equipment to read out and record the inspection results. The system also incorporates features for it to be operated self contained in the field, in conditions ranging from Arctic to Tropical to Offshore pipe lay barges.

4.2.2. Technological history

Sound and the physics involved with its propagation have been studied since ancient times, going back to the times of Pythagoras (Woo, 1998, O'Brien, 1998, Dijkstra, 2006). The use of sound for detecting objects started mostly in shipping.

In the early 1900s lightships were outfitted with underwater gongs, the sound of which was picked up with hydrophones, to supplement foghorns. After the Titanic sunk in 1912, one of the technologies proposed to prevent this kind of accident to happen again was using an early sonar system to detect icebergs.

Prior to World War II, sonar, the technique of sending sound waves through water and observing the returning echoes to characterize submerged objects, inspired early ultrasound investigators to explore ways to apply the concept to medical diagnosis. In 1929 and 1935, Sokolov studied the use of ultrasonic waves in detecting metal objects. Mulhauser, in 1931, obtained a patent for using ultrasonic waves, using two transducers to detect flaws in solids. This was still based on the use of two separate transducers in through-transmission. It was the development of radar instrumentation that ultimately led to the ultrasonic pulse-echo technique: Floyd Firestone built his “Reflectoscope” around 1940 in the USA. This modified radar instrument was able to detect flaws in steel using a reflection technique. Donald Sproule presented a similar device in the UK around the same time. These people had no knowledge of each other, as war time had them work in strict secrecy; not even their patent applications were published.

Sproule and Firestone found industrial partners for their instruments: Kelvin-Hughes and Sperry Inc. Kelvin-Hughes produced their first commercial machine in the 1940s (RTD bought 10 systems in 1946). In Germany two persons received information about the Firestone-Sperry-Reflectoscope in 1949 in technical literature: Josef Krautkrämer in Cologne and Karl Deutsch in Wuppertal. Both independently started developments. Josef Krautkrämer and his brother Herbert were physicists, working in the field of oscilloscopes. They could develop ultrasonic instruments alone. Karl Deutsch, a mechanical engineer teamed up with an electronic engineer who had got some technical experience in radar-technique during the war. Within a year both companies presented their Ultrasonic testing-flaw-detectors, starting companies still existing today. Krautkrämer became world-wide market-leader in the early 60s and has kept this position until today. Besides Karl Deutsch new names came up: Nukem in Germany, Panametrics and Staveley in USA, Sonatest and Sonomatic in the UK, Gilardoni in Italy and Mitsubishi in Japan. Krautkrämer was bought by AGFA NDT, which was later itself bought by GE inspection technology, which now uses Krautkrämer as one of its core brands.

Until the early 50s Ultrasonic inspection was done by moving a probe by hand. Weld inspection is customarily done with an angle beam probe which is simultaneously move to and from and along the weld; a movement along 2 axis. One of the obvious ways to improve this was mechanization, and the first attempts were based on making a 2 axis movement with a manipulator. The insight of Arie de Sterke was that the same result could be achieved much faster by using multiple probes and moving them mechanically along one axis. This was the start of the zone discrimination principle.

4.2.3. Case History

The development of the Rotoscan systems of Applus RTD and comparable systems of other suppliers has been elaborately described in 2 books (Ginzel, 2006, Raad de, 2007) and several papers (Moles and Fortier, 2007, Ginzel, 2000, Dijkstra and de Raad, 2006). The development started soon after ultrasonic equipment had come to the normal market. Already in 1952 Arie de Sterke of Applus RTD filed the patent for the zone discrimination inspection approach (Sterke de, 1952). In this approach a weld is divided into several zones, parallel to the material surface. Each of these zones will have a separate ultrasonic probe, generating a beam that is aimed at this zone, and will reflect back sound if a defect is present. The significance of this approach is that the probes will now be able to be moved in a linear fashion along the weld, while the combination of beams ensures that the entire weld volume is inspected in one pass. This movement can be mechanized very easily, while until that time the customary method was to let one probe make a meander like movement which is much harder to mechanize, and results in a slower inspection.

This however is not the only invention that makes up a girth weld AUT (Automated Ultrasonic Testing) system. Over the years, the system was continuously improved. For details please refer to the books mentioned above. Phased Array probes and ToFD will also be treated as a separate innovation in this thesis. Important improvements were:

- Recording of the signals on multichannel paper charts, and later computers
- Incorporation of tandem probes, ensuring perpendicular insonofication of the flaw
- Invention of several different display methods e.g. go-nogo and color mapping
- Adaptation to arctic conditions
- Adaptation of the system to the offshore environment of pipeline lay barges
- Adaptation of the system to scan recently welded (i.e. very hot) materials
- Development of standardized reference plates
- Incorporation of the ToFD inspection technique (see also section 4.4)
- Development of several methods for automatic interpretation of the signals

- Development of a several manipulators, the most important one enabling the use of one guide band for both welding equipment and ultrasonic system
- Development of underwater systems for inspecting sub-marine pipelines
- Incorporation of Phased Array probes (see also section 4.7)
- Incorporation of automatic routines for flaw height sizing based on signal amplitude, using sizing curves

At RTD alone, a development team of at least 10 people has been working on improvement of the system for at least 30 consecutive years (i.e. 300 man years of development work). These developments are continuing to date, for example new inventions for the inspection of corrosion resistant alloy layers (van der Ent et al., 2007), and new ultrasonic imaging methods (Pörtzgen, 2007).

The first multi-zone/multi-probe application was a portable system for inspection of longitudinal pipe welds at pipe insulation yards prior to coating, soon followed by stationary systems for use in pipe mills. It was realized that this concept was also suitable for girth weld inspection by portable a system which became the Rotoscan in 1959. However, the system was ahead of its time and shelved for a number of years. Around 1965 the multi-zone concept was further developed for use on nuclear components. Euratom granted RTD a contract to develop and evaluate inspection methods for thick wall pressure vessels of nuclear reactors. This in turn resulted in a contract from Mitsubishi Japan to develop and deliver a system to inspect nuclear pressure vessels during production and very important for RTD a long term contract with Siemens/KWU. In addition to the mutual development with Siemens/KWU of ultrasonic methods for pre-service and in-service inspection in 1972 RTD in cooperation with BAM institute became involved in inspection work of the Borssele Nuclear plant.

The second generation Rotoscan was developed with partners Shell KSLA and BGC, with a particular interest in pipeline lay barge applications. The first offshore application was for SAIPEM in 1978. Commercial cross country application was initiated by AGTL (now NOVA) in Canada. Commercial breakthrough happened in 1989 with TCPL as a launching partner, but was also important in getting the Canadian national codes adapted for the use of the system. Finally a lot of the further development was co-funded by AGA (which later merged into PRCI) and Nederlandse Gasunie. These partners also encouraged and funded the entrance and development of competitor systems, most notably Guardian-Hyalog (now Shaw pipeline systems) starting 1991.(Moles and Fortier, 2007)

Just as important as the technology was the development of the organization around the inspection system. The team at Applus RTD that originally got the task of running the Rotoscan system was a mix of people coming from the R&D department, and a number of people coming from the department that had done the inspection of nuclear plants when they were constructed, mostly in Germany. The work in Germany had these people work side by side with academically schooled people from Siemens Kraftwerk Union and BAM (Bündes Anstalt für Material Forschung und Prüfung), something that had not been realized before in RTD (see Frits Dijkstra interview later in this thesis for details). Also, these people were accustomed to be away from home for a project of many months duration in another country, with a very elaborate equipment setup. Inspection projects often have unexpected events, and the lead technician going on such a project has to be exceptionally resourceful both technologically and in communicating with clients and regulators. Imagine finding an unexpected signal while inspecting a weld in a nuclear power plant.

This translated into a structure where the inspection systems are build up centrally and shipped around the world, in a strictly project based organization. The project leader doubles as lead technician. These are often colourful people (the word cowboy is often used in this context) with a long international career and are highly sought after in the market. The rest of RTD worked in an environment where people operate from a regional office and are called out to a refinery or work site individually for the day’s work, supervised much more closely. These two ways of organizing did not always go along well. RTD has done virtually no Rotoscan projects in countries where there was also a regional office organization. A number of spinout companies were founded by ex-RTD personnel in the girth weld AUT market. Examples are UT quality and Weldsonix.

It is interesting to note that all the companies that have become successful at running girth weld AUT equipment adopted this same kind of organization, with important aspects being an in house developed equipment, with direct support of a development team with engineers with higher education and a project based operation. Prime examples are Shaw pipeline services, Saipem NDT (with support from R/Dtech) and UT quality (with support from GE). Several other companies, like Vinçotte and SGS Gottfeld, that did develop a system, never became big players in the girth weld AUT market. It seems reasonable to assume that since these companies were also mainly organized as a regional office operation, they did not realize the right environment for this type of projects.

The commercial success of the Rotoscan and other AUT systems came after intensive cooperation with both the future pipeline operators and the companies building the pipelines. The drivers for these companies to cooperate however were very different. The pipeline owners were interested in building pipelines of high tensile strength steels. The advantage of these steels is that the overall weight of the pipeline goes down, because less wall thickness is needed to get the required pressure rating. This does however require new welding methods, in this case GMAW welding. The flaws present in these welds are very hard to find with radiography, and thus ultrasonic testing was brought in. The pipeline owners had to overcome, that these systems were not allowed under regulatory systems, and early adopters had to convince regulators to allow them. It is therefore not surprising that the first applications were in situations where regulators and pipeline owners were already working closely together, e.g. TCPL and Gasunie.

The driver of the pipeline builders was mainly operational. The total cycling time of a welding process is the main driver of the speed at which a pipeline can be laid from an offshore pipe laying vessel. These massive vessels are expensive to operate. Bringing the cycle time down results in a big cost saving. Radiographic films have to be processed and interpreted after the exposure has been made, while ultrasonic testing can be interpreted virtually real time. Effective cycle times of 3 minutes per weld have been realized with AUT, against around 15 minutes for radiography. This advantage did not become significant until welding processes had become sufficiently advanced that they also had fast cycle times.

An interesting paradox emerges around using new inspection technology. As can be seen in the PISC and NIL thin plate reports, advanced AUT will detect significantly more defects than radiography. Furthermore, because it is new technology, the results will be scrutinized much more thoroughly. As a result, when using a “better” technology, a construction company will incur significantly more cost for repairing rejected welds. The first response of a client will usually be, “those welds should have been flaw free to start with”. While it would be unfair to say that the construction companies were afraid that too many flaws would be found, there was an expressed fear of getting many rejected welds, from false calls and oversized defects, i.e. a fear of a faulty inspection technology. When the cost advantage of being able to produce faster is not present, it is almost always financially beneficial, and organizationally easier to stick with the old, flaw missing, technology. This paradox has been partly overcome by introducing ECA based acceptance criterions. These criterions require even more stringent inspection but will then allow for the defect being assessed on its impact on the strength of the weld, and left in the weld when not significant. ECA based acceptance criterions opened the door for the breakthrough of AUT, but also added another layer of technology, assessments and organization, as the ECA process requires a significant number of trial measurement on artificial flaws.

4.2.4. Case analyses table

Date	Actor Institution	Countries involved	Event	Type of activity	Reference
1952	RTD	Netherlands	Patent award zonal concept	Patenting	(Raad de, 2007, Dijkstra and de Raad, 2006)
1956	RTD	Netherlands	First stationairy AUT system for long seams	Prototyping	(Raad de, 2007, Dijkstra and de Raad, 2006)
1959	RTD	Netherlands	First circ. Prototype Rotoscan	Prototyping	(Raad de, 2007, Dijkstra and de Raad, 2006)
1973	RTD / KWU / BAM	Netherlands, Germany	Inspection of Borssele plant		
1976-1978	RTD / Shell KSLA / BGC	Netherlands	Development projects	Development	
1978	RTD / SAIPEM	Netherlands, Italy	Test on SAIPEM Castoro Sei	Prototype trial	(Raad de, 2007, Dijkstra and de Raad, 2006)
1978	RTD / NOVA	Netherlands, Canada	Involvement with NOVA / AGTL starts	Prototype trial	(Raad de, 2007, Dijkstra and de Raad, 2006)
1979	RTD / NOVA	Netherlands, Canada	Trial jobs alongside X-ray inspection	Prototype trial	(Raad de, 2007, Dijkstra and de Raad, 2006)
1980	RTD	Netherlands, Canada	Introduction of Z-shaped reference plate	Reference defect	(Raad de, 2007, Dijkstra and de Raad, 2006)
1989	RTD	Netherlands, Canada	Commercial introduction	Product launch	(Raad de, 2007, Dijkstra and de Raad, 2006)
1990	SGS / Vinçotte / R/D tech	Belgium, Canada, Germany	Development of competitor systems by SGS and R/Dtech / Vinçotte	Product development	(Moles and Fortier, 2007)
1991	Shaw / NOVA	Canada/USA	Development of competitor system by Shaw pipeline systems	Product development	(Moles and Fortier, 2007)
1993	RTD / TCPL	Netherlands, Canada	Mapping channels introduced	Product improvement	(Moles and Fortier, 2007)
1994	RTD / NGU	Netherlands	Inclusion of ToFD in first	Product improvement	(Raad de, 2007, Dijkstra and de

			work for NGU		Raad, 2006)
1994	CSA	Canada	Formal adaptation of CSA Z662 for AUT with ECA	Standard development	(Moles and Fortier, 2007)
1996	RTD / SAIPEM	Netherlands, Italy	First offshore job	Commercial use	(Raad de, 2007, Dijkstra and de Raad, 2006)
1996	RTD / AGA	Worldwide	Evaluation projects for AGA/PRCI	Evaluation project	(Raad de, 2007, Dijkstra and de Raad, 2006)
1996	Weldsonix	Canada	Introduction of Weldsonix competitor system	Product launch	(Moles and Fortier, 2007)
1998	ASTM	USA	ASTM E 1961	Standard development	
1998	R/D tech	Canada	First phased array system by R/D tech	Product launch	(Moles and Fortier, 2007)
1999	API	Worldwide	API 1104 - 19th ed	Standard development	(Raad de, 2007, Dijkstra and de Raad, 2006)
2000	DNV	Worldwide - offshore	DNV OS F101	Standard development	(Raad de, 2007, Dijkstra and de Raad, 2006)
2001	RTD / Technology Design	UK / Netherlands	First Phased Array system at RTD	Product development	Firsthand author experience
2002	RTD / TU Delft	Netherlands	Start of IWEX research	Next generation technology	Firsthand author experience
2008	RTD	Netherlands /USA	Large scale Phased Array system production	Product diffusion	Firsthand author experience

4.3. RTD-INCOTEST® testing of insulated components

4.3.1. Description of the technology

The RTD-INCOTEST (an acronym for INsulated COmponent TESTing) probe is used to create a pulsed magnetic field that penetrates through any non-magnetic material between the probe and the steel object under investigation. This varying magnetic field will induce eddy currents at the surface of the object. The diffusive behaviour of these eddy currents is related to the material properties and the wall thickness of the object. The eddy current signal is processed and compared to a reference signal. This eliminates the material properties and the result is a reading for the average wall thickness within the magnetic field area. Detailed descriptions of the technology can be found in the original patents of Lara (1989) and Spies (1989), and in several papers by developers of INCOTEST at Applus RTD (Robers and Scottini, 2002) and developers of the PEC (Pulsed Eddy Current) system of Shell Research (Crouzen and Munns, 2006).

Figure 12: RTD-INCOTEST equipment

The area over which the measurement is taken is referred to as 'the footprint'. Probe design is such that the magnetic field focuses to a minimal area at the surface of the object. The result of the INCOTEST measurement is an average reading over this area, which makes the tool suitable for rapid detection of corrosion areas, like Corrosion Under Insulation (CUI). Detection of more irregular corrosion types like pitting is not reliable with this tool.

Although originally developed for CUI detection INCOTEST is well suited to detect internal erosion like Flow Accelerated Corrosion, again without removal of the insulation. Also detection of corrosion through coatings, concrete and marine growth were identified as good applications, as well as surveying heavily corroded pipes on which grinding (needed for UT measurements) is not safe. New applications are steadily emerging.

The non-contact characteristic makes it possible to detect corrosion on high temperature surfaces without many probe adaptations. A simple thermal shield protects the probe from extreme temperatures allowing measurements up to a component temperature of +500 ºC. Above this temperature the reduction of the magnetic permeability in the object prohibits the use of INCOTEST.

4.3.2. Technological history

Eddy currents were discovered as a result of experiments in the field of Electromagnetism in the middle of the 19th century. In 1831 Michael Faraday had discovered electromagnetic induction; if a current passes through a conductor, a current will also start to run through another conductor if it is near, and has a closed path through which currents can run.

French physicist Leon Foucault expanded on this in 1851 when he showed that this closed circuit does not need to be a wire, but can also be a copper disk. He showed this by moving the copper disk through a strong magnetic field. He called the currents that are thus created eddy currents.

In 1879 David Hughes, demonstrated that the impedance of a coil changes when placed near different material, in particular metals with different conductivity and permeability (Waidelich, 1970). However, it was not until the Second World War that these developments in the transmitting and receiving of electromagnetic waves were put to practical use for materials testing.

Starting in 1933 Professor Friedrich Förster adapted eddy current technology to industrial use, developing instruments for measuring conductivity and for sorting mixed-up ferrous components (McGonnagle, 1961). Förster founded his own company that continues to this day. Other companies soon followed. Eddy current is now an established NDT method.

The common eddy current instrument uses a sine wave excitation signal to a drive coil. The complex impedance of this coil is measured, sometimes in combination with a measurement on a reference coil, and this coil is moved over the object to be inspected. A flaw will show up as a change in impedance.

Already early in the development of eddy currents the use of a pulse signal instead of a sinusoidal signal was considered. The advantages are that this signal is an excitation on a broad frequency band, compared to a narrow frequency band for the traditional method. This will potentially yield a bigger penetration depth of the signal, and the ability to locate defects by using time-of-flight techniques. Pioneering research was done at the Argonne National Laboratory in the USA in the 1950s (Waidelich, 1955). Early systems did not achieve the performance of normal eddy current systems however, with the most serious issue being a lack of signal to noise ration, and a high susceptibility to outside electronic interference. Research was aimed at improving signal to noise ratio and resolution.

The early Pulsed Eddy Current systems found their way into niche applications, especially those where contact with the object to be inspected is impossible or difficult. Pulsed Eddy Current was applied to characterization of irradiated fuel rods, measurement of the thickness of hot steel plates during rolling and the measurement of coating and cladding thickness, starting in the 50s and continuing until today, for example at Iowa state university (Johnson et al., 2003) and at Huddersfield university and TWI (Tian and Sophian, 2005). GE is marketing a Pulsed Eddy Current system under the name Pulsec. The INCOTEST technology however took a different route that resulted in a system that is very different from these Pulsed Eddy Current developments.

4.3.3. Case History

In 1968 the Atlantic Ridgefield Company (ARCO) found oil in Prudhoe Bay on the north slope of Alaska. The same year work was begun to lay the legal foundation for oil production and the building of a pipeline across Alaska. From the start this project faced opposition from both the indigenous population and environmentalists (Coates, 1991).

From a corrosion management point of view, the Prudhoe Bay field offers a unique challenge. During the summer snow and ice melt, but as the permafrost underneath remains frozen, water does not drain away. The result is a very high humidity environment. This combined with insulated oil pipelines that are kept at elevated temperatures to prevent the oil from solidifying, makes for an ideal environment for external corrosion to develop (Shepard, 2001). The ARCO patents explicitly refer to the Prudhoe Bay environment (Spies, 1989, Lara, 1989). Please note that the patents are issued only 2 months after the biggest oil spill in the North American history, the Exxon Valdez disaster of 24 March 1989, bearing the name of ARCOs partner Exxon in, and carrying oil from, the Prudhoe Bay field. ARCO merged with BP in 1999. In 2006 the Prudhoe field had big oil spill incident. Corrosion Under Insulation (CUI) was an important factor in this incident.

The scientist that went to work to develop technology for these issues took their inspiration from Geophysics, the background of Brian Spies (Romig, 2006). The method of transient electromagnetic sounding was modified for use on insulated components. He initiated the rental of a system that he had developed in a previous job, and connected it to an experimental coil that he had constructed in his PhD research, many years earlier. The resulting system was named TEMP (Transient ElectroMagnetic Probe). Spies received the highest technical commendation at ARCO for his invention.

The development resulted in a system that has technical characteristics that are exactly opposite to the direction that the older Pulsed Eddy Current systems had taken; with a much lower resolution as opposed to older Pulsed Eddy Current techniques which had all looked for higher resolution. By doing this, a dramatically bigger penetration depth of the signals was reached measuring centimetres instead of millimetres, and a dramatically higher standoff distance capability, going from millimetres to tens of centimetres.

After the development had reached a point where the system had been demonstrated, ARCO tried to find a commercialization partner, but at first NDT companies showed little interest. In 1990 prof. Kröning of IZFP alerted Jan de Raad of RTD to the ARCO system (Kröning, 2006). RTD approached Shell research, who themselves had also had contact with ARCO, for a joint research program. ARCO then supplied the two companies with a reference system (Du Pon et al., 1999). Both RTD and Shell performed some research. Shell did not want to take a license on the technology. RTD then proceeded to take a worldwide exclusive license on the technology in 1995, and started marketing its INCOTEST system both for leasing and services in the same year after a considerable improvement program. Shell entered the market some time later with its PEC system, claiming that it was based on different technology. The result was a patent infringement case in 1998 which ARCO and RTD won. Shell appealed and cancelled a number of contracts with RTD, at which point RTD initiated a settlement because it could no longer afford to further alienate its biggest customer. The settlement included Shell taking a license on the ARCO technology.

Both the INCOTEST and PEC system were used for a number of applications. The INCOTEST system was used for finding Flow Accelerated Corrosions (Stalenhoef and Raad, 1998) in nuclear plants which got a lot of interest after the Mihama nuclear disaster, and finding corrosion through fire proofing on sphere tanks and marine growth on port structures (Robers and Scottini, 2002). PEC was used for finding carbon steel material in austenitic welds (Kronemeijer et al., 2003), finding the deepest point of corrosion patches (Crouzen et al., 2006) and finding cracks in road bridges (Looijer, 2004).

The biggest success of INCOTEST was in France. A small company called PS&I had leased several INCOTEST systems and started offering them for inspection of sphere tank legs. In case of a fire these legs may collapse. To prevent this sphere tank legs are protected with a concrete fire proofing. Under this fire proofing corrosion may occur out of sight. Total had an incident where this kind of corrosion caused a sphere tank collapse when it was being hydro tested (Pecquois, 2002). PS&I managed to bring the method under the attention of regulators and proceeded in inspecting a large number of sphere tanks in France starting in 2002.

Further commercial success has been with small NDT companies that leased INCOTEST equipment from Applus RTD and offered specialized services. Beside PS&I notable ones are Can offshore, PNDT and Q pro. Between 2002 and 2006 both PS&I and PNDT were acquired by Applus RTD, while Q pro was acquired by Shaw Pipeline services, one of RTD's main competitors in girth weld inspection.

Within RTD the operation of INCOTEST has been problematic. Beside tension around technical issues, a lot of the operational managers were opposed to licensing the technologies to other service companies, whereas the business development department pointed out that more money was being made with leasing equipment than with the operational services. Eventually this argument was won by the operational departments, and all leasing of equipment was terminated.

The technical issues are related to the fact that INCOTEST does not directly measure wall thickness, but instead gives an indication of the average thickness over a wide area (the footprint). This may miss the deepest point of corrosion, which is what clients are interested in. It is very tempting to think of INCOTEST as measuring minimum wall thickness through insulation, and this has led to a lot of misunderstandings with clients. On more than one occasion severe defects were found in objects that had just been inspected with INCOTEST, and that had not been indicated in the testing report. Another issue is that most types of insulation are protected by metal sheeting. Some of these types of sheeting prevent taking an INCOTEST reading. Most clients however are not sure which type of sheeting they have, leading to disappointments when a crew comes back from the field, and reports that the measurements failed.

Given the tension around INCOTEST it is not surprising that very little development budget was available for doing further development on INCOTEST. Even though research performed by Dolabdjian et al. (Dolabdjian et al., 2006) was very well received in the academic community, this program was cancelled for not being a priority project. Several other programs also suffered from lack of attention and understaffing. Between 2002 and 2011 the R&D department of Applus RTD had no permanent staff working on the application development of INCOTEST.

The market for PEC and INCOTEST is still growing and the systems are still being improved. A second generation of INCOTEST equipment was released in 2003 and a third generation was released in 2010. A dramatic commercial breakthrough however did not happen.

4.3.4. Case analyses table

Date	Actor Institution	Countries involved	Event	Type of activity	Reference
1968	ARCO	USA	Oil find in Prudhoe bay	News event	
1987	ARCO	USA	Patent filed	Patent	(Spies, 1989)
1989	Exxon	USA	Exxon Valdez disaster	Disaster	
1989	ARCO	USA	Patent awarded	Patent	(Spies, 1989)
1990	IZFP, RTD, ARCO	Germany, Netherlands, USA	RTD learns about TEMP		(Kröning, 2006)
1991	RTD, Shell, ARCO	Netherlands	RTD and Shell agree to study TEMP	Cooperation agreement	(Du Pon et al., 1999)
1995	RTD, ARCO	Netherlands, USA	RTD takes a license	Technology licensing	(Du Pon et al., 1999)
1995	RTD	Worldwide	INCOTEST system introduction	Product launch	
1995	Shell	Worldwide	PEC system introduction	Product launch	
1998	RTD, ARCO, Shell	Netherlands, USA	Patent infringement case	Court case	(Du Pon et al., 1999)
2002	RTD, Shell, ARCO	Netherlands, USA	Patent case is settled	Court case	
2002	RTD, PS&I	France, Korea	Sphere tank legs inspection	Standard development	

4.4. Time of Flight Diffraction (ToFD) inspection of welds

4.4.1. Description of the technology

In the Time of Flight Diffraction (ToFD) technique, two probes are used either side of the flaw, and the time of arrival of pulses diffracted from the extremities of the flaw are used to detect and size it, as shown in this diagram.

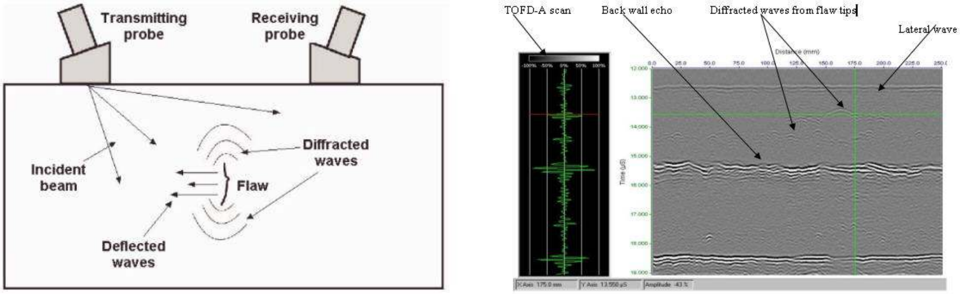

Figure 13: Left: typical drawing used to explain ToFD. Right: The data presentation of ToFD

Generally the probe beam widths are very broad in ToFD, so that a wide range of depths can be covered with a single probe separation. For wall thicknesses up to several centimetres a single probe separation can be used to cover the full range of depths from just below the frontwall to the backwall. For thicker sections, a number of different transmitter/receiver probe separations are needed to cover the full range of depths from the inspection surface to the backwall.

Signals indicating the front surface (known as the "lateral" wave) and the backwall are also generally present in the inspection data, and can be used to calibrate the measured arrival times of the signals from defects.

ToFD inspection is generally carried out in the form of line scans of the two probes, made with constant separation. A computer-based ultrasonic recording and imaging system is used to digitize and store the unrectified RF waveform data, which is then displayed in B-scan or D-scan format.

ToFD was originally developed for detecting and sizing cracks by means of the signals diffracted from the crack tips. Buried cracks as well as frontwall and backwall breaking cracks can be detected and sized, although the resolution of ToFD is poor very close to the frontwall.

ToFD is also used for applications which do not involve cracks or diffraction, including corrosion mapping and inspection of weld root erosion where the ultrasound scatters or reflects from the points on the defect closest to the inspection surface.

The key feature of ToFD is the use of measurement of arrival times to determine the through-wall extent or depth of flaws - a process which has been shown to be inherently more accurate than those methods based on amplitude. Accuracies are typically ±1mm or better in well controlled cases.

4.4.2. Technological history

The start of Ultrasonic testing was treated in section 4.2. One of the developments not treated in that section was, that during the Second World War, the electronics needed for both radar and ultrasound detection was improved considerable(O'Brien, 1998). Gradually all components became better and thus also the quality of the data obtained. These improvements were not only in electronics, but also in probes and manipulators. Newer piezoelectric ceramics, which are needed for the generation and detection of ultrasound, such as barium Titanate, PZT, Lead Metaniobate and PVDF (Woo, 1998) were discovered. This led to the observation of signals that did not correspond to normal reflections. These diffraction signals were to become the starting point for the development of ToFD.

4.4.3. Case History

Maurice Silk started research into ToFD at the NDT Centre, Harwell Laboratory (UKAEA) in 1971 using ideas from previous research into neutron time-of-flight spectrometry (Scruby, 2007). In the year following the invention from 1971 until 1979, ToFD was mainly the subject of laboratory work. The background for developing ToFD was, that defect sizing based on reflected amplitude as is done in conventional ultrasonic testing, was deemed insufficient for the building of nuclear pressure vessels. The first real test of ToFD came in 1980 when it was used for sizing flaws in 2” thick welds in cooperation with The Welding Institute at the United Kingdom Atomic Energy Association's (UKAEA) Risley Nuclear Laboratories.

ToFD was entered into a number of international trials, including the PISC II trials of JRC (Nichols and Crutzen, 1988) (the joint nuclear energy research center of the European Commission) and the defect detection trials of the CEGB (Central Electricity Generation Board of the UK). In both these, and several other, trials ToFD performed outstanding.

The good results in trials resulted in ToFD being picked up by other research institutes, like TWI, FORCE institute of Denmark, EPRI in the USA, and the Norwegian institute of technology (Verkooijen, 2004). Also it led to ToFD being used in application specific research, like HOIS offshore trials, and EPRI trial for the detection and sizing of SCC (stress corrosion cracking). From 1984 until today ToFD was used in a long series of validation trials, for a range of different applications both for construction and in service inspection. Please see the table below and presentation by Jan Verkooijen (2004) for details. In general the results of these trials have been that ToFD considerably outperformed alternatives, with the exception of highly advanced laboratory systems, at a lower cost. A typical result, treating both performance and cost is found in the TOFDPROOF project (Chauveau et al., 2006). ToFD found between 70% and 90% of the flaws in test pieces, compared to between 60% and 70% for radiography.

It was realized that ToFD would also need dedicated equipment. An important aspect of the technology is that signals are not displayed on a simple oscilloscope screen, like in conventional ultrasonic testing. Instead they are processed in a computer and displayed side by side in a grey scale image. The equipment also had to be portable for on-site inspection work. This called for powerful portable computers that had not been used in NDT so far. The contract for developing this equipment was awarded to SGS Sonomatic in 1983 and led to the development of Zipscan in 1984 and Zipscan2 in 1986 (Gardner, 1986). SGS Sonomatic and AEA had been cooperating before on the development of inspection manipulators. Sonomatic was interested in this work, as they were expecting to be using this equipment in combination with their manipulators in their existing offshore inspection market. Equipment development continued when computer equipment became powerful enough that commercial computer components could be used. This led to the development of Microplus at Sonomatic in the early 90s, and other equipment at competitors, like e.g. PortEquip at RTD.

ToFD became the center of a heated international debate, often portrayed as the English and their collaborators (mostly Dutch) against the Germans (Hecht, 1999, Erhard et al., 1998). The ToFD supporters (English and Dutch) would typically point to the extensive trial results already present, and take the position that a technology that is so much better than what is in use now, is clearly an improvement and should be used. The ToFD critics (Germans) would typically point to the fact that ToFD will miss some specific types of flaws (surface breaking weld root flaws), and has a much lower signal to noise ratio than other ultrasonic technologies. Also they dismissed trial results as these were not published in international scientific literature. They therefore take the position that ToFD should not be accepted as a general method. This discussion, which is not resolved today, has had a big impact on the speed at which European standards have been accepted. A full set of European standards was finally written in the TOFDPROOF project, in which all trials were done again, gave the same results, but this time with participation of representatives from 7 countries, including a representative from MPA (a German federal institute) and one from TÜV.

Figure 14: ToFD inspection in the field

The ToFD case is a clear example of the issues often present around new NDT methods. The technology had to be validated individually for every country it was applied in and was opposed on the basis of not finding every flaw, where each and every alternative performs worse. At the same time clients of inspection companies started to voice concerns about unnecessary repairs of welds, comparable to the concerns encountered with the introduction of Rotoscan (section 4.2). In the Netherlands this issue was subject of a joint industry research project starting 1997, with participation of 17 organizations from client industries, service providers and government. The objective was to find acceptance criterions, i.e. rules that state what flaws are acceptable and what flaws are to be rejected (Dijkstra et al., 1997). This research was turned into the national standard NEN 1822:2005. While this was readily accepted nationally, it was vehemently opposed at the European level.

ToFD enjoys its best commercial success in small specialized inspection companies. Examples are Veritec Sonomatic in the UK, the continuation of SGS Sonomatic independent from AEA and SGS, and Sonovation in the Netherlands which was spun-out of Sonomatic while it was owned by AEA. In RTD, ToFD was on one side welcomed and included in the portfolio of special services, but on the other side opposed by regional managers active in standard NDT (Goossens, 2002). The supporters of ToFD inside RTD, other themselves with a background in advanced ultrasound, pointed to the advantages of ToFD in being cheaper than radiography and working without radiation, while giving a better inspection result. The opposition, which was silent for most of the period, dreaded the big investments in equipment, the amount of training needed for inspection technician who until that time had no computer skills and the almost certain conflicts with clients on finding more flaws.

ToFD is by now considered an accepted inspection technique although debate continues and acceptance is partial in some countries.

4.4.4. Case analyses table

Date	Actor Institution	Countries involved	Event	Type of activity	Reference
1971	UKAEA	UK	Start of Research	Fundamental Research	(Scruby, 2007) (Silk and B.H., 1974)
1974	UKAEA	UK	Internal report AEA	Fundamental Research	(Scruby, 2007) (Silk and B.H., 1974)
1977	UKAEA	UK	First paper referenced by main stream literature	Applied Research	(Hecht, 1997)
1980	TWI and Norwegian technology institute	UK, Norway	ToFD picked up by other institutes	Applied research	(Verkooijen, 2004)
1981	JRC ispra	Europe	ToFD used in PISC II trials	Applied research & validation	(Trimborn, 1998)
1982	AEA & SGS Sonomatic	UK	Zipscan development	Technology transfer & Equipment development	(Scruby, 2007)
1983	AEA CEGB Sonomatic	UK	Sizewell B Defect detection trials	Validation	(Scruby, 2007)
1984	HOIS	UK	ToFD included in HOIS trials	Validation	(Dijkstra et al., 1996) (Scruby, 2007)
1985	EPRI Sonomatic	USA	Qualification for IGSCC	Qualification	(Verkooijen, 2004)
1989	EPRI Sonomatic	USA	Qualification for under clad cracking	Qualification	(Verkooijen, 2004)
1990	Stoomwezen	Netherlands	First Dutch in service inspection	Field services	(Verkooijen, 2004)
1993	British Standard	UK	BS 7706 code on ToFD	Standard development	(Scruby, 2007)
1993	ASME sonomatic	Netherlands	qualification for in service inspection piping welds ASME XI	Qualification	(Verkooijen, 2004)
1997	NAM	Netherlands	Weld Root corrosion validation	Validation	(Verkooijen, 2004)

1993-5	PMP/NIL/KINT Sonomatic RTD	UK, Netherlands	NIL thin plate project	Validation	(Dijkstra et al., 1996) (Stelwagen, 1995)
1995	Sonomatic ASME	Netherlands, USA	Code case support trials	Validation	(Verkooijen, 2004)
1995-7	PMP/NIL/KINT Sonomatic RTD	UK, Netherlands	Complex geometry project	Applied Research	(Verkooijen, 2004)
1997	PMP/NIL/KINT Sonomatic RTD	UK, Netherlands	ToFD acceptance criterions	Standard development	(Dijkstra et al., 1996)
1999	TüV	Germany	High temperature hydrogen attack trials	Validation	(Verkooijen, 2004)
1999	ASME	USA	Code Case 2235	Standard development	(Wassink et al., 2009)
2000	CEN	Europe	EN 584-6	Standard development	(Verkooijen, 2004)
2002	Institute de Soudure	UK, NL, FR, DLD	EU project TOFDPROOF	Validation	(Chauveau et al., 2006)
2003	CEN	Europe	prCEN TS-1475	Standard development	(Verkooijen, 2004)
2004	NEN	Europe	NEN 1844 acceptance criterions	Standard development	

4.5. Guided Wave Testing

4.5.1. Description of the technology

The principle of Guided Wave Testing is based on an ultrasonic pulse being sent through the pipe around the whole circumference. Due to the propagation around the whole circumference there is no geometric spreading of the wave and thus low attenuation of the sound travelling along the pipe. In this way inspection ranges can be achieved of 5 - 100 meters along the pipe from a single probe position, in both directions. Defects need to have a significant size, and thus the method is suitable for the detection of significant general corrosion areas.

Figure 15: Guided Waves equipment in the field

The tool is operated by placing a probe ring around the pipe at a location where it is (made) clean and accessible. This probe ring, linked to electronics and a computer, will excite the pipe with a low frequency ultrasonic wave. By processing all the reflected signals a pseudo-A-scan representation is obtained indicating features and defect areas along the pipe. In this way, the pipe can be inspected in locations that are otherwise inaccessible, for example under roads or inside insulation.

The presence of the pipe features like welds and welded attachments makes it easy to overlay separate measurements, because defects can always be reported relative to a specific geometric feature. In monitoring this can be helpful if the exact measurement location can not be reproduced on a repeated measurement. The combination of a long inspection range and a short measurement time per location (5-15 minutes per location) make this tool highly suitable for a screening approach.

Figure 16: 2nd generation Guided Waves equipment

4.5.2. Technological history

The mathematical description of waves that are guided by the geometry of the object that they propagate in was made in 1917 by Horace Lamb (Lamb, 1917), for the case of a plate. Starting in the 1950's research was done to assess the suitability of using these waves for Non-Destructive Testing (Worlton, 1957). An overview of early uses of Lamb waves can be found in the standard work by Viktorov (Viktorov, 1967). Subsequently many researchers and practitioners realized the suitability of these waves for quickly screening a large area. Alleyne lists many references to this idea (Alleyne, 1991). Notable ones are the EMAT based systems of IZFP (Sawaragi et al., 2000), and the research at Penn state university (Rose et al., 1994). Early experiments on using Lamb waves in a pipe geometry where done by Silk and Bainton in the late 1970s, which were encouraging but suffered from signal to noise problems (Silk and Bainton, 1979).

4.5.3. Case History

The development of Guided Waves piping inspection systems has two separate stories at the start in the early 1990s, one in the United Kingdom and one in the United States. The development in the United Kingdom starts when TWI, Phoenix inspection systems and Imperial collage start a joined project inside the LINK industrial measurement systems program (Alleyne et al., 1995) in 1991. All three partners had been involved in guided waves research before, but mostly in plates. Additional funding was provided by Esso Engineering and ICI. Lowe and Cawley

(Lowe and Cawley, 2006) remark that CUI was a considerable concern for oil and gas industry at this time.

At the time of these developments the UK had just had two serious industrial accidents. The first was a fire at Grangemouth refinery on March 13th 1987, which killed two people. The other was the Piper Alpha offshore platform disaster. In a complicated incident a gas leak developed into an explosion. In total 167 people were killed. Subsequently the UK government started an inquiry led by Lord Cullen. Among the recommendation was, to transfer the responsibility for safety on the platforms from the Department of Energy to the Health and Safety Executive (HSE) to prevent conflicts of interest between the economic benefits of cheap oil and gas production and expensive safety measures. HSE itself is under nearly continuous criticism for being too lenient to industry.

One of the things HSE did was to make an inventory of the causes of hydrocarbon release (McGillivray and Hare, 2008). Corrosion was the number 2 issue in this evaluation, and inside the corrosion category CUI is the number one concern. HSE did not assume the responsibility for safety of offshore platforms until 1994, but it is in this environment that the Guided Waves Piping Inspection research project was started.

The LINK project was succeeded by a project funded under the EU Thermie program which included practical demonstration of the technology. During this project a target defect size was established as 16% of the cross section of the pipe and during the project it was established that the technology could find this defect size. This program had support of a larger group of industrial sponsors; Shell, Esso, BP, Total, Marathon, HSE and ICI. After this project the technology was commercialised independently by TWI in a spin-off company called Plant Integrity entering the market in 1998, and Imperial College in a spin-off company called Guided Ultrasonics entering the market in 1999.

Important steps in the technology development of the inspection system were:

- Introduction of dry coupled transducers (Alleyne and Cawley, 1996)
- Indication of circumferential extend of defects by using mode converted signals (Alleyne and Cawley, 1997)
- Introduction of the use of torsional wavemodes in addition to the use of longitudinal waves modes around 2000
- Improvement of sensitivity with every generation of equipment (all vendors currently offer 3rd generation equipment, Guided Ultrasonic has announced the 4th generation)

- Improved information on the geometry of defect by using a c-scan display (Guided Ultrasonics) or a focussing option (Plant Integrity)

The development in the United States focussed on a different application, inspection of unpiggable pipelines. Unpiggable pipelines are those pieces of pipeline where no facilities are present for sending an inspection tool (commonly called a pig) through the pipeline. Two projects were performed for developing inspection technologies for these situations. One was a project led by TWI and funded by the American Gas Association and PRCI starting in 1992, and running until 1997 (Lank and Mudge, 1997). The other project revolved around the Magnetostrictive Sensor (MsS) technology of South West Research Institute (SWRI). This technology had initially been demonstrated for use on steel cables of highway bridges (Kwun, 2003). In 1996 a consortium of 11 companies was founded to apply the MsS technology to pipelines, resulting in a field deployable system in 1998.

Kreher (Kreher, 1997) mentions two specific pipeline failures leading to the drafting of the 1996 Accountable Pipeline Safety and Partnership Act. The first involved the release of diesel fuel into the Potomac river near Washington D.C. in 1993 from a pipeline of Colonial pipeline co. The second a rupture of a natural gas pipeline destroying or damaging 14 apartment buildings (Granito and Sabella, 2004) in Edison N.J in 1994. The Accountable Pipeline Safety and Partnership Act requires the pipeline operator to have a risk management process and do an assessment of the risk of a pipeline which in most cases means the pipeline has to be inspected. One of the areas that runs a substantial risk, but is very hard to assess are “unpiggable” pipelines. Guided Waves would be one of the technologies that could prevent expensive dig up programs for these stretches of pipe.

Many of the regulations already present in the The Accountable Pipeline Safety and Partnership Act did not get implemented until the Pipeline Safety Improvement Act was passed by congress in 2006. (this bill is often linked to the pipeline explosion in Carlsbad, New Mexico in which 12 people were killed). In the environment created by the drafting of this legislation the writing of the first standards for Guided Waves started. It was also around this time that the technology really took off in the market. The biggest commercial success of Guided Waves inspection is in the United States for the inspection of road crossings (where pipelines cross roads). This success is mostly with small dedicated companies with personnel that has higher education than the typical NDT company. Traditional NDT companies have mostly done poorly with the technology.

The involvement of RTD with Guided Waves inspection started in 1995, when Gasunie offered a field location in Putten for testing the TWI system on large diameter piping. This was in the context of the AGA project. Gasunie next approached Shell and RTD for a joint industry project to evaluate the commercially available systems. This project, running from 1998 until 2003, was funded by Gasunie and PRCI and concluded that the 3 Guided Waves systems had a very similar performance and that difference where mainly in how well the system had been adapted for use in the field. During the project RTD decided to start commercial services and initially had negotiation for procurement of a system with all 3 suppliers (Plant integrity as spin-out of TWI, SWRI, and Guided Ultrasonics as spin-out out of Imperial College) in the end buying a system from Guided Ultrasonics mainly because the terms and conditions of Guided Ultrasonics best suited a service company. The training of the first operators was performed in early 2000.

At Applus RTD the initial outlook for Guided Waves testing was promising. Several successful jobs were done, notable ones being the inspection of the Bapco jetty in Bahrain and the inspection of dyke crossings in the Shell refinery in Gothenburg. A major breakthrough was the inclusion of Guided Waves testing in the corrosion under insulation program at DOW in Terneuzen. DOW first commissioned a study into the effectiveness of the technology, by performing tests with both Guided Waves testing and visual inspection, and performed calculations into the life cycle cost of both approaches (Wassink, 2008). Guided Waves testing turned out to be more effective and more cost efficient. This success however also prompted the Applus RTD management to transfer operations of Guided Waves testing from the R&D department to normal operations.

Leadership over Guided Waves operation was handed over three times in four years, and Guided Waves testing was no longer performed from the R&D department. Operational department in Applus RTD typically wait for clients to demand a new technology, as opposed to the R&D department which at the time had product champions for new techniques, that actively promoted technologies. The result was that the demand for Guided Waves testing almost vanished.

One of the issues remaining with Guided Waves is that no accepted methodology exists for dealing with the results of the measurement. Although the measurement data has some relationship to the size of the flaw it does not contain direct information about the remaining wall thickness of the pipeline. Several research programs are underway to solve this issue, one of which is performed by TWI and Applus RTD. Similar activities are performed by Guided Ultrasonics and RCNDE.

It is remarkable that the same sequence of a catastrophic incident, followed by a research program and a university spin out company happened again with the same technology, but for the application of rails. The Hatfield derailment (BBC, 2000) lead to research into using Guided Waves for the long range inspection of rails. Subsequently Guided Ultrasonics Rail Ltd. (GURL), a sister company to Guided Ultrasonics, was founded for the commercialization of the resulting technology.

Around 2009 Guided Waves technology has started to be standardized in NACE TG410 and ASTM, and several other national initiatives. The ASTM standard E2775 was put on ballot in 2011 and is awaiting publication.

4.5.4. Case analyses table

Date	Actor Institution	Countries involved	Event	Type of activity	Reference
1917	Royal society	UK	Mathematical description of Guided Waves	Scientific publication	(Lamb, 1917)
1956	US Atomic Energy commission	USA	Experiments and patent for application on plates	Scientific work	(Worlton, 1957)
1979	AEA	UK	Experiments on pipes	Scientific work	(Silk and Bainton, 1979)
1987	n.a.	UK	Grangemouth fire	Industrial Disaster	(HSE, 1989)
1988	n.a.	UK	Piper Alpha disaster	Industrial Disaster	(Cullen, 1990)
1991	IC, TWI, Phoenix, Exxon, ICI	UK	Link project started	Applied research	(Alleyne et al., 1995)
1992	AGA, TWI	USA	AGA project started	Applied research	(Lank and Mudge, 1997)
1995	IC, TWI, Exxon, ICI, Shell, Chevron, BP	UK	Thermie project started	Applied research	
1996	n.a.	USA	Accountable Pipeline Safety and Partnership Act	Legislation	(Kreher, 1997)
1996	SWRI	USA	MsS project started	Applied research	(Kwun, 2003)
1998	SWRI, TWI	USA, UK	MsS and PIL enter the market	Product launch	(Lowe and Cawley, 2006)
1999	IC	UK	GUL enters the market	Product launch	(Lowe and Cawley, 2006)
2003	GUL, PIL	UK	2nd generation systems	Product launch	
2006	US government	USA	Pipeline safety improvement act	Legislation	
2007	GUL, PIL	UK	3rd generation systems	Product launch	
2009		Italy	Italian standard UNI/TS 11317 published	Standard development	(Demma and Alleyne, 2011)
2009	NACE, BSI, IIW, ASTM	USA, UK	Start of standards development NACE, BS, IIW and ASTM	Standard development	(Demma and Alleyne, 2011)
2010	JIS	Japan	Japanese standard JIS – NDIS 2427 published	Standard development	(Demma and Alleyne, 2011)
2011	ASTM	USA	ASTM E2775 standard publication	Standard development	(Demma and Alleyne, 2011)

4.6. Transition from film based radiography to computed radiography

4.6.1. Description of the technology

Radiography involves using radiation to make an image of an object. Commonly the source of the radiation is on one side of the object and the radiation is picked up on the other side with a photographic plate, or some other detector. The radiation sources can be an X-ray tube, a radioactive isotope, or a particle accelerator. The radiation penetrates the object, and any changes in the density of the material in between will become visible where the photographic material is more or less exposed to the radiation.

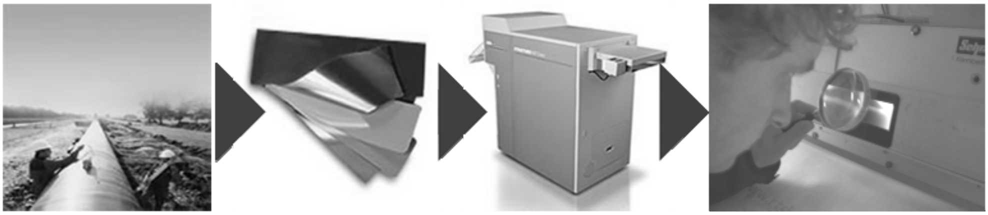

Figure 17: The work flow of Radiography with from left to right: exposure in the field, X-ray film, processing machine and interpretation of the film on a light bench

Traditionally the photographic material for NDT was based on silver-halide materials, virtually unchanged from the early 20th century. The process is to make the exposure, develop the film, and then view the resulting radiograph on a light box.

With Computed Radiography the film is replaced by a plate with a storage phosphor layer. These phosphor material stores the energy of the radiation it absorbs. The energy is later released as visible light when the phosphor is illuminated with a laser in a scanner. The light is picked up by a photo multiplier and converted to a digital image. This digital image can then be viewed and processed on a computer screen.

4.6.2. Technological history

X-rays were discovered in 1895 by Conrad Röntgen who was a professor at the Würzburg University when experimenting with a cathode-ray tube in his laboratory. He quickly realized the importance of his discovery and in the same year he made the first medical Radiograph of the hand of his wife Bertha.

Another source of penetrating rays was discovered in 1896 by Henri Becquerel. Studying fluorescence he found that Uranium would blacken radiographic plates, even when protected by heavy paper wrappings. Marie and Pierre Curie later discovered other elements emitting rays, and called this radioactivity.

The discovery of X-rays immediately caught the imagination of scientists and general public alike. Other research was dropped in favour of studying X-rays, and comic heroes soon had X-ray vision. Already in 1896 X-ray was being used by battle field surgeons to locate bullets in wounded soldiers. In 1905 Röntgen was awarded the Nobel prize for his discovery.

The application of X-rays for industrial applications took a bit longer, as the early X-ray generators were not able to operate at energies high enough to penetrate steel. In 1922 a 200,000 Volt generator provided the first effective tool. In 1931 General Electric developed a 1,000,000 Volt generator and in the same year ASME permitted the use of X-ray approval of fusion welded pressure vessels. From the late 1930s on X-ray became the most important NDT technology, basically creating the NDT sector.

4.6.3. Case History

Computed Radiography was initially developed by Kodak, and patented in 1975 by its employee George Luckey (Luckey, 1975). The inspiration for trying to develop digital imaging systems came from the success of computed tomography, which had been developed by EMI since 1967. This technology had shown the power of image processing with computers, although the long scanning and processing times and high equipment cost were drawbacks of that technology. Another driver was to be able to make a digital image filing system possible.

Kodak and Agfa both performed R&D into the technology but hesitated in bringing it to the market for fear of damaging their existing silver-halide business (Rowlands, 2002), and in the case of Agfa also for fear of patent issues. Fuji was the first to develop a commercial system in 1983 (Sonoda et al., 1983). At the time of these developments, the resolution achievable with CR was much better than of other digital detector systems, 10 pixels/mm compared to 2 pixels/mm for photodiode systems. The resolution offered by CR systems was sufficient for most medical purposes. Other technologies quickly took over the lead in image quality, however, and very soon most digital radiography applications used direct detector arrays instead of CR systems (Rowlands, 2002). This left a number of niche application to CR, mainly those where the system has to come to the patient, like emergency equipment and applications where the patient is too sick to be moved.

The development of the technology took a number of directions that were indicated by the needs of the medical applications. One of the core applications was chest radiology. In many cases patients cannot be transported to an x-ray unit, and the image plates used with CR had a clear advantage over other digital systems. Important features for this niche were to have a large dynamic range as it is hard to get a uniform exposure in an area with big differences in density like the chest. Another important feature for the radiology application was the radiation dose that the patient would be exposed too. The resulting image plates (IPs) offered a trade-off between exposure time (and thus radiation dose) and resolution by changing the thickness of the phosphor layer. Another limitation is the readout speed of the IPs. Where the required resolution is higher, more pixels need to be read, and the readout process is longer.

One of the other drivers in the medical sector was the incorporation of CR images in digital filing systems (PACS, picture archiving and communication systems). In the medical sector this was the main financial driver as it freed up radiological workers from retrieving x-rays for docters (Thrall, 2005). Out of this development the DICOM standard for medical images was developed. This standard has been modified for use in NDT, as the DICONDE standard.

The introduction of digital radiography to NDT was dominated by direct radioscopic systems at first. These systems where mostly referred to as real time radiography system, a reference to an older technology where x-rays were directly converted to visible light in a phosphor screen. The first digital radiography system simply added a CCD to these systems.

After the expiration of Luckey' s patent new equipment manufacturers started to enter the market. Early CR readout systems were very large stationary system occupying several cabinets, making them unattractive to the NDT market. With the introduction of a table top scanner by Lumisys this changed. AGFA and Kodak both took a share in Lumisys. The system was subsequently offered to NDT service providers by both AGFA and Kodak. Other systems were built by OREX, an Israeli company, and Dürr out of Germany. These systems were both also offered by multiple suppliers: small companies that acquired a CR scanner from the medical sector and added NDT specific software to it. Fuji started to offer their medical system to the NDT market. In 2005, Applus RTD identified six companies marketing CR equipment from at least three sources each, produced by five different equipment manufacturers (Rosendaal, 2005).

The NDT sector was eager to get started but at the time the resolution of systems, which had been sufficient for medical purposes for a long time, was insufficient for NDT, particularly for weld inspection which is a very large part of the NDT market (>80% of radiography at RTD). The resolution of systems started to approach sufficient quality for weld radiography in 2006, with the certification of the Dürr

HD-CR 35 NDT system by BAM, to the requirements of EN 14784-1 (Zscherpel and Ewert, 2007). Readout time at these resolutions is as yet too long to make them competitive. Both GE and Dürr are developing systems to overcome this.

Standard organizations were quick to start making standards for CR systems but were also faced with the performance issues and with converting performance measures from the analog to the digital domain (Ewert et al., 2004). prEN 14784 called for CR systems to at least match or improve on traditional film systems in every measure. This resulted in requirements that were so far beyond the state-of-the-art that some people assumed that they would not be reached in the foreseeable future. The traditional film makers did not mind this at all (dePrins, 2006). This left the niche applications in NDT where codes and standards do not apply to the CR systems.

RTD started to have a successful business using CR in 2003, mainly inspecting in-service piping for corrosion. Initially many clients were sceptic as they expected the new technology to be more expensive (Frost&Sullivan, 2006). This remained a hurdle until prices had dropped to a level where cost of a CR system was similar to traditional film radiography (replacing the processing machine and processing chemical with a digital scanner and the film with an image plate). The success however came from the additional value offered by the images being digital allowing many additional things to be done with them, like making measurements in the pictures and zooming on detailed features. Other additional values were, that less retakes had to be made, because of bad exposures, and that results were available on shorter notice which helps work planning in plant shut downs. Exchange and filing of images was of much smaller importance as the oil and gas sector generally was very hesitant in allowing 3rd party data and readout programs to be introduced on their networks.

Initially the market introduction in the Netherlands was very successful. The earn back time of the first system was less than a year, and within a year the business development team dedicated to CR was operating 5 systems. Operational department in Applus RTD then demanded the technology to be turned over to them. In the opinion of the business development team, this was not a wise decision, as CR needed to be sold on the added value of the images obtained. Operational department typically wait for clients to demand a new technology and do not have sales force that introduces new technology to clients, explaining the added value. The turnover on CR seriously declined after the product was turned over.

In the mean time, the business development department at Applus RTD was discontinued. The personnel of the department went to a new department focussed on the off-shore sector. Very soon they had a large number of CR systems running offshore. This time, the system was sold as part of a new inspection approach (nick named 'the RTD ambulance') where multiple techniques were brought offshore, and the decision on the technique to be used was made locally, instead of at the office on shore. Pilot projects at Total realised saving for the client numbering in millions (Clason, 2007). The success was short lived, as a new manager was appointed to the offshore department who had more traditional ideas about NDT operations. The personnel origination from business development left the company in protest, and the use of CR collapsed again.

Meanwhile the CR equipment vendor market was going through a phase of consolidation. Lumisys and OREX were fully acquired by Kodak. AGFA bought RADview, a company specialized in digital radiography software in 1999. AGFA NDT itself was bought by GE and started selling AGFA systems (CR system production remained at AGFA) in 2004. It is interesting to note that all of the radiography market (medical, NDT and otherwise) has now converted to digital imaging, except for weld radiography. This transition is however considered to be unavoidable and expected to be happening in the first half of the current decade.

Standards development for CR systems started early compared to technology maturity. The first standard for CR scanner / image plate systems was published in 2005 (Ewert, 2007). In 2011 the ISO standard for radiography, EN ISO17636-1 and 2, is being revised for inclusion of both CR and Direct Digital Radiography.

4.6.4. Case analyses table

Date	Actor Institution	Countries involved	Event	Type of activity	Reference
1975	Kodak	USA	Patent for CR	Patent	(Luckey, 1975)
1983	Fuji	Japan	First commercial medical system	Product introduction	(Sonoda et al., 1983)
1984	Fuji	USA	First use of medical CR systems in USA	Product introduction	(Rowlands, 2002)
1990	Fuji	USA	Market acceptance of CR for medical purposes	Validation	(Rowlands, 2002)
1998	Lumisys	USA	First desktop CR system	Product introduction	(Kodak, 2005)
1999	RADview, AGFA	USA			
2000	Kodak, Lumisys	USA	Kodak buys Lumisys	Merger & acquisition	(Kodak, 2005)
2001	AGFA, Seifert, Pantak	Belgium, Germany, USA	AGFA buys Seifert and Pantak	Merger & acquisition	Contemporary press release
2004	Kodak	USA	Kodak merges medical and industrial imaging units	Merger & acquisition	(Kodak, 2005)
2003	RTD	NL	Launch of Service delivery	Product introduction	(Rosendaal, 2005)
2004	GE, AGFA	Belgium, USA	GE buys AGFA	Merger & acquisition	Contemporary press release
2005	OREX, Kodak		Kodak buys OREX	Merger & acquisition	(Kodak, 2005)
2005	ASTM, NEN		First standards	Standard development	(Ewert, 2007)
2006	Dürr, GE, BAM	Germany, USA	First CR systems certified to EN-14784-1	Validation	(Zscherpel and Ewert, 2007)
2011	NEN, ISO	International	Revision of ISO standard to include CR and DR	Standard development	

4.7. Introduction of Phased Array equipment in ultrasonic testing

4.7.1. Description of the technology

Huygens principle states that any wave front can be approximated as a series of small sources. Phased Array technology uses this principle by using an array of small sources to generate a wave field. By applying a small time difference to these sources the direction in which the wave is sent, or in which the array is receiving can be steered. Phased Array technology was invented for use in radar and sonar systems in the Second World War.

4.7.2. Technological history

Phased array systems have their origin in radar and sonar technology. The use of this approach for NDT had already been proposed in 1954 by Bradfield and Tom Brown of Kelvin and Hughes, who applied for a patent on a transducer design in 1959 (Woo, 1998). The technology was used in sonar and radar application at that time already, but as this research was kept secret, it took until 1964 for the technology to be applied elsewhere. Jan Somer built a first prototype system, meant to be applied for imaging of the brain (Somer, 1968). In 1964, while working at TNO he had received a European grant to study radar technology in England. The first system was demonstrated in 1967, and after some improvements was able to make images of the head and heart in 1969. The technology was offered to Philips, but they did not see any commercial prospects for it. The technology was picked up by a small American company Diagnostic Electronic Corporation and in 1976 the first units were sold for medical purposes. Somer stated in 2004 that Phased Arrays were involved in 95% all echo-cardiological investigations (Somer, 2004). For other echo applications the same was true. In NDT Phased Arrays took a lot longer to get established.

Figure 18: Left, the principle of Phased Arrays. Right, an R/D tech Omniscan portable phased array system

4.7.3. Case History

In NDT the technology was picked up in scientific research virtually parallel to the medical developments. Whittington and Cox (1969) report about their experiments with a piping inspection system in 1968. In the decades thereafter research into Phased Arrays was done in the UK (McNab and Campbell, 1987), USA, Germany (Erhard et al., 1986) and Japan (Komura et al., 1985). McNab (McNab and Campbell, 1987) in particular reports issues with respect to the cost and bulk of electronics and difficulty in producing probes. Applications were almost exclusively in the nuclear sector. Other early applications involved large forged shafts and low pressure turbine components.

The main stream NDT market started to switch to Phased Array when developments in micro-electronics made more affordable Phased Array systems a possibility. One of the key companies offering these systems was R/Dtech. R/Dtech was founded in 1990 after Allain Allard and a group of shareholder acquired the assets of Tecrad; an equipment manufacturer specialized mainly in eddy-current inspection. Tecrad had some experience with Phased Array technology after having cooperated with IZFP in the area of eddy current array systems (ref. interview with Gerd Dobmann in chapter 6 of this thesis).

R/Dtech went into extensive product development programs together with clients like EPRI and Vinçotte and suppliers like Vermont and Imasonic (both probe manufacturers). Research received additional grants from the Industrial Research Assistance Program (IRAP) of the National Research Council of Canada (NRC, 2005) and PRCI (Dubé et al., 2000). From 2000 to 2005 R/D tripled its workforce to 246 employees and increased sales from 19 to 47 million.

RTD started to consider phased array as a next generation technology for the Rotoscan system in 1999 when it was approached by R/D tech. R/Dtech had previously build a girth weld inspection system with AIB Vinçotte and saw an opportunity to cooperate with RTD which had traditionally been the innovator in the girth weld inspection niche. Trials with an R/Dtech system were held in early 2000 after which RTD concluded that the technology was viable. In the same year R/Dtech also demonstrated their capabilities to PRCI, an association of companies involved in the pipeline industry that funds and directs research projects (Dubé et al., 2000). At RTD a business case confirmed that the reduction is setup time of a phased array system compared to a multi probe system would cover the cost of the system (Wassink, 2000a). A commercial agreement with R/Dtech was not reached however. RTD then proceeded in inviting R/Dtech and several other companies to tender for building a girth weld system for them. RTD awarded the contract to Technology Design, helping that company on its way to introduce another affordable Phased Array system to the NDT market.

Miniaturization of Phased Array technology continued and by 2004 R/Dtech and others introduced Phased Array systems with a build in displays that could be conveniently hand carried into the field. This opened up the possibility of using the advanced imaging capabilities of Phased Arrays, and applications like inspection of complex geometry welds, that had previously been impossible with ultrasonic inspection. Other manufacturers of portable Phased Array equipment also emerged. EPRI, one of the launching customers for R/Dtech, helped former R/Dtech employee François Mainguy to establish Harfang to develop portable PA equipment (Vidyasankar, 2007). Krautkrämer, the champion of the ultrasonic system market, was acquired by GE, and subsequently changed direction to also introduce portable Phased Array systems in 2006. R/Dtech was acquired by Olympus after having some internal issues in developing from the technology development company to being one of the market leaders.

Prices of systems are starting to get down to the level of traditional single probe ultrasonic systems. The NDT sector however is unsure how to proceed as little regulation exists. On the one hand Phased Array holds great promise and is treated almost like a cure-all technology; on the other it does not change the fundamental physics of ultrasonic inspection making the writing of new codes and standards not applicable. For some applications, the capabilities offered by Phased Array have been added to existing codes and standards. Examples are ASME code case 2235 and pipeline standard API 1104.

Although the sales of Phased Array equipment has taken off, with RTD building 60 units in 2008, a next development step is still needed to come to full replacement of all ultrasonic instruments.

4.7.4. Case analyses table

Date	Actor Institution	Countries involved	Event	Type of activity	Reference
1954	Kelvin and Hughes	UK	First ultrasonic Phased Array patent	Patent	(Woo, 1998)
1964	TNO	Netherlands	First medical phased array system	Invention	(Somer, 1968)
1968	Tube investments research laboratories	UK	First NDT phased array system	Invention	(Whittington and Cox, 1969)
1990	R/Dtech	Canada	Founding of R/Dtech	Company founding	(NRC, 2005)
2000	R/Dtech	Canada	R/D tech system trial at RTD	Validation	(Wassink, 2000b)
2002	Technology Design	UK	TD focus scan	Product Launch	Contemporary product brochures
2004	R/Dtech	Canada	R/D tech Omniscan	Product Launch	Contemporary product brochures
2006	GE	USA, Germany	GE phasor	Product Launch	Contemporary product brochures
2008	RTD	Netherlands, USA	Large scale implementation at ApplusRTD	Product roll out	First hand author experience

4.8. Cross case analyses

This thesis started with the observation that innovation in NDT takes longer than innovation in other industries using similar technology. Using the cases described in this chapter, this statement can be verified. Each of the research questions will be examined in the light of the cases and finally some characteristic events that happened in multiple cases will be discussed.

4.8.1. Innovation in NDT takes longer

The length of the innovation process has been analysed using the notions of pre-diffusion phases introduced by Ortt (Ortt and Schoormans, 2004, Ortt, 2010). The pre-diffusion phases are the period in which the technological principle is known, and several attempts are made to further develop and introduce it, but without the technology becoming widely used. Ortt distinguished two pre-diffusion phases which are introduced below. After these pre-diffusion phases a standardized product has become established and becomes widely used. The design at this point could be treated as a dominant design following the terminology of Utterback (Utterback, 1996).

Several moments or events can be taken as the start or end of a phase. Ortt (Ortt, 2010) introduces three milestones to identify the pre-diffusion phases:

Milestone 1: **Invention**;
the technological principle is demonstrated and mastered.

Milestone 2: **Introduction**;
the products are available for sales and can be transferred to others.

Milestone 3: **Diffusion of a standard product**;
a standard product can be reproduced multiple times.

These three milestones result in two separate pre-diffusion phases:

- Pre-diffusion phase 1: start at invention and end at introduction
- Pre diffusion phase 2: start at introduction and end at diffusion

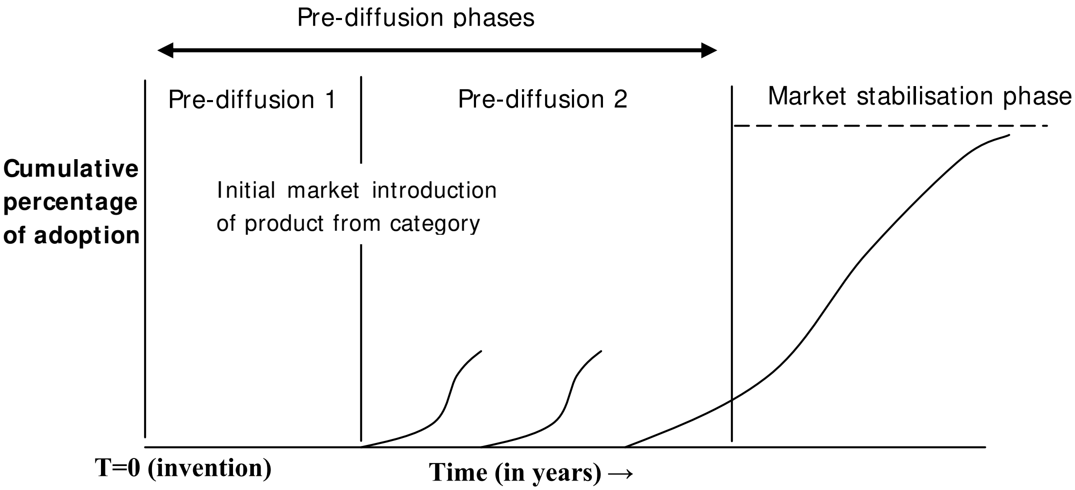

Figure 19: Graphical depiction of the two pre-diffusion phased

In the case of Non-Destructive Testing, determination of the moment of invention can be hard, as the technology has typically been used in another sector before, and the physical principle has typically been known for at least a century. There are however two events that can be readily identified in most, but not all, cases. These events are the first patent filed for the technological application in NDT and the start of a first NDT dedicated development project. The main reason for taking two events is that neither event gave a consistent start date for all cases. Not every technology had a patent filed, while in some case no project for development was started for many years after the technology was clearly known.

Similarly, two events have been taken as the start of the diffusion phase, again because no single event gave consistent results. The most obvious event in the context of NDT, i.e. an industrial standard being established did not give consistent results, as in some cases this standard did not result in commercial success, or a standard was written before a standardized product existed. On the other hand, not every technology treated had commercial success.

In all cases a clear commercial introduction date could be identified based on product brochure information on file at RTD.

The definitions used for invention and start of diffusion milestones thus become:

- Invention 1: First patent
- Invention 2: start of dedicated development

- Diffusion 1: first code or standard
- Diffusion 2: commercial breakthrough as indicated by equipment production figures

Table 7: Events delimiting the pre-diffusion and diffusion phase

	MFL Floor-scanner	**Roto-scan**	**PEC / Incotest**	**ToFD**	**Guided Waves**	**Computed Radio-graphy**	**Phased Array**
Physical principle	Magnetic flux leakage (1868)	Ultra-sonic testing (1794)	Eddy currents (1851)	Diffraction (1815)	Lamb Waves (1917)	Radio-graphy (1895)	Huygens principle (1690) Array technology (1905)
Prior use in other sectors	Oil exploration		Geo-physics	Neutron physics		Medical	Medical
First patent in NDT	1963	1952	1989	n.a.	1994	1975	1954
Start of development project	1982	1956	1987	1974	1992	1983	1969
First commercial offering in NDT	1988	1989	1996	1983	1999	2001	2000
First codification	1991	1994	2002	1993	2006	2005	1999
Commercial break-through	1994	1996	none	Differs per country UK 1993 USA 1999 Dld 2004	2006	2006	2005

In each of the cases the technology had been around for an extended period of time before a trajectory of commercial implementation started. In most cases the technology had been successfully applied in other fields, or in specific niche NDT applications. Table 7 shows the years for the milestones as described above.

To convert these dates into a clear period for each case, a final choice had to be made for the date representing the milestone. For the invention date, the first patent in NDT was chosen in most cases, as this date is documented better and gives a clear comparable date. The exceptions were the ToFD case, for which no patent was found and the Guided Waves case in which a patent was filed late in the development project.

For the start of diffusion, the date chosen is the data in which a clear commercial breakthrough was evident from a big increase in the number of equipment manufactured and transferred to service delivery organization. The only exception is the INCOTEST case which is not considered to have had a commercial breakthrough. In this case the date of the first standard was used. In Table 8 these years are converted into a period measured in years.

Table 8: Pre-diffusion phases for the cases

	MFL Floor-scanner	Roto-scan	PEC / Incotest	ToFD	Guided Waves	Computed Radio-graphy	Phased Array	Mean
Pre diffusion phase 1 (years)	25	37	7	9	7	26	46	22.4
Pre diffusion phase 2 (years)	6	7	6	16	7	5	6	7.6
Total	31	44	13	25	14	31	52	30.0

The tables show that the period from the start of technology development to start of commercial services has a much bigger spread than the period from start of commercial services to commercial breakthrough. When related to the results of other sectors as shown by Ortt (Ortt, 2010) it can be concluded that the length of the innovation process is indeed longer than any other sector covered by Ortt. Technologies particularly take more time to move through the first pre-diffusion phase.

Table 9: Length of the pre-diffusion phase in NDT compared to other sectors. All data except for data on NDT from Ortt (Ortt, 2010)

	pre-diffusion phase 1 (invention > introduction)	**pre-diffusion phase 2 (introduction > diffusion)**	**Total (1+2)**
NDT	22.4	7.6	**30**
Chemicals, metals & materials	4.9	6.5	**11.4**
Pharma & healthcare equipment	21.6	4.5	**26.1**
Telecom, media & internet	8.9	6.4	**15.3**
Electronic equipment	7.2	12.0	**19.2**
Aerospace and defence	7.6	4.0	**11.6**

Going back to the cases and the circumstances surrounding the commercial introduction it becomes clear that characteristic events cause the technology to move from the pre-diffusion to the diffusion phase. These events will be treated in the next section.

One of the primary reasons often mentioned for going to a new technology is the relative performance of old and new technologies. In most of these cases the performance of the technology has been evaluated in qualification projects and evaluation trials. Given the relatively high performance of ToFD in performance trials while being a slowly adopted technology compared to the relatively low performance of MFL in performance trials while be a very quickly accepted technology, it does not seem likely that technical performance is the main factor in adaptation. From the cases it was concluded that instead, the technologies follow a specific trajectory based on the issue to be solved. Once the steps of these trajectories are fulfilled commercial introduction and success follow a similar diffusion pattern.

4.8.2. The technical issue to be solved

Table 10 lists the technical issues and mitigated risks associated with the cases. Across the cases a pattern can be observed between the type of inspection and the innovation trajectory.

Maintenance inspection and construction inspection each have their own cause for the innovation project to start, and their own drivers for commercial success. In the cases where the inspection itself is not new but the equipment is a direct replacement for older technology, yet another trajectory is found.

In the maintenance inspection cases public pressure for better safety regulations, often caused by industrial incidents, is the starting point for innovation projects. Commercial success depends to a large degree on the developed inspection approach ending up in the maintenance regulation for the object under investigation. In the MFL Floorscanner case this happened very quickly, resulting in a quick commercial success. INCOTEST/PEC on the other end, did not end up in regulation for CUI, and did not have commercial success in that area. Where INCOTEST was used for the inspection of sphere tank legs through fire-proofing it had substantial commercial success in countries where the approach was codified.

The success and recognition that these technologies achieve then, subsequently, serves as a motivator for further development of the technology. Quickly successful technologies like MFL and Guided Waves also had a succession of improved systems, and development still continue into improving the technology today. Slowly successful technologies like INCOTEST on the other hand have a hard time to get development resources allocated.

In the construction inspection cases, the implementation of the innovation is a reaction to changes to the construction technology being applied. Rotoscan was implemented by virtue of a new welding process being introduced. ToFD and Phased Array weld inspection were both developed in the nuclear energy sector because the wall thickness of vessels in nuclear reactors is too big to be inspected with radiography, and existing ultrasonic technologies were not able to size defects. The commercial breakthrough for more applications that just the one that drove the implementation, came after the cost of the inspection itself became lower than the cost of the technology it replaced. It has to be realized that the decision for the type of construction technology is typically made by the future owner of the object, while that cost consideration is mainly for the construction company. The eventual commercial breakthrough is thus driven by another stakeholder than the first application.

This cost consideration can also be found in the two process improvement cases. In these cases the research into better imaging of inspection results ran virtually parallel to the medical sector till the point of implementation. The higher cost of equipment than stopped further innovation until savings in the total inspection cost could be achieved. A higher quality inspection result apparently has little value for NDT clients, or could even have a negative effect on acceptation.

Table 10: technical issues solved by the case technologies

	Case	Type of inspection	Technical issue	Risk mitigated
1	MFL Floorscanner	Maintenance inspection	Tankfloor bottom corrosion	Regulatory intervention, pollution
2	Rotoscan	Construction inspection	Finding the flaws generated by a new welding technology	Manufacturing flaws in pipelines
3	Pulsed Eddy Current / Incotest	Maintenance inspection	CUI	Regulatory intervention, pollution
4	Time of flight diffraction	Construction inspection	Improved sizing of flaws	Nuclear incidents
5	Guided Waves piping inspection	Maintenance inspection	CUI and Pipeline corrosion	Regulatory intervention, pollution / accidents
6	Digital radiography	Both	Radiography process improvement	n.a.
7	Phased Array	Both	Ultrasonic weld inspection process improvement	n.a.

4.8.3. Start-ups and competition

The source of technology in all cases is a research institute or corporate research department. In the sub-sequent stories however small companies, mostly technology start-ups, play an important role. Commercialization is first attempted through established NDT service and equipment companies. Table 11 shows this in a table. In 5 out of 7 cases, a start-up is eventually more successful than the company first commercializing the technology.

New technology apparently has a hard time in the established NDT companies. This will be further investigated in the interviews later in this thesis.

Another interesting issue is that in some cases, powerful clients intervene to prevent the situation where there is one supplier for a technology. In the case of Rotoscan, Shaw was financed by TCPL to become a competitor to RTD. In the case of Phased Array, Harfang was financed by EPRI, and TD was financed by RTD, to become a competitor to R/D tech. In the case of INCOTEST, Shell and RTD had a legal conflict over patents.

Table 11: Source of technology and the role of start-ups. More successful company bolded where applicable.

	Case	**Source of technology**	**Primary commercialization**	**Start-up**
1	MFL Floorscanner	AEA (research institute)	RTD	**Silverwing / MFE**
2	Rotoscan	RTD (NDT service company)	**RTD, Shaw**	Weldsonix, UTQ
3	Pulsed Eddy Current / Incotest	ARCO (Oil company)	RTD, Shell	n.a.
4	Time of flight diffraction	AEA (research institute)	Sonomatic	**Sonovation**
5	Guided Waves piping inspection	IC (university) TWI and SWRI (research institutes)	PI (TWI) and SWRI	**Guided Ultrasonics**
6	Digital radiography	Kodak (photographic equipment company)	FUJI	**Orex**, **Dürr**
7	Phased Array	TNO (research institute)	Siemens, Krautkrämer	**R/D tech**

4.8.4. The order of development activities and Codes and Standards

The cases confirm the importance of codes and standards for the adaptation of new NDT technology. They also give new insights into when they become important in relation to other development activities. The traditional way of looking at this step is that a new technology will be accepted into a standard when its development is complete and it has been thoroughly validated (Scruby, 2007). The cases however show that standards instead already play a role early in the development activities. The regulatory activities surrounding the Piper Alpha and Seveso disasters brought the societal need for inspection technology to the attention of the R&D teams involved in the MFL and Guided Waves research. Issues with corrosion in Prudhoe Bay, and the public attention to oil production in Alaska, started ARCO to develop their Pulsed Eddy Current system.

The technological approach also plays a role. In cases like MFL and Guided Waves the determination of the defect size to be found was one of the most important decisions at the start of the development, as this laid the relationship between the inspection technology and the degradation mechanism to be found. In the Rotoscan and ToFD case, the development of standardized reference objects was an important step towards acceptance. These defect sizes and reference standards later formed a part of standards developed for the inspection technology.

4.8.5. Cross Case conclusions

Three different trajectories were observed for the development of new NDT technologies, and their eventual adaptation.

In the case of maintenance inspection developments are started as a response to public attention drawn to integrity problems by disasters and public enquiry. In these cases the technology is eventually adopted if the technology becomes embedded in codes and standards and the regulatory environment surrounding the object.

In case of construction inspection, new technology is investigated as a response to new construction methods. The technology is adopted when the cost of inspection becomes lower than the cost of the previous inspection method, or a cost saving is achieved for the construction method itself.

In the case of technology that improves the inspection process the driver for investigating new technology is improvement of the inspection result, but adaptation is only achieved when cost of inspection becomes lower than previous methods.

Small companies played an important role in the success of new technologies. In some cases they were financed by powerful clients to prevent a monopoly.

4.9. Requirement for a model to study innovation in NDT

Studying innovation in a systematic way requires a model of the innovation process. Research into innovation is done in many disciplines and for many reasons. When the focus of study shifts between scale of aggregation, i.e. the economy, an industry, a company or a single project, often the reason for research changes and along with it will the terminology and models used. The practical result of this is, that there are now many concepts for innovation (Nieto, 2003) which are to some extend congruent, but use different terminology. They do not seem treat the same processes, and the assumptions made are widely different (Gopalakrishnan and Damanpour, 1997).

In the next chapter a model for studying innovation in NDT will be selected. In the research an overview was made of customary concepts in innovation text books. Although this helped to shape the picture of the model that was needed to research innovation in NDT, treating this part of the research here would have the discourse deviate from innovation in NDT too much. The concept overview can be found in the appendix.

From the cases and cross case analyses a number of requirements for a model can be derived. The requirements will be derived by taking the dimensions of innovation that were found in section 1.2.2 and finding how these dimensions show up in the cases of this chapter.

4.9.1. Scale of aggregation: need for a scale free model

In the case described in this chapter, the events happen on many different aggregation scales. Some things happen on the scale of one person, like Brian Spies in the INCOTEST case or Maurice Silk in the ToFD case, who happens to bring a technology from one sector to another. Some things happen on the scale of a sector, like AEA approaching RTD for commercialization in the Floorscanner case or Exxon and ICI starting a research project with TWI in the Guided Waves case. Yet others happen on the level of a national system, like the standardization processes that are needed for every NDT technology. The fact that national differences are important is particularly visible in the ToFD case, where acceptance of the new technology was different for every country.

It is concluded that a framework for studying innovation in NDT should be capable of modeling NDT on several scales of aggregation. A model that is valid on multiple aggregation levels has many advantages. A model that is applicable to multiple scales would give the possibility for companies to assess the value of a technology not only for themselves but also for the rest of the supply chain they are part of, and for neighbouring industries. Industrial sectors would be able to see where innovation is frustrated and why. On the level of the economy it would be possible to get a better picture of the effectiveness of economic stimuli aimed at innovation.

4.9.2. Actor and network dependency: Open innovation

The cases show that none of the technologies was developed in house and commercialized in the same company. Techno entrepreneurship plays an important role. The model for studying innovation in NDT should thus be capable of showing development both in a company and across its boundaries.

Many of the finding of Christensen (Christensen, 1997) that are linked to his Disruptive Innovation concept also play a role. Large companies failed to see the potential of technologies like Computed Radiography and Phased Array at first, and an established service company like RTD failed at innovation compared to small start ups.

Another factor that makes Openness of the innovation model important is that many client companies in NDT increasingly outsource maintenance and inspection activities. This changes the environment in which innovations have to be implemented.

The model used by Chesborough (2003) to describe Openness is a modification to old stage gate models of innovation. Many smaller companies never saw this as a new development as they didn’t have all capabilities in house at any time (Trott and Hartmann, 2009). A model that would be constructed from an open starting position would benefit small and large companies alike.

4.9.3. Knowledge generating processes: IP protection and knowledge generation

In several of the cases, technology was not simply developed from fundamental research, but instead taken from a neighbouring technology area. A model for studying innovation in NDT should be able to model knowledge exchange from a sector other than the NDT sector. Knowledge and managing knowledge also plays a role in case where patents are challenged.

At the moment ‘knowledge economy’ is a common political concept, but without a suitable epistemology and taxonomy of what knowledge is and how knowledge and the economy impact each other. The model for knowledge generation is typically considered to be linear, starting with basic research. Stokes (Stokes, 1997) considers the Vennevar Bush report (Bush, 1990) to be the origin of this model. In this report it is stated that basic research is the source of new knowledge. Many sources however show that knowledge may originate in different areas than basic research, and that not all knowledge is scientific. ‘Knowledge intensive’ and ‘science based’ have become interchangeable, even though a lot of the knowledge and experience needed to innovate successfully comes from basic engineering and practical application of new products and services (Santamaría et al., 2009). A lot of innovation and economic growth comes from low-tech companies but is no less knowledge intensive (Jacobson et al., 2005).

NDT would be categorized as low-tech based on R&D spending. The cases presented have shown that NDT is very technologically involved, beside this low level of R&D.

4.9.4. Time dependant and feedback processes: A dynamic system

The time scales in the cases varied considerably. A model for studying innovation in NDT should be able to handle the development over time of a technology. The fact that the time scale vary this much suggests that the processes are non-linear.

Several innovation concepts appear to have a high applicability to the cases. In some cases user of the NDT equipment or services have a high impact on the innovation process. A concept like lead user innovation (Hippel, 1987) could help understand innovation in NDT.

The fact that NDT innovation seems to follow specific trajectories, would suggest the use of concepts like Dominant Design (Utterback, 1996) or Technological Trajectories (Dosi, 1982).

In systems engineering the main properties of a dynamic system are, that the behaviour is time dependant and that feedback processes occur (Vande Vegte, 1990). In the context of innovation in NDT both properties are clearly important. Time scales for basic research, product development and operational deployment are vastly different and have to be taken into account for effectively assessing innovativeness over time. Feedback of user was already mentioned.

4.9.5. Actor and network dependency: Link between public/political processes and corporate behaviour

Especially in the maintenance NDT cases, technology gets developed in response to public pressure for better oversight of oil, gas and nuclear activities. This cannot be modelled simply as a change of demand like it would in a second generation innovation models, as these technologies then get developed in a relationship between end-users and research institutes, without equipment or service companies being involved.

A model for studying innovation in NDT should thus be able to show the influence of public opinion and policies on the innovation process, which an important influence going from the end user of NDT to scientific institutes.

5. Model selection

In this chapter the model for analysing innovation in NDT will be selected. Work in previous chapters has produced the criteria on which the selection will be made. In section 1.2.2 the dimensions along which different innovation model differ were identified based on an overview of comparative studies of innovation literature. In section 4.9 these dimensions were used to identify how they are important to the NDT sector and how innovation in the NDT sector is taking place along these dimensions.

In this chapter, the conclusions from this investigation will be used as requirements for selection of a model to study innovation in the NDT sector. First the selection of candidate models will be discussed, after which three candidate models will be presented. These models will be more thoroughly investigated according to these requirements.

5.1. Model selection process

Studying innovation in the Non-Destructive Testing sector requires a model which sufficiently covers the areas of the conclusions of chapter 4. Secondly the model should be capable of giving new insights into the research questions of the thesis. Very few existing innovation models meet the complex set of requirements arrived at in section 4.9.

The requirements identified earlier are:

1. Possibility to model on different scale of aggregation
2. Possibility to model relationships inside and outside of a company (open innovation)
3. Possibility to model both industrial and societal developments in interaction
4. Possibility to model the creation of knowledge and intellectual property
5. Possibility to model development over time, and including feedback processed (dynamic model)

The first requirement, to be able to model on different scales of aggregation excludes most innovation models, as these typically start from a given aggregation level as dictated by the research tradition they originate from. Business school models tend to treat cases on the aggregation scale of companies, while economist's models treat national or sector economics on the aggregation scale of national or regional economies.

As Chesborough already described, the second requirements to study innovation in an open setting excludes many older innovation models (Chesbrough, 2003), as these tend to treat R&D and intellectual property as enclosed in corporations. An example of a model rejected on this issue is the stage gate project management model. Although the extended stage gate model does potentially allow for project with multiple companies, stage gate is not capable to accommodate portfolio decisions for multiple companies. Imaging the effect the decisions of the gate committee of a large multinational will have on the single technology start-up that they are running an open innovation project with.

The third requirement, to describe both development in society and development in industry in interaction, excludes another set of models. Although many models developed for information technology innovation do treat the development of standards, these standards apply to agreement on common technology platforms for commercialization purposes and do not apply to government empowered standards for safety of installations. One of the models that comes very close to all requirement but that is rejected on this point is the user based innovation model of Von Hippel (1987). The reason is, that this model studies the behaviour of user, as independent from rather than influenced by regulatory influences.

The fourth requirement of being able to treat intellectual property both as patented and codified intellectual property and as tacit knowledge excludes models like Open Innovation and Dominant Designs, as these models look primarily at technology as captured in designs and patents, whereas in the NDT sector these typically come from other sectors. The knowledge is created when applying existing technology in a new field, with an important role for the development of tacit knowledge.

The fifth and final requirement, that innovation should be treated as a dynamic process, excludes many managerial solutions that look at technology on a very short term basis. The dynamics observed in the NDT sector shows both changes in technological solutions and in societal demands. Thus also models that take one as fixed, and the other as time based will be rejected. For example, another model that is excluded on this requirement is the diffusion of innovation theory, as in this theory the technology is typically fixed and does not change anymore.

Finally, the fact that this thesis is trying to solve a managerial issue of speed of innovation, requires a model that can be operationalized and that will suggest courses of action, or suggested policy changes. Models like the technological trajectory model of Dosi (Dosi, 1982) and the punctuated equilibrium model of evolutionary economists are rejected on this item as they only describe how innovation went a particular way, and not why and how it can be influenced.

Three models were identified that fulfil these requirements and will be further investigated to determine which fulfils them best. These models will be introduced in the next three paragraphs after which they will be further investigated along the 5 requirements of section 4.9.

5.2. Functions of innovation systems approach

The functions of innovation systems approach created by Prof. Hekkert of Utrecht University (Hekkert et al., 2007b), is an extension of the Innovation Systems (IS) approach. Hekkert remarks that the IS approach was previously determined to be insufficiently flexible in dealing with the non-linear dynamics of innovation, and as having insufficient attention to micro level details. The central idea of the extension is to create a model that focuses on the goal of innovation by systematically mapping the activities taking place in an innovation system that result in technological change.

The Innovation Systems approach was developed in the context of institutions and policy makers like OECD trying to influence the innovativeness of the economy (Sharif, 2006). As a result the innovation systems approach is most often used as applied to innovation in an administrative or sovereign area, for example as National System of Innovation (Freeman, 2002) or Regional System of Innovation (Malerba, 2002). Hekkert gives an overview of the relationships between these different uses of the innovation systems approach and adds those that are not specific to administrative boundaries; Technology Specific Innovation Systems (TSIS) and Sectorial Systems of Innovation (SSI).

The innovation system approach was developed by a group of evolutionary economist as a response to neo-classical economist. The opinion of the evolutionary economists was that the neo-classical view does not sufficiently capture the development of new technology and its impact on productivity and the economy.

Suurs (2009) identifies four features that are common to the innovation system approach. The first is that innovation is interpreted as a learning process, where the knowledge obtained is captured in routines, i.e. customary ways of solving a problem. Secondly there is a big emphasis on the role of institutions and the way they shape rules and regulations. Thirdly is the treatment of the relationship of actors and institutions in a system. This system is then often compared to a similar system, e.g. another country or region. Fourthly the IS approach is predominantly used as in intervention model for shaping policies.

The Functions of Innovation Systems approach expands on this by introducing a set of functions which are used to map the activities in the system. These functions are:

1. Entrepreneurial activity
2. Knowledge development
3. Knowledge diffusion through the network
4. Guidance of research
5. Market formation
6. Resource mobilization
7. Creation of legitimacy/counteract resistance to change

The first function, entrepreneurial activity, is used by Hekkert as a measure for the overall functioning of the innovation system. The other functions are used to analyse the circumstances and conditions that entrepreneurs encounter when they adopt a new development. These functions are seen as independent for the actors in the system, as any of the actors may have several roles. An assumption of the functions of innovation systems approach is that system change (i.e. innovation) only takes place when a certain threshold for function fulfilment is reached. This set of functions was determined to be sufficient, to show innovation system functioning, by applying them to a number of cases (Hekkert et al., 2007b), and by harmonizing the list of function with the list of functions used by other groups active in studying innovation, most notably Chalmers university.

Analysis is performed by gathering data on an innovation system by studying the events that have been taking place. These events could be meeting, workshops, the start or end of R&D projects, news releases, etc. These events are then categorized by function. Hekkert uses the method of events analysis as developed by van der Ven (Van de Ven, 1999) to map the activities. In this method, the occurrence of the innovation function is plotted against time to show when which function was being performed, and to spot which function might be missing and should be added in order to encourage entrepreneurial activity. Hekkert's paper on the diffusion of co-generation in the Dutch energy system is a clear example of this process (Hekkert et al., 2007a).

5.3. Social Construction Of Technology model (SCOT)

The Social Construction Of Technology (SCOT) model is used in the context of Science and Technology Studies (S&TS). It is treated in books by Bijker (Bijker, 1995), and Bijker, Hughes and Pinch (Pinch et al., 1987). The main aim of SCOT is to offer a theory for socio-technical changes.

As described by Bijker ((Bijker, 1995), page 6), science and technology studies have three main components; the systems approach, Actor Network Theory and SCOT. SCOT has a lot in common with these other elements. Treatment of SCOT can only be understood in connection to these other concepts of social constructivist studies.

The systems approach in this constructivist context holds that innovation is observed as a change on the level of society, which functions as a system. One of the core assumptions of social constructivist is that it is not technology that shapes society, but the other way round; that society gives meaning to artefacts, and thus shapes the interpretation of and demands on technological development. The influence of Actor Network Theory (ANT) can be seen in the fact that both technological artefacts and societal groups are both equally seen as actors in the innovation process.

SCOT explicitly rejects linear models of innovation ((Bijker, 1995), page 7) and can be interpreted as a reaction to linear development models, that start with an inspired invention that is cast into society with more or less success. It is argued that both the development and subsequent use of technology can only be understood by understanding the social context of those involved. As such, an artefact cannot be simple labelled as success or failure, as it may be one to the social group it was intended for, and another for a social group that sees specific problems (or possibilities) for its use of the artefact, possibly for a completely different purpose that it was intended for.

In the SCOT four types of elements are mapped together. These are the technological artefacts, social groups, the problems that each social group sees with the artefact, and the solutions to these problems that lead to a next generation of the artefact (Figure 20).

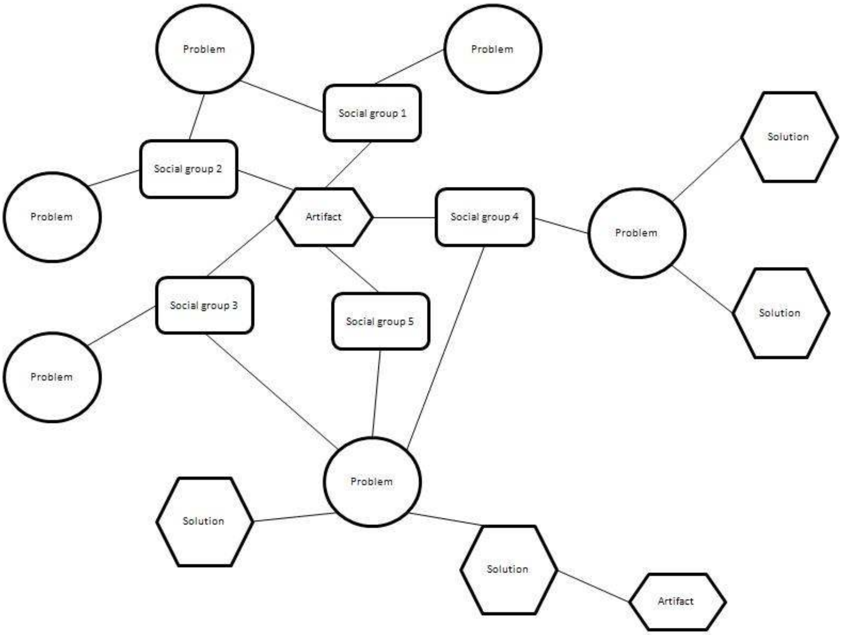

Figure 20: Mapping of problems, solutions, artifacts and social groups as performed when using SCOT

Bijker uses the terms Closure and Stabilization to describe how artefacts evolve from one interpretation to another. The process of stabilization is where relevant social groups converge on an interpretation of the problems and solutions that the artefact brings, often inventing new problems as the use of the object changes. Closure is where multiple groups adopt a similar perspective and these social groups interpret that a problem is solved, often as a result of marketing. As a result the need for alternative solutions disappears.

The SCOT model is used in collecting information about the development and use of the technology being studied, along with information on the relevant social groups. This information is then mapped to show when and how the process of closure took place.

5.4. Cyclic Innovation Model

The cyclic innovation model was developed in the context of scientific and engineering practitioners in innovation teams (Berkhout, 2000). Berkhout, Hartmann and Trott (Berkhout et al., 2010) describe CIM as being developed from the experience gained in the Delphi geophysics consortium, and several other investigations, most notable the Dutch water sector (Sommen et al., 2005), the use of new types of catalysts in chemical industry (Kroon et al., 2008) and Thixomoulding as an example of regional innovation (Van Der Duin et al., 2007).

The basic element in CIM is the feedback process between different roles in the innovation system. The roles are presented as connected by double feedback loops very similar to the system dynamics structures used by Senge (Senge, 2006).

The first double feedback system described is the dynamics surrounding technological research (Figure 21). Development of new technological solutions is driven by discoveries in the natural and life sciences, but also from functional specifications received from product development. A central notion is that each cycle represents a vital function in the system, each role has a large portfolio of capabilities at its disposal. Often multiple organizations are involved in each role.

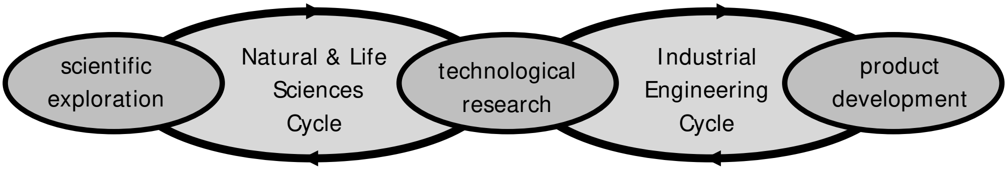

Figure 21 the dynamics surrounding technological research, showing the distinctive roles of the science and engineering communities

The other double feedback system describes the dynamics surrounding market transitions (Figure 22). The behaviour of the market is driven by both new scientific insights into consumer behaviour as well as the supply of new products and services by industry.

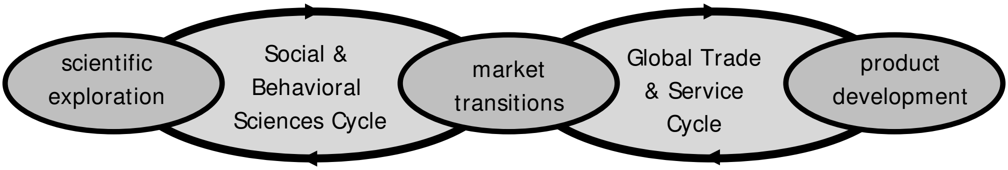

Figure 22: the dynamics surrounding market transition, showing the distinctive roles of the scientific and service communities

The dual nature of socio-technical and socio-economic developments is realized when the two double feedback processes are combined in a cycle (Figure 23). This is also where the entrepreneur role is added, as a circle captain.

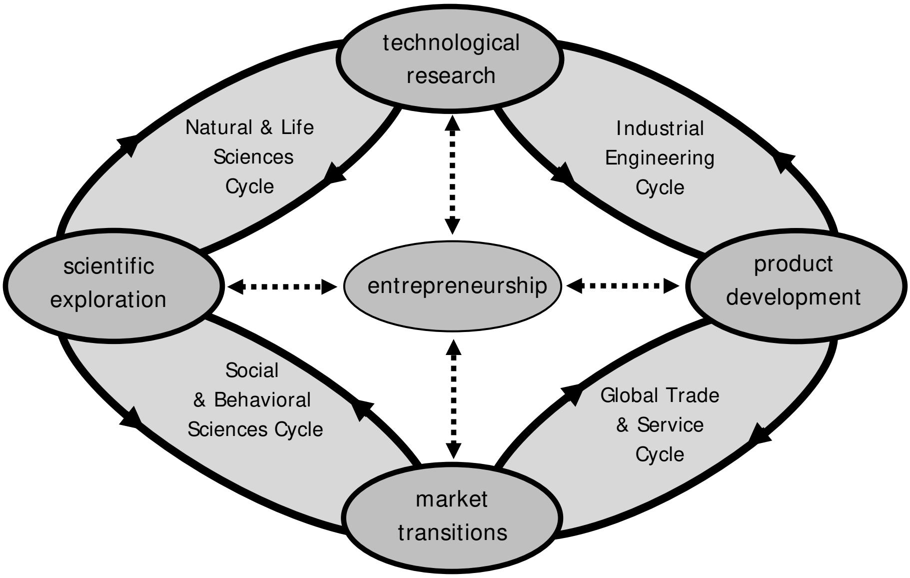

Figure 23: the Cyclic Innovation Model (CIM), showing four communities and their role in innovation.

CIM was developed as a response to a number of limitations to existing innovation models. Berkhout (Berkhout et al., 2010) lists:

1. The continuation of linear thinking as the basis of innovation and R&D management in the industry, most specifically the dominance of the stage gate model
2. Science and scientist being viewed as technological, giving insufficient attention to behavioural sciences, and as a consequence the dominant view of product over service innovation
3. Insufficient exposure to the interaction between technological and market processes
4. The entrepreneur role being neglected in most innovation models
5. The failure of most companies to include innovation in their strategic thinking (leadership circle of CIM, see chapter 1)

The most common way to use CIM to analyse an industrial sector is to identify which roles are occupied by the companies and institutions in the innovation system. This will in most cases already identify either an unbalancing of the circle, with most emphasis being on one of the feedback processes, or a disconnection between either the market and technology development, or scientific exploration and product development.

Table 12: Overview of three candidate models to model innovation NDT

Model	Background	Perspective	Extension	Opposed too
Functions of innovation model (Hekkert)	Evolutionairy economics / National systems of innovation	Institutional	Functions in innovation systems	Neo-classical economics
Social Construction Of Technology model (Bijker)	Science and technology studies	Societal	Technological development in social systems	Linear development models
Cyclic Innovation Model (Berkhout)	Science and engineering in industry	Entrepreneurial	Roles in innovation systems	Stage gate R&D management

5.5. The models as assessed according to the requirements

Now that we have become familiar with the three candidate models (Table 12) it is possible to assess them against the requirements derived in section 4.9. The assessment will be made in five separate paragraphs and a final overview will be given in section 5.6.

The assessment has been done by looking for evidence of the models fulfilling the requirements in studies performed with the models so far. If such literature is found the model is considered to have fulfilled the requirement. A qualitative assessment will be made on which model fulfils the requirements best, based on the evidence found.

5.5.1. Modelling on different aggregation levels

Each of the three candidate models has a natural initial level on which the modelling takes place.

For the Innovation System (IS) approach underlying the functions of innovation systems model, this is clearly the national level. Even though the innovation systems approach has been used in different levels of aggregation Freeman maintains that the national level is the most appropriate one (Freeman, 2002). This comment reflects that the IS approach was originally meant to assess the economic impact of innovation, which is a measure at the national aggregation level. When transferring this to the industrial sector level, some problems will be encountered, in this case mainly because of the institutional bias of the model. Hekkert himself acknowledges that the IS approach suffers from lack of attention to the micro level (Hekkert et al., 2007b). The extension of the model with the function approach helped to remedy this, but in the examples given in papers so far (Hekkert et al., 2007b, Suurs, 2009) the emphasis stays on institutional and national issues.

The social construction of technology approach models relevant social groups and technological artefacts. Because of this, the level of aggregation is fixed. In the examples in the SCOT books however Bijker and Hughes make excursions to the national and economic level (e.g. large technological systems like the railway system) and to the personal level in the case of inventors and their work (e.g. Bakeland in the Bakelite case (Bijker, 1995)). The excursions to other levels are made when the relevant social groups are active on different aggregation levels, e.g. issues regarding railroad and other large technological systems are almost invariable nationally organized. The flexibility of the concept of relevant social group makes application of SCOT at different aggregation levels possible.

CIM, until now most commonly used to investigate on sector level, has been conceived to be scale free and usable on multiple aggregation levels. In order to achieve this, the role descriptions are such that they could apply to governments, organizations, institutions and individuals alike. In a number of places, for example when discussing the entrepreneur role, this is underlined by stating that both an individual and a team could be involved. Examples in literature that show the use of the scale free approach can for example be found in the study on the Dutch water sector, which also suggests policies on the national level, and on the level of individual companies (Sommen et al., 2005).

On the requirement of being able to model on different aggregation levels, CIM most easily facilitates this, but SCOT has been demonstrated a capability to address multiple levels. The Innovation Systems approach suffers from its institutional heritage, and is not easily used on multiple levels.

5.5.2. Modelling relationships inside and outside of a company

Each of the candidate model is able to model relationships across companies naturally, however when modelling the relationship inside a company this is achieved in different ways.

In the case of the Functions of Innovation model this would be achieved by assigning different functions to different people or groups in the innovation systems. This can of course be done equally easy inside organizations and between organizations. Very little evidence can be found in the studies performed so far, as these have all been conducted by identifying functions in the network as a whole, and do not analyse who performed the function. For example, the study on the diffusion of cogeneration (Hekkert et al., 2007a) does identify the functions in the system at the micro level, but at the analysis stage this information is discarded by only plotting the occurrence of the function against time.

In the SCOT approach modelling of relationships inside a company would be achieved by determining that people or groups belong to different relevant social groups. Examples could be a different social group for sales people compared to production personnel. A clear example of how this could be done can be found in the fluorescent lighting case described by Bijker (1995).

In CIM it would be achieved by having different people or groups perform activities in different nodes or operate in different feedback processes, together working on achieving the innovation target. It is not uncommon for companies to have the activities in multiple nodes in house (e.g. product development and technological research) and other nodes at partner organizations (e.g. scientific exploration and marketing). A good example of a study in which both in company and sector wide aspects are covered is the analysis of the Dutch wind turbine industry (Kamp and Duin van der, 2011).

It is concluded that each of the model would be able to accommodate open innovation equally well, with SCOT and CIM showing examples in literature of treating both in company and across company aspects. On this requirement, CIM and SCOT are determined to be the best models.

5.5.3. Modelling both industrial and societal developments

In the functions of innovation systems approach, the difference between industrial and societal development would be assigned according to functions. However, the typical societal roles are not present in list of functions given by Hekkert. Instead the institutional functions to guide societal processes are present. Although the activities of for example users and pressure groups are identified, the result of analysis would be a set of institutional activities.

These processes are the very core of the SCOT model. SCOT is the candidate model best developed to deal with the interaction between the different interests between industrial and societal needs. The case of the development of fluorescent lighting ((Bijker, 1995), page 199) is an example.

The Cyclic Innovation Model can accommodate both societal and industrial developments. In CIM, the societal developments are considered to be part of the market transition node, as ideals, needs and concerns of users. So far no distinction between individual and collective (or governmental) requirements has been made. Both could be modelled, but for some situations a separate treatment of government or regulatory involvement may be useful.

It is concluded that SCOT is best suited to model the interaction between societal and industrial processes. CIM can also model these relationships, but so far has no specific features for modelling societal values (work is being performed to expand CIM in this area (Berkhout, forthcoming)). Conversely, the FIS approach can analyses industrial processes, but so far only the institutional ones have been clearly described.

5.5.4. Modelling the creation of knowledge and intellectual property

In the function of innovation systems approach the creation and diffusion of knowledge are two separate functions of the model. In the background National Innovation System approach it is one of the core attributes. However knowledge is treated in a very specific way, as a productivity increasing routine. It is not clear how the creation and protection of intellectual property would be treated in the function of innovation system approach, other than concluding that the ‘knowledge development’ function is fulfilled.

In SCOT knowledge generation is treated as a social construction issue, with the meaning of an artefact being constructed by the relevant social group. Similarly patents are treated as something that gets its ultimate meaning in patent settlement cases, where different interest parties meet and the judge provides closure. Several cases of patent settlement are presented in the SCOT material. The role of tacit knowledge is also treated in SCOT cases, for example where plastic makers had to acquire laboratory skills much more refined then the cookbook recipe approach used so far, in order to be able to replicate results (Bijker, 1995).

Although knowledge and intellectual property are not in the foreground of CIM, the idea that knowledge is created in every node and every cycle of CIM has been a part of the model from its first publications. Specifically Berkhout ((Berkhout, 2000), page 95) assigns to each node the creation of a different type of knowledge, identified by different type questions; why?, how? what?, and who? The traditional patent would be a *how* -type knowledge. This approach is applied in the report on the water sector, where available products, knowledge and skills are mapped to find what activities would be promising for the future (Sommen et al., 2005).

Both for CIM and SCOT, clear examples of the treatment of both codified and tacit knowledge can be found. It is concluded that SCOT and CIM are both suitable for modelling knowledge creation and intellectual property development.

5.5.5. Modelling development over time, and including feedback processed (dynamic model)

The Function of Innovation System approach was developed to improve on IS which was experienced to be too static. The original IS framework does not have an explicit way to include time dependant processes. The addition of event analysis adds this attribute. As a result cycles are detected in the innovation processes, as virtuous and vicious cycles, where the fulfilment of a particular function leads to starting of cancelling of other functions (Hekkert and Negro, 2009). An issue is, that event analysis is only used as an after the fact analysis method.

The time dependant process in SCOT is the process of stabilization and closure. This process is presented by Bijker as a cyclical process, where closure and one stage may raise a new problem for the next development stage. This way both time dependant behaviour and feedback are modelled. The only drawback is that time is not actively modelled, and remains an after the fact analysis.

CIM was built from elements out of feedback modelling, and therefore has some inherent ways to deal with time dependant behaviour and feedback. Time dependant behaviour is captured by assigning characteristic times to the feedback cycles between each node. The best treatment of this feature of CIM can be found in (Berkhout, 2000). CIM has the advantage of drawing on the experience gained with using dynamic system descriptions in the work of Forrester (Forrester, 1961) and Senge (Senge, 2006). This opens the door for actively using dynamic systems theory in suggesting course of action.

All three models clearly show evidence of cyclic processes and dynamic behaviour. It is interesting that each of the models concluded that innovation is governed by cyclic processes. It is concluded that CIM best fulfils the requirements for dynamic modelling of innovation process in NDT.

5.6. Model selections

Table 13 gives an overview of the material that was presented in section 5.5. Out of the three candidate models, CIM is determined to be the best model on most (three) requirements, while SCOT being best on two requirements. Therefore CIM is selected as the model for analyzing innovation in NDT.

SCOT would also have been a valid model to do this research, and particularly the treatment of relevant social groups dealing differently with a technology would have been of value to the analysis.

The function on innovation systems approach has a valid and valuable addition in identifying functions of innovation systems. These functions could be used with the other two models. The underlying Innovation System approach however is too much biased to institutional factors to be used for analysis of innovation at sector level.

Table 13: Overview of the process by which the different candidate models fulfil the modelling requirements

Model	**Scale of aggregation**	**Open innovation**	**Industry and society**	**Knowledge and IP**	**Dynamic modelling**
Functions of innovation model (Hekkert)	National and institutional	Different functions	Institutional functions	Learning routines	Event analysis
Social Construction Of Technology model (Bijker)	Artefacts and social groups	Different social groups	Relevant social groups	Constructed in relevant social groups	Stabilization and closure cycles
Cyclic Innovation Model (Berkhout)	Inherently scale free	Different roles	Technological research vs. market transition	Each role generates different knowledge	Double Feedback and characteristic timescales
Models fulfilling the requirement	CIM	SCOT & CIM	SCOT	SCOT & CIM	CIM

6. Interviews in the Innovation Network of NDT

In order to gather further information on the network of companies and people involved in innovation in NDT, interviews were performed with people working in a variety of roles. These interviews were structured according to the Cyclic Innovation Model (CIM), both in terms of the questions posed in the interview as well as the selection of interview respondents. The aim of the interviews was to further investigate the issues regarding innovation in NDT.

In this chapter it will be explained how the Cyclic Innovation Model was used, and how questions were derived from modelling the innovation network and innovation processes according to CIM. Next the interview protocol and interview process will be described. The selection of respondents will be explained and the method for analysis of the interview results is described.

The majority of this chapter however is dedicated to the results found in interviews, and their interpretation.

6.1. Three different ways to view CIM

One of the contributions of this research is to view CIM in three different ways. This notion arose out of studying the different ways in which CIM has been used since its first presentation in 1995. In this section these three ways of viewing CIM will be described. The interview questions were structured using these three different views as a guide.

The Cyclic Innovation Model (CIM) has been presented as a fourth generation innovation model (Berkhout, 2007). First and second generation models (Rothwell, 1994) assume a linear progression from either fundamental discoveries (1st generation) or market demands (2nd generation). During the 1970s and 1980s it was realized that these generations were extreme cases, and more flexible and interactive (3rd generation) models were developed, which were however still essentially represent a chain. CIM and other fourth generation models allow innovation to start at any point in the process and added the notion that innovation is not a linear process. CIM is the only innovation model that introduces a circular architecture.

Table 14: Thee ways to use the Cyclic Innovation Model

CIM interpretations	Unit of analysis
Model of roles in the innovation process	Synergy between roles in the innovation process
Model of actors in the innovation process	Network of actors in the innovation process
Model of knowledge in the innovation process	Integration of knowledge

6.1.1. CIM as a model of roles in the innovation process

The notion that innovation can start anywhere was based on many years of experience in innovation projects for the energy sector, in particular for the geophysical industry (Berkhout, 2000). CIM was developed in the context of the Science and Industry consortium Delphi which incorporates knowledge institutes, engineering and technology companies, service providers and corporations active in oil and gas exploration and production worldwide. It was realized that contributions are needed from sciences, technology creators, product developers and market observers.

In this original interpretation CIM is a description of the roles involved in innovation. The four primary roles; scientific exploration, technology research, product development and market transition, each interact with two other roles. The entrepreneur is seen as a central role that coordinates between the other four roles.

Since its publication CIM has however been interpreted in two additional ways.

6.1.2. CIM as model of actors in the innovation network

A second way to interpret CIM is to use it as a model for innovation network interaction between individuals, companies or larger groups of individuals and companies. An example of this kind of application of CIM is the investigation into the water sector in the Netherlands (Sommen et al., 2005). Each of the participants in the innovation network is positioned in the model by investigating which role or roles they are performing. By doing this a picture will arise about the distribution of innovation participants across the circle. Possible over or under representation of particular roles can be identified. In the case of the Dutch dredging sector (part of the water sector investigation), it was determined that the institutes active in the natural and life-sciences cycle (upper-left quadrant of CIM) were few, and not working on issues that corresponded to the needs of the industrial sector. The social and behavioural sciences cycle (lower-left) was virtually unpopulated and for that reason both sciences and industry had a lack of awareness on new regulatory requirements.

Other innovation network descriptions have so far put emphasis on the links between network actors, for instance by measuring degree centrality or betweenness of nodes. In these descriptions the nodes do not describe a role, and the competences or potential for each network node are less important. CIM conversely places emphasis on the role of the network actor, and groups the network actors with similar roles. Doing this reveals which network links are essential to innovation

6.1.3. CIM as a model of knowledge in the innovation process

The third way of interpreting CIM arose from comparison of CIM to the knowledge model used by Van der Ven in his book engaged scholarship (Van de Ven, 2007). From its inception each of the CIM nodes was identified with a defining question. The science node is identified with the "why?" question, the technology node is identified with the "how?" question, the product development node with the "what" question and the market transition node with the "for who?" question (Berkhout, 2000).

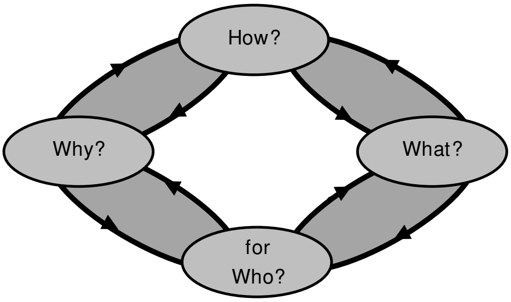

Figure 24: knowledge based creation in CIM

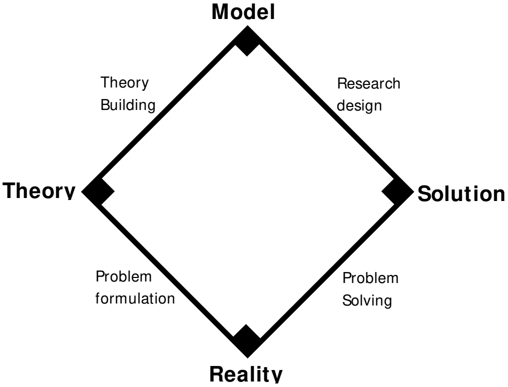

Figure 25: The engaged scholarship model of Van der Ven

Van der Ven (2007) builds up his knowledge model by starting from the different kinds of knowledge distinguished by Aristotle, being techne, episteme and phronesis (techne, the arts and craftsmanship; episteme, logical knowledge which is sometimes equated with science; phronesis, practical wisdom on how to act in a social situation) . He takes the reader through the recent discourse on the nature of scientific knowledge and particularly notes the lack of a concept for empirical observations about reality in most knowledge frameworks. He concludes that observation is different from practical knowledge, and ends up with a model where one kind of knowledge is transformed into another. Knowledge areas are identified by the type of results delivered in the process; models, solutions, theories and changes to reality. It is asserted here that the question of CIM and the knowledge distinctions of the Engaged Scholarship model are highly similar.

When interpreted this way, CIM can be used to assess whether each participant in the innovation process is generating relevant knowledge, needed to create a new solution. In practical cases it has been observed that companies or universities are generating a different kind of knowledge than they set out to generate.

6.1.4. Using the different views in the interviews

The interviews were structured to use all three views of CIM, and to use the different interpretations to reinforce and validate the conclusions reached with the other interpretations. Respondents were first asked to identify the participants in the innovation network, and the way they interact (CIM interpreted as an actor model). Next they were asked to describe a typical project, and the activities that were performed in the project. The activities asked for were of cause the roles of CIM (CIM interpreted as a model of innovation roles). Finally the respondents were asked whom they considered to be the keeper of a kind of knowledge; scientific knowledge, technological knowledge, product knowledge and knowledge about user needs (CIM interpreted as a knowledge model).

The interpretations were used to find answers to the research questions. The structure of how each interpretation was used to answer the research question will be treated in the section describing the interview protocol (section 6.3).

6.2. Interview respondent selection

In order for the interview results to be used in the CIM framework, the respondents needed to cover each of the roles identified in CIM. CIM however only describes roles, and not the company, institution or individual performing the role. In order to identify the people performing these roles, the respondents were first asked the open question, who they considered to be participating in the innovation network, and how they interacted with these people. The organizations mentioned were then added to the list of people to approach for an interview. Also, the description of these people contributed to the framing of actors into CIM roles. The type of interaction described gives a good indication about the role the mentioned person, company or institute plays in the innovation network. The respondents were then asked who performs each of the CIM roles in the innovation model directly, as verification of the initial open question.

An additionally dimension considered was the aspect of cultural and traditional differences between national NDT communities. Within Applus RTD, the UK business unit had substantial revenue in innovative NDT services, whereas the German business unit only has a small central team performing advanced NDT. Therefore, the German innovation culture is considered to be traditional and conservative, while the English system is considered to be innovative. Respondents were selected to be from three different countries; The Netherlands, the United Kingdom and Germany to address this dimension.

Table 15: Interview respondents

Respondent	**Company**	**Country**	**Position or Job title**	**Reference in this thesis**
Frits Dijkstra	Applus RTD (NL)	Netherlands	NDT consultant	Int1
Arno Volker	TNO Science and Industry	Netherlands	Innovator	Int2
Andreas Hecht and Peter Rost	BASF Technical and Engineering Services	Germany	NDT manager	Int10
Erik Zeelenberg	Lloyds register	Netherlands	Lead specialist NDT	Int9
Hugo van Merriënboer	Total E&P Nederland	Netherlands	Inspection and integrity manager	Int4
Sieger Terpstra	Shell Global Solutions	Netherlands	Inspection technology engineer	Int5
Jim Costain	GE sensing and inspection	United Kingdom	Oil and Gas segment leader	Int7
Ken Seward	Acergy	United Kingdom	NDT coordinator	Int13
Steve Burch	ESR technologies	United Kingdom	NDT project coordinator	Int14
Raman Patel	HSE	United Kingdom	Off shore inspection regulator	Int15
Ralf Dix	Applus RTD (Germany)	Germany	Advanced inspection manager	Int12
Alan Hipkiss	Applus RTD (UK)	United Kingdom	Advanced inspection manager	Int16
Marcel Blinde	Applus RTD (Corporate)	Netherlands	Chief Operating Officer	Int3
Norbert Trimborn	SGS	Netherlands	Advanced NDT manager	Int8
Gert Dobmann	Fraunhofer IZFP	Germany	Deputy institute leader	Int11
Jan Verkooijen	Sonovation	Netherlands	Director / owner	Int6

6.3. Interview protocol

The interview was performed as a semi structured interview. Prior to the interview a protocol was made, and discussed with the PhD supervisor. The interview with Frits Dijkstra was performed as an initial test of the protocol, after which the protocol was revised. This revision was very minor however, leading to the test interview being used as part of the data set. Specifically, the protocol was shortened by dropping a section on the role of codes and standards and some of the questions were slightly reformulated to make them more suitable for an interview situation. The section on codes and standards was dropped as this made the interview impractically long and did not yield additional information on the innovation process. Issues brought up in this section had already been addressed in interview section B and E in the trial interview. The final protocol can be found in the Appendix. The interview protocol is organized in five sections A through E which will be described below.

Table 16: Interpretations of CIM and the way they are used in the interview process

CIM interpretations	Unit of analysis	Section in interview protocol
Model of roles in the innovation process	Synergy between roles in the innovation process	Section C; discussion of a typical innovation project
Model of actors in the innovation process	Network of actors in the innovation process	Section B: discussion of actors in the network
Model of knowledge in the innovation process	Integration of knowledge	Section E: discussion of who has which kind of knowledge

Table 17: Schematic overview of the interview protocol

Interview section	Description	Primary research question answered	Provides validation to sections
A	Identification of respondent.		
B	Description of network actors the respondent is interacting with.	- Who are the actors in the innovation process? - How do actors interact?	
C	Description of a typical innovation project in NDT.	- What are the technical issues to be resolved?	Validation of B
D	Questions regarding the events and conditions that hurt innovation.	- Why is innovation slow? - Who benefits from innovation?	Validation of B and C
E	Investigation to find out who has which knowledge in the innovation network.		Validation of B and D

After asking for the information on the respondent's organization and position, the interview was opened with an open question; asking the respondent what they considered innovation to be (section A in the interview protocol). This question was mainly meant to open up the conversation and take it away from everyday activities, but also gave information on the innovation culture of the respondent, and respondent's organization, before having been framed by other interview questions.

The second section of the interview (section B) focused on who is active in the innovation network. The questions in this section were ordered, to first ask the respondent an open question; listing the innovation participants, and then asking for specific other actors. Where necessary the respondents were asked if they were in active contact with other innovation participants.

In section C of the interview the respondent was asked to describe a typical project. These questions were meant to uncover what innovation trajectory was taken in the project, and to find out how the project mapped onto CIM (the process of mapping is explained in chapter 7). An additional benefit of treating a typical project was that the information could be used to back up the information of section B, on who was active in the innovation network.

In section D some of the research question of this thesis where directly posed to respondents. In the actual interviews, these questions were often illustrated with information from the case study in chapter 4 of this thesis. The objective of asking these questions directly was to uncover what interpretations about the speed of innovation are present in the NDT community. These interpretations were then explored with the respondent.

The last section of the interview (section E) asked the respondents who they considered to have certain kinds of knowledge. The objective of this section in the interview itself was primarily to be a check on the information given in sections B and C. In the broader academic context, this set of questions is a check on whether the use of CIM as a knowledge model is useful and accurate.

6.4. Interview process

Interview respondents were approached in joined industry meetings and conferences and in some cases by phone and asked if they would be willing to be interviewed. On a positive response, an appointment was made by e-mail in most cases. In this e-mail the goal of the research was explained. In some cases, respondents suggested someone else in their organization for an interview and these people were contacted.

The interviews were taken face to face in most cases. Where possible this was done at the respondents facilities. Two interviews were held in hotel lobbies (int7 and int13). Having interviews face to face was not always easy to arrange as almost every company involved had travel restrictions in place after the 2008 financial crisis. The remaining interviews were held over the telephone (int14, int15 and int16).

All respondents agreed to have the conversation recorded. These recordings were transcribed and returned to the respondent for comments. In several cases the respondents asked for comments about other people and companies to be removed as they were considered to be too sensitive. In general however the transcriptions were confirmed for use in the research without major changes.

All interviews were taken by the author. Special attention had to be paid to the role of the interviewer as he was in a professional relationship with the majority of the respondents prior to the interview, being an employee of Applus RTD. In some cases, especially while interviewing competitors of Applus RTD, time had to be taken to justify the research as independent from Applus RTD's interests. Where this was the case, the sharing of case research results was used to get the interview going.

6.5. Interview analysis methodology

The transcriptions were analyzed in two ways. The first method was to tabulate the responses to the research questions directly. These results are presented in sections 6.5 through 6.8. The second method was to code the transcriptions for typical remarks and responses, and then use elements out of the grounded theory methodology to find relationships between these comments. The results are presented in sections 6.9 through 6.11. In this section both analysis methods will be further explained.

The tabulated answers to the interview questions were used primarily to determine how the innovation network in NDT maps on the Cyclic Innovation Model, but the answers also give some information on the innovation process itself. The interview results given below try to present a picture of the material discussed with the interview respondent as a response to the question. The analysis with respect to CIM will be treated in Chapter 7.

The analysis with methods derived from grounded theory was performed in the following way. The interviews were analyzed line by line and coded for subjects and conversations that came up in the interview (this process is called open coding in grounded theory). These subjects were written on index cards, with each index card listing in which interview, and at what line the subject was encountered. These subjects were then sorted into categories. The interviews were then reread and compared to the categories (along the constant comparison concept of grounded theory). The categories were then conceptualized and a summary of the insights reached was written up.

The second analysis method was used to have a structured way of analyzing the interview that would allow for unexpected results to show up out of the interviews. It was not used as a way to arrive at new theory, as CIM remains the main theory underlying the investigation. This is the main reason why the methodology used is not referred to as grounded theory.

6.6. Interview results – innovation network

During the interview the respondents were asked about the participants in the innovation network in three different ways. In the first way, the respondents were asked to state whom they considered to be the participants. Some of the respondents initially chose an internal company perspective naming departments they had to interact with, while others chose an external perspective naming other companies or institutions they had to interact with. Overall 8 respondents primarily chose an internal perspective, while 7 chose an external perspective. One respondent explicitly stated that the way innovation was viewed in his company was changing, with seminars being organized to educate people on viewing innovation differently and being more open to external parties participating (int5). Table 18 shows the responses ordered by respondent role:

Table 18: Initial perspective taken on innovation projects

Respondent role	**Internal perspective**	**External perspective**	**Perspective changing from internal to external**
Asset operator	2		1
Service provider	2	4	
NDT equipment supplier		1	
Regulator	1	1	
Asset builder	1		
Scientific institute	1	2	
Total	**7**	**8**	**1**

The results presented in Table 18 show almost as many people taking an internal as an external view. Given the fact that all respondents were in project with external parties in order to innovate, the amount of people with an internal perspective is remarkably high.

All respondents eventually continued to discuss the other companies and institutions in the network. The initial spontaneous response, when asked with whom they interact in order to innovate, differs significantly from the response that is given once respondents get asked if they cooperate with a specific other party. Table 19 shows the different roles that respondents distinguish in their response, as well as the parties that were involved in the project or product they chose to discuss as an example for innovation in their organization.

Table 19: Participation in innovation projects by role. The 16 respondents were first asked to name the participating roles themselves. Roles that were not named were then put forward by the interviewer. The respondent could then acknowledge if this role was participating. Finally the projects that the respondents choose as a typical innovation project also show a number of roles participating.

Organizational role named by respondent	**Roles that were spontaneously named by respondent**	**Roles that were acknowledged with the aid of the interviewer**	**Roles that were present in the project described by the respondent**
Asset operator	14	16	15
Service provider	12	15	13
Asset builder	5	13	8
NDT equipment provider	7	8	7
Scientific institute	5	13	10
Regulator	4	12	6
University	2	6	0
Government	4	4	0
Internal R&D department	4	n.a.	n.a.
Insurance company	2	0	0

In the spontaneous response of the respondents the innovation is primarily carried out by an Asset Operator (often classified as End User of the NDT by the respondent) and a Service Provider, this is confirmed by the examples of projects given by the respondent. The only example where no Asset Operator was directly involved was the acquisition of a CT equipment business by GE (Int7). The cases where no Service Provider was directly involved were the development of a Rod Anode digital radiography system where BASF performed the NDT from their internal NDT department, the acquisition of a CT business by GE (Int7) and the development of CUI regulations at the HSE (Int15).

A remarkable result was the low recognition and participation of equipment providers. In a number of interviews, the equipment providers were explicitly excluded as an innovation partner and being described as slow, inflexible and unresponsive. In more extensive responses it was explained that many of the problems that service providers get asked to solve, the response time needs to be very short, and the parameters for the problem are such, that small, highly specific alterations to equipment have to be done. Service providers have a number of ways to solve this, including getting an equipment provider involved (Int8, Int16), making their own modifications (Int12, Int14) and making their own dedicated equipment (Int11, Int2, Int6, Int1, Int3, Int10). In the discussion a number of issues regarding cooperation with the equipment providers are revealed. Firstly service providers and equipment suppliers are on a completely different timeline concerning innovation. Service providers need to respond quickly or be faced with a client that gets angry (Int16) and in an internal company culture where projects longer than a year are considered a problem (Int3). In contrast, the equipment providers are talking about five year future scenarios for their equipment (int7). A second issue that is revealed is that the information about problems is communicated very badly across the industry. A very clear illustration is that three respondents chose the same issue, pipe support corrosion, for their innovation example and came up with a different solution. In each of the cases a Shell facility was one of the initial clients. Each of the three respondents looking at support corrosion explains that even though this issue was widely considered to be a problem, only the specific clients seemed interested in their solution. In other words; practical problems are solved on a short term, case by case and plant by plant basis, and are not picked up as an industry wide issue. Solutions are then communicated by word of mouth (Int12, Int16).

The conclusions out of this section are:

- Innovative solutions are demanded by the clients industries on a plant by plants basis in a direct relationship between a service company and asset owner
- Solutions are demanded on a completely different timescale then the times scale on which they get produced by equipment providers
- Solutions are communicated by word of mouth

6.7. Interview results – benefits of innovation

When asked to state; who would benefits most from innovation in NDT, the answer of the respondents was one of three typical answers. The answers were:

1. Asset owners benefit most
2. It is unknown who benefits most
3. NDT is done for the benefit of the general public

Table 20 shows the distribution of the three typical answers. One answer did not fit in any of the three typical responses and the subject was not discussed in one interviews. From Table 20 it can be observed that these opinions are spread remarkable even over the respondent roles, with the exception that service providers seem to be more positive about the value of their service than other respondents.

Table 20: Benefits of innovation. Response to the question; "who benefits most from innovation in NDT?" The answers of respondents fitted into three categories: (1) the asset owner benefits most (2) the general public benefits (3) it is unknown who benefits.

Respondent role	**Asset owner benefits most**	**Unknown who benefits**	**The general public benefits**	**Other answer or not discussed**
Asset operator	1	2		
Service provider	4		1	1
NDT equipment supplier			1	
Regulator			1	1
Asset builder		1		
Scientific institute	2	1		
Total	**7**	**4**	**3**	**2**

Most respondents have the opinion that the asset operators benefit most from innovations. The service providers don't mind that the asset owner benefits most and state that it is the end user who runs most risk, and in many cases also funded the innovation and should thus be rewarded (Int6, Int8). The actual savings described by the respondents are typically a cost saving compared to the alternative conventional inspection method. Hecht and Rost (int10) give examples of saving due to not having to access vessels and not having to build scaffolding. Burch (int14) had an example where a new inspection method saved the client 6 million pounds compared to the alternative method of inspection of pipe supports, which would probably have meant that the main pipeline for importing gas from the North Sea into the UK would be shut down for the inspection.

Zeelenberg (Int9) expresses a tension between cost and benefit of innovation in NDT. He describes a case where the prescribed inspection of vessels filled with CO2 was internal visual inspection. This type of inspection is meant to detect corrosion, but this kind of vessel will not start to corrode unless opened for inspection. The inspection that was originally described in the regulation was ineffective and harmful to the asset, and the alternative cost saving compared to the initial regulation. However this innovation does not solve the issue of the initial inspection being ineffective and to some extent unnecessary.

In cases where no clear example is given, the respondents often point to the avoidance or prevention of downtime of major plants. Finding a defect that would have otherwise shut down a refinery for days and thus save millions is of course an impressive achievement.

Those respondents, who say that they don't know who benefits, point to the fact that inspection and NDT are part of a larger system. They also refer to the prevention of downtime, but now explain that with all that is going on in a refinery or chemical plant it is very hard to say, at the end of the year, what prevented downtime that did not happen. There are many service providers active, providing many different services, all contributing to undisturbed operation (Int5, Int16, Int14). When something goes wrong, it can often be found out what kind of preventive measure would have prevented the problem from occurring. When no accident happens however, it is almost impossible to say which of a number of preventive activities was responsible for preventing an incident, as nothing happened.

Van Merrienboer (Int4) comments that innovators have to realize how much additional cost is involved in implementing a new inspection system into the asset owners system, and specifically mentions the cost of validating the new technology which is often not done by the service provider themselves.

The third typical response is that inspection and NDT, in the end, are performed for safety of the general public. The process they describe is where a new safety issue is found, and a new inspection technology has to be invented to ensure safety. Often it is a regulator raising this issue with the asset operator (called Duty Holder by the regulator in this respect) who then charges the Asset Operator with inspecting the asset (Int14, Int15). The regulator is often mistakenly regarded as a law maker (Int1, Int9). In these cases there is often no previous way of inspecting the asset and thus no cost saving comparison. Dobmann (int11) explains that since inspection is a government mandated activity, it should also be the government that oversees and funds research into NDT up to and including the validation. This is also observed by Zeelenberg where he finds that the industry has the attitude that if inspection needs to be improved, the government has to provide funding for research and development of standards (Int9).

When combining the three typical responses the overall picture is that since the original value of inspection is expressed as a compliance with regulations, it is very hard to express any change in this value for the asset owner. It doesn't matter how well and good an inspection technology is; when the intrinsic value of the inspection is not known, it is also impossible to express the improvement. The fact that many people in the NDT sector don't know how their results are being used (Int2, Int4) also contributes to an overall picture where value is insufficiently expressed. A contributing factor is that many NDT technologists are bad at explaining their often complicated technologies (Int6, Int16).

The conclusion out of this section is:

- The value of NDT is not known very well, making the value of NDT innovation hard to express

6.8. Interview results – why is innovation in NDT slow?

During the interview the respondent were asked to state why they think innovation in NDT is slow. This question was often preceded by a discussion on the cases studied in chapter 4. From the response it is first of all clear that none of the respondents think it is inevitable that innovation in NDT is slow, many literally stating that innovation in NDT need not be slow (int11, int10 and int14). The discussion that followed focused on factors making innovation slow compared to disciplines with similar technology.

In the interviews many different reasons were given for the relative slow pace of innovation in NDT. No preference for any one reason could be determined. The reasons are given here in arbitrary order and are followed by a short description of the discussion regarding them. The reasons given were:

- The inherent conservative nature of the NDT industry
- Low priority assigned to inspection and NDT in public and political debate
- The NDT sector is a small sector and therefore unattractive for investors
- Lack of organization in the NDT sector
- Difficulty of getting the value of new technologies across to clients

A number of respondents mention that the NDT industry is inherently conservative (int1, int3, int9). When asked what is meant by conservatism, the respondents either explain that people generally don't like change, or they link it to some aspects of the sector. An example is the structure of codes and standards (int1, int3). This structure favours technologies that are already in the standard compared to new technologies. In many cases the NDT client will simply look what NDT method is described (and in some cases prescribed) in the standard or recommended practice regulating the issue he is working on, and never look for innovative alternatives.

Many standards do offer a possibility to use new technologies, but in many cases a long and expensive validation program has to be performed in order to be allowed to use a new technology. Not only is this a barrier to entrance of new technologies, it is also an area which scientist and technologist are not paying much attention to (int2, int11, int14), and which practitioners are not capable of performing (int2, int3, int4). This is linked to the relative low level of education in NDT, and the resulting lack of reflective skills (int2, int4, int11).

Another factor linked to the inherent conservatism in NDT is the relative old age of people involved in NDT in general (int3) and in codes and standards committees specifically (int7). The dominance of older people in committees seems to be an indication of the value placed on age and experience in nominating people for committee work (vs. for example financial or academic successes).

Several respondents mention the low priority of NDT and inspection in the industry and in public debate (int2, int4, int8, int12, int15). The result of this low priority is that investments in NDT innovation are low compared to neighboring technology area's (e.g. medical and geophysics research) (int14, int15, int11, int16). It is understandable that government research funds would go to something that has public interest. Most large corporations closed their NDT research facilities (int6, int8, int10) and there are few research funds that allow for NDT projects to be submitted. The only time when NDT comes into view, is when a large industrial accident happens.

NDT suffers from the fact that unless an accident happens, the importance of inspection is not evident (int2, int8, int12). Often investments in NDT only take place after regulatory pressure (int7). This makes NDT a likely candidate to be targeted for cost cutting. A number of respondents mention the cost oriented approach Asset Operators take to NDT service providers (int2, int3, int7). One even goes so far as to call the relationships between service providers and their client's dysfunctional (int7). The low priority of NDT also causes, that when NDT finally gets the opportunity to innovate, people have been turned down on their plans so often that they no longer know how to innovate (int11).

On top of being low priority, the NDT sector is relatively small, certainly compared to the medical diagnostics sector. The small size makes NDT an unattractive market for investments (int4, int14, int15, int16). Recent valuation of NDT companies in mergers and acquisitions and initial public offerings (e.g. purchase of RTD by Applus and IPO of Mistras holding (Weyers, 2010)) does not support this view, or at least seems to indicate that given enough concentration the NDT sector might be more attractive than these respondents think. It should be mentioned however that this is a relatively recent development.

Related to the small scale and low priority, one respondent mentions that innovation in NDT suffers from lack of organization of NDT research (int4). Apart from industry initiatives like HOIS and PRCI (int9, int4, int5, int7, int14, int15, int16) solutions typically get developed on a plant by plant basis (see also section 6.6). It seems plausible that some benefit of scale could be achieved by pooling resources. A number of other respondents are critical about these joint industry initiatives however, as they see issues with respect to intellectual property (int3, int6, int8).

A final factor in the slowness of NDT innovation is in a lacking sales process. The NDT sector is very technologically oriented, and technicians often do not make very good sales men (int6). Many of the NDT clients in the interviews give examples of technologies being either oversold, or being sold by just stating the technical capabilities, but without making a link to the application it could be used for. The result is that the value of NDT technology is not gotten across to the client (int9, int10). A typical story is of NDT technology being advertized as finding more flaws, which actually made clients afraid to try the technology, as they were afraid of having more rejected welds (int1). The technical orientation of the NDT sector also shows in the fact that many NDT companies have very little marketing activities, resulting in their clients, and sometimes even their own employees being unaware of new solutions (int10).

The conclusions out of this section are:

- Codes and standards play a role in keeping NDT conservative
- NDT has a low priority unless an accident happens
- Service providers lack a marketing and sales process which results in clients getting techniques sold in glossy brochures, where they need statistical proof

6.9. Interview results – relationship between practitioners and scientists

Innovation in NDT involves basic, sometimes fundamental science, high tech engineering, as well as practical work. Some of the remarks of interview respondents indicate that the people performing these activities don't cooperate effectively. This section will explore the comments that point to this finding.

On the scientific side, NDT is described as a cross section science, requiring the involvement of various scientific (physics, materials sciences, mathematics) and engineering (electronics, computer and mechanical engineering) disciplines (int11). Keeping knowledge at the state of the art requires active involvement in each of these disciplines, which is time consuming and expensive. It also makes NDT an attractive subject for people with a science and technology interest (int1, int2, int5, int6, int8, int10, int12, int14). These people describe their work as varied and exiting.

On the practical side, the work is described as hard, requiring long hours and perhaps being underpaid given the risk and hardships endured while working in heavy industry (int2, int5, int7). Also the work is far from simple, as practical situations tend to be more complicated than expected (int14) while at the same time requiring precise work (int6).

Several respondents are critical of the attitude of the people active in the development of new NDT techniques. Scientist are criticized for going from subject to subject like a bee flying from flower to flower, only tasting the nice sweet honey of a new subject (int11), while at the same time not being occupied enough with validation of their findings (int11). The need to finish projects, bringing prototypes to the field (int13) and continuing work until the result is implemented into a procedure by practitioners (int10) is mentioned.

The practitioners are also criticized. Practitioners are said to have little imagination (int2) and to reject ideas that have been developed using scientific methods out of hand (int1, int2, int4, int6). An example is the reluctance to accept acceptance criterions for flaws that are based on probabilistic methods (int1, int7, int9). Practitioners are not used to work to the rules for accuracy and registration of results needed to draw valid scientific conclusion from the measurements they make (int8). It is not uncommon for delicate instruments to return from the field broken, as practitioners simply didn't understand what they were working with (int2).

In general practitioners do not have higher education, and this turns out to be a problem in implementing new techniques. The validation work that is needed to accept a new technique as an acceptable method for assuring the integrity of an installation requires skills in statistics and scientific methods which the typical practitioner does not have (int4). Instead people are certified for the next practical skill without these people also having the necessary background knowledge (int9, int4). In the background is the desire to perform NDT with cheaper labor (int3).

At the same time nearly every interview respondent seems to rely on NDT service providers for taking the innovation the final step. This is evident from the response to the question on who has practical knowledge. When asked who has practical knowledge, each and every interview respondent only mentioned field personnel. In every other area of knowledge, more than one group is mentioned, except for practical knowledge. From the interviews themselves it is very clear however that those respondents who have an academic education, or work as scientists have been in the field, and have practical knowledge (int1, int2, int4, int5, int 11, int14).

Table 21: The types of organisations that the respondents credit for having particular types of knowledge. Respondents were asked who had a typical type of knowledge and then named the organisations that they consider this knowledge to have.

Type of organization named for having a particular kind of knowledge	**Scientific knowledge**	**Engineering knowledge**	**Practical knowledge**	**Requirements knowledge**
Scientific institute	6	2	0	0
University	8	2	0	0
Asset operator	2	1	0	8
Service provider	4	5	11	2
Equipment supplier	2	6	0	0
Trade association	1	2	0	0

The result of the reliance on field practitioners to innovation is that a small number of practitioners with an aptitude for science are called on for every new technique (int1, int16). They often however are not proficient at these new techniques, because, as a result of being involved in every innovation, they never do enough work to remain trained for performing each of them (int10). In the concluding chapter of this thesis it will be argued that both scientific and practical skills are needed for the person taking an innovation through the last step, and that the industry has relied too much on these few talented people.

In the atmosphere of mutual criticisms the reality is, that scientist and practitioners do not communicate, leading to findings out of research not being known in the field (int2, int4). At the same time conclusions reached in the field are not implemented in research, and research just goes on without validation (int1, int4). In other words; people in NDT are not aware of what others are doing on their subject. This was also evident in some of the respondents not being aware of major findings and research by other respondents (int1, int2, int8, int10). One of the impacts is, that developers of new technologies do not receive feedback, and that therefore these technologies do not get updated and improved, resulting in products that remain incomplete and underdeveloped.

The conclusion out of this section is:

- Service providers lack competences to develop complete products for the industry, and the distrust between scientists and practitioners prevents them from obtaining those.

6.10. Interview results – intellectual property

The protection of intellectual property was mentioned in a lot of interviews. The way in which it is important is different depending on the role of the respondent.

The representatives of research institutes explain that although they would like to protect the intellectual property they develop as soon as possible, this is not always straight forward. Companies and the government have different desires. Governments typically want the knowledge to be available to anyone in the industry, while big industrial companies want to obtain exclusive licenses (int2, int11). Research institutes themselves want to keep title to the intellectual property, as it is the material that is needed to be able to start new projects.

In NDT a lot of intellectual property is developed in Joint Industry Projects (JIP). In the project charters for these projects the intellectual property that gets developed typically stays with the organization that produced it. All companies that participated will have some rights to the knowledge produced. In practice this often means that scientific work is done in the project, but that complementary work that will make the intellectual property into a finished product, that can be used in the industry, is done by the research institute internally, or in a project separate from the JIP by the institute and a company that was part of the JIP, but wants the product for itself.

NDT service providers then find themselves with rights to some Intellectual Property, but not being able to use it without paying for the complementary work (or having to perform complementary work). Service company representatives in the interviews express that this makes them feel as if they have to pay twice for the same work (int6, int8), as they feel the essential part of the product was developed with their money. Also the complementary work will now be locked in an exclusive arrangement, limiting the availability of the IP to potential other partners.

One of the common subjects of research in a JIP is the validation of inspection techniques for a specific application. These 'blind trials' or 'round robin tests' involve the research institute making a sample of the object or component to be inspected with artificially induced flaws (or sometimes real flaws). Inspection companies are then invited to demonstrate that they can find these flaws with their latest invention. The objective is to show to asset owners, who are typically paying for the trial, which technique works and which doesn't. After the trial is finished there are often some inventions that turn out to be disappointing and some that did well. At the end of the project the institute will want to publish these results, as scientific work. The inspection service providers will have mixed opinions, based on whether they are able to offer one of the techniques that performed well. The asset owners however will typically not want to publish results, as non participants to the JIP will benefit from this. In a number of trials this has resulted in a stale mate, where the report is not being made public for many years (int14). The CRIS report is an example of this happening (Burch and Hood, 2011). This report is based on work performed in the late 90s, but was only published in 2011.

New technology in NDT often originates from other application fields (int1, int14). This in itself makes NDT technology harder to protect by means of patents, than technology in an application field that does more fundamental research itself (int14). This seems to have resulted in a sector where being secretive about technology is the norm (int1, int2, int3, int6, int8). As can be seen from the cases in chapter 4 there is good reason for this, as in most of these cases some technology was copied. For the acceptance of new technologies, however, it would be much better if the NDT sector were to use open standards (int1, and next section).

The conclusion out of this section is:

- Protection of new NDT technique as Intellectual Property often leads to a stalemate and to a culture of secrecy.

6.11. Interview results – acceptance of new technology

The acceptance of new technological solutions by the asset operators, as a valid way for inspecting their assets, was discussed in many interviews. The main criterion for accepting a new technological solution is its reliability as an inspection method. The asset operator needs to get information on this reliability. This information needs to be of good quality, meaning that it is statistically relevant and has some degree of scientific rigor (int4, int8, int10). The reason is that the inspection technique will be incorporated in an Asset Management system that is itself statistical in nature, with statistical methods making the link between the different engineering disciplines involved in asset management. In the case of NDT, this link is mostly between the measurement physics involved in NDT, and the engineering discipline involved in assessment of defects; e.g. fracture mechanics, materials and corrosion engineering and welding engineering.

One of the problems in this acceptance process is that the traditional methods that are often used for inspection (e.g. weld radiography) never had to pass this test. As is attested by many of the respondents, these traditional methods are not very good, and would never pass a scientific test. The main reason is that they are impacted too much by the human factor (Wall et al., 2009). These inspection methods however have been used for at least 50 years, and have a track record of preventing most serious incidents (int9). These traditional methods, when used properly, have made the oil, gas and chemical industry one of the safer places to work. With respect to new technique this situation creates a double standard. Many new techniques are much better than their traditional counterpart, but do not meet the much higher standards of scientific evaluation (int9).

Traditionally the information on reliability of NDT techniques was gathered by the research departments of the large industrial companies, or in research programs setup by national laboratories or trade organizations. Overtime, these research departments and national laboratories have been reduced and now the asset owners mainly rely on the service providers to supply them with the background information needed to assess the technological solution. The asset operator representatives interviewed are very critical of the quality of information received from service providers. The information typically takes the shape of glossy brochures that do not have a lot of technical detail, and are experienced by the asset operators as overselling (int10, int4, and int5). Mr. Hecht of BASF has a collection of examples of overselling in brochures which he showed me, where some service companies literally claim to solve all inspection problems.

Overselling in brochures and in conference presentation is acknowledged by service providers (int1, int6 and int12), although the respondents interviewed all go to considerable length to avoid it. For the service companies, the ability to offer new techniques is seen as a competitive advantage. Service companies try to be able to offer every technological solution available, sometimes just to be able to keep competitors of the clients' grounds (int1, int16).

Asset operators use their network with NDT experts in other asset operating companies to gather information on new techniques. The interview respondents offering new techniques comment that rumours, especially about new techniques failing on a job, spread quickly (int2, int12). This network is also the main avenue for new techniques to be requested by asset operators. They have heard something good about it from a colleague, and now want to try it too (int12). Yet, because of the incomplete information of the asset operator until that point, trying a new technique is experienced as taking a risk, and somewhat of a leap of faith (int1, int2, int3, int8 and int9). Asset operators are experimenting with new techniques, despite having insufficient data on the performance of these techniques (int4, int5). One respondent stated that it was easier to get funding for applying an un-validated technique and risk wasting money, than it was to get funding for validation (int4).

The start of working with a new technique is typically a validation of the technique at the plant where it is to be used. These validations are often performed for every location individually. There are several reasons for this. Firstly, the regulator for this location also has to be convinced, and is similarly critical to new technological solutions as the asset operator (int9). While an asset operator may have similar plants in other countries where the technique was performed, these may be in a different country with different regulations. The second reason is that performing a validation will give the local NDT expert of the asset operator bargaining material for his network. The result is that for service companies, performing validation is a very repetitive activity, and experienced as something that is to some extent pointless (int3, int6, int7).

Service providers typically do not have the competences to perform validations and even if they had, they might not be acceptable performing validations. Self validation would be considered to result in a conflict of interest. The solution is to have a qualified third party do the validation. These validations are very costly to the asset operator (int4). This also introduces another party to the process. Validations are typically performed by companies that either are or used to be national laboratories, or by certification companies like TÜV, Dekra, Lloyds Register and DNV. Of course these companies also want to make money, and try to create a business model around doing validation projects (int12). This is seen as a negative development by service companies, and as ultimately making acceptance of new technique even harder (int6, int8). These service companies would rather see some national authority re-installed (int16), or a new cross industry institute founded (int5, int8).

Given the lack of scientific expertise at service providers it is not surprising that the new techniques often have significantly less performance than originally claimed. The result of validation projects are often the starting point for explorations leading to improved or new techniques. According to a large number of respondents, the acceptance process of new technique has the character of a hype cycle, with a period of hype being followed by a period of disillusionment, and then finally acceptance (int2, int4, int5, int10, int12, int14, and int16). Hype cycle is a term that has been coined by Gartner (Fenn and Raskino, 2008) since 1995, but descriptions of this kind of behaviour have been recorded much earlier than 1995 in NDT (Scruby, 2007).

In addition to confirming the conclusion that the relationship between scientist and practitioners is an issue, a conclusion out of this section is:

- Codes, standards and regulation favour established technologies. New technologies are judged by a more demanding standard than established technologies.

6.12. Interview results - the regulatory process

Related to all the issues describe in the previous sections is the regulatory process in NDT. It should be noted that not every industry is regulated in the same way. For example, the railway industry is regulated differently than the oil and gas industry. The general structure of regulation is that the industry determines an acceptable level of inspection and testing. This is done by publishing a recommended practice or standard. The government then refers to this standard in laws, and appoints a regulator to oversee the adherence to these laws (and consequentially the adherence to the referred standards) (int9). As described in section 3.2 the exact structure is different in every country.

One of the consequences of this structure is that the regulator is seen as an extension of the government, which in most cases is not correct. It is then also assumed that since the government makes the law, the government is also responsible for the content of the standards to be adhered too. These two common mistakes combined can lead to many misunderstandings. Combined they result in regulators being regarded as law makers (int1, int9).

The regulators primary role is to prevent hazards (int15). In this role he needs to react proportionate to the problems observed in the regulated industry. He wants to avoid conflicts (int9), but will also need to appear vigilant to avoid the prejudice of being soft on industry. Industry will need to maintain a good safety record or risk a challenge to their license to operate. This is considered a real concern for duty holders (int4).

The response of a regulator to a new threat to safety is to flag the issue with the duty holder. If insufficient action is observed the regulator will officially raise the issue and at some point the regulator will charge the duty holder to perform inspection (int12, int14) or other remedial actions, up to and including shutting down operations. If the issue is present more broadly in industry, he may also call for industry to make a new recommended practice (int15). The speed at which the issues are resolved is linked to the perceived risk (int11 and int16), and as a result incidents drive innovation as an incident will increased the perceived risk associated with an integrity issue.

The response of regulator to new NDT technology is mostly indifferent. The regulator has no intention to innovate (int9). When a regulator gets approached by an NDT service provider with a new technology, his role is to assert that the new method is suitable for meeting the legal requirements. In cases where the NDT method is regulated this means that the duty holder has to convince the regulator that the new technology is at least equivalent to the usual on. Both service providers and duty holders regularly try to get regulators to approve new techniques that are not up to standards (int9). Combined with the fact that regulators do not have the technical expertise and technical capacity to keep up with the state of technology, it is understandable that regulators are hesitant where it comes to new technologies. One respondent talks about preventing anarchy (int9).

An important factor is the privatization of pressure vessel regulation under the Pressure Equipment Directive. Government inspection organizations that used to have technical capabilities have discontinued them. Other companies have started commercial activities to regulate and certify inspection and NDT. These companies are paid by the Asset Operator they are meant to supervise.

Innovation is easier if the current NDT method is not regulated, but even in these cases, some demonstration is needed of the detection capability of the NDT technique to be used. It is a general practice to have a regulator or validation company present at these demonstrations (int12, int16).

In order to finally get a new NDT service to be adapted into the recommended practices and standards it is generally needed to update the standard for the asset to be inspected such that it mentions the new technique, and for a new standard to be written for the application of the new technique. However, the participation in the committees that make codes and standards is low, especially from service companies (int9, int10). The fact that existing participation is low, makes it easier to get into standards committees, but also creates the problem, that making an effort to write standards for common use needs to be justified with the management of the parent company (int9). Respondents disagree about whether the government should facilitate or pay for these activities (int11) or these should be organized be the sector itself (int4, int8, int9)

It should be noted that the American system of standards, where any interested party has the legal right to participate in standard writing, produces standards much faster than the European system, in which committee members have to be delegated by their national standards organization (int9).

The conclusion out of this section is that the regulatory process acts as a conservative force, as regulators have difficulty keeping up with new technologies and are limited in their actions by the need to be proportionate to perceived threat of an integrity issues. As a result, innovation will practically be very limited unless public opinion favours a pro-active regulator (e.g. nuclear industry or after an incident) or the NDT method is not directly regulated.

- The regulatory structure in NDT acts as a barrier to innovation as regulators have neither intention not capability to assist innovation
- The opportunity to facilitate innovation by participating in code and standard committees is not recognised and used

6.13. Interview conclusions

The overall picture of the innovation process resulting from the interviews is that while innovation in NDT is primarily taking place between the asset operator and his service provider, the relationship between these two bodies is not conducive to innovation. The factors contributing to this are:

- Innovative solutions are demanded by the client on a plant by plant basis in a direct relationship between a service company and asset owner;
- Solutions are demanded on a completely different time scale than the time scale on which they get produced by equipment providers;
- Solutions are communicated by word of mouth;
- Service providers lack a marketing and sales process which results in clients getting techniques sold in glossy brochures, where they need statistical proof;
- Service providers lack competences to develop complete products for the industry, and the distrust between scientists and practitioners prevents them from obtaining those;
- The value of NDT is expressed insufficiently, leading to low investments and low priority to innovate;

- Protection of new NDT technique as Intellectual Property often leads to a stalemate and to a culture of secrecy;
- Codes, standards and regulation favour established technologies. New technologies are judged by a more demanding standard than established technologies;
- The regulatory structure in NDT acts as a barrier to innovation as regulators have neither intention not capability to assist innovation;
- The opportunity to facilitate innovation by participating in code and standard committees is not recognised and used.

Further conclusions and scenarios for breaking out of this situation will be discussed in the next chapters.

7. Analysis of the NDT Innovation System using CIM

In this chapter, the material gathered in the case studies (chapter 4) and the interviews (chapter 6) will be analyzed using the Cyclic Innovation Model (CIM). CIM can be interpreted in three different ways, as was previously explained in chapter 6. The analysis in this chapter is structured by considering each of these interpretations.

Firstly the material is presented with CIM as a model of roles in the innovation system, secondly with CIM as a knowledge model and thirdly with CIM as a model of the actors in the innovation system. Finally the flaws in the innovation system are identified.

7.1. Mapping of roles, actor and knowledge to CIM

In a number of places in this chapter the activities of the people, involved in the interviews and cases, will be mapped onto CIM. The actors and roles have been classified based on the objectives and output of the organizational unit to be classified. There is an element of interpretation to this classification. The background of this interpretation is that not everyone will perceive an outcome (e.g. scientific insight, technological capability, product and service performance) to be complete at the same level of development. Archetypical examples are the scientist, who declares that practical implementation (i.e. engineering) is trivial, or a production department that is angry at the commercial department for selling things that cannot be done. In practical situations it is not uncommon for a research technician to say something is ready for use, when a practitioner only sees a crude prototype. The resulting classification scheme is displayed in Table 22.

To give an example of classification; the respondent in the first interview, Frits Dijkstra, is an engineer by education and works in a role to provide technological solutions to the Applus RTD businesses. This role would be classified as upper right-hand quadrant in CIM. Additionally he has been active in a number of code and standards committees, specifying how NDT techniques should be applied in order to fulfil their purpose. This role would be classified as lower left-hand quadrant in CIM. The department he works for, the Applus RTD technological center, is the Research (upper-left hand quadrant) and Development (upper-right hand) department of Applus RTD. Applus RTD is itself an NDT service company, which would be classified in the lower right-hand quadrant of CIM. This example illustrates that one person can be active in a number of roles. In cases where a person performs multiple roles, a distinction will be made between the primary role and secondary roles, of the organizational unit to be classified.

Table 22: Classification to CIM quadrants

CIM quadrant	Roles in the innovation process	People classified in this quadrant	Departments classified in this quadrant	Companies classified in this quadrant
Upper Left	Connecting scientific insights to technological capabilities	Scientists studying NDT capabilities (e.g. measurement physics)	Departments creating new NDT technologies	Technological research institutes
Upper Right	Connection technological capabilities to products	Engineers	Departments producing NDT equipment	Equipment suppliers
Lower Right	Connecting products to market needs	Practitioners	Departments performing NDT services	Service providers
Lower Left	Connecting market needs to scientific insights	Scientists studying needs (e.g. safety issues)	Departments coordinating NDT needs	Institutes working on integrity and risk assessment, asset operators, regulators

Descriptions of the companies named in this analysis chapter can be found in the appendix to the thesis.

7.1.1. Mapping of knowledge

CIM can be described as process of transformation of one kind of knowledge into another. In the seminal publication of CIM, this was formulated in terms of characteristic questions concerning this knowledge, with the scientific node pursuing “know why?”, the technological node pursuing “know how?”, the product node pursuing “know what?” and the market node being concerned with “know who?”. Using the similarity of CIM with the engaged scholarship model of Van de Ven, the different kinds of knowledge can be further characterized. (Please see section 6.1.3 for more on these similarities). The parallel notions of both models are listed in Table 23.

Table 23: Parallel notions between CIM and the engaged scholarship model of Van de Ven

CIM node	**Characteristic question**	**Parallel notion used by Van de Ven**	**Associated public knowledge**
Scientific exploration	Why?	Theory	Research papers
Technological research	How?	Model	Patents
Product development	What?	Solution	Product offerings
Market transition	Who for?	Reality	Sector Standards

In order to use CIM as a knowledge model, it is necessary to assess when the particular kind of knowledge was created in the NDT cases. This can only be done if the knowledge has been made public or accessible in some way, which is not always the case in the NDT industry (as described in previous chapters). For the purpose of this chapter, each kind of knowledge is associated with a specific kind of public knowledge, which can be found in Table 23.

The publication of research papers was chosen as an indication that new theories have been established and new knowledge has been produced in the scientific exploration node. Patents were chosen as an indication that new models and designs have been established, and that the technological research node has produced new knowledge. Patents considered where those where a new technological capabilities was linked to application in an NDT apparatus. New product offerings as evidenced by product brochures, magazine articles and as mentioned in price lists were chosen as an indication that a new product has been established, and the product development node has produced new knowledge. Finally, the emergence of new sector standards has been taken as an indication that the market has recognized a new NDT application and that the market transition node has produced new knowledge. Some more consideration on this classification can be found in the next paragraphs.

7.2. CIM as a model of roles in the innovation process

In the cross case analysis it was noted that innovation in the construction stage of assets and innovation in the in-service stage of assets follow a different trajectory. To start this section, the trajectories discovered in section 4.8 will be mapped onto CIM. CIM is used as a model of roles in the innovation process in mapping the trajectory onto CIM. Additionally, some of the more minor innovations discussed in the interviews, will be mapped onto CIM as well. A distinction is made between incremental and radical innovations. This distinction can be found in many innovation text books e.g. (Tidd et al., 2005b) and has also been used in the CIM framework before (Berkhout, 2007).

7.2.1. Incremental innovations in NDT services

The innovation processes discussed in a number of interviews (int10, int5, int12, int16) are incremental innovations. As discussed in section 6.6 in the interview analysis, innovations are considered to take place between the asset operator (or asset constructor) and the NDT service provider. When mapped onto CIM, this would imply that the innovation takes place in the lower right quadrant of CIM. The examples discussed in the interviews with Alan Hipkiss (int16) and Hugo van Merriënboer (int4) and the discussion on how innovation generally happens in SGS in the interview with Norbert Trimborn (int8) offer good descriptions of incremental innovations in NDT. A request is received at the service provider, and a specialist looks into this. He will try to solve the issue with available techniques and resources, and will typically write a new procedure for the investigation. In these cases, there may be some requests towards suppliers of NDT equipment for minor changes to user interfaces, manipulators etc. These are activities characteristic of the upper right quadrant of CIM. Some additional descriptions of this process are found in the interviews with Ralf Dix (int12) and Jan Verkooijen (int6). Changes to the fundamental inspection method (i.e. upper left quadrant) do not take place, as the scientific resources that would be needed for this are too far from the field (int6) and the process would take too long. A schematic representation of this process can be found in Figure 26.

When mapping incremental innovations onto CIM, these happen in the lower right quadrant of CIM, with some activities in the upper right quadrant. Of course there will also be incremental innovation happening simultaneously in NDT equipment, existing technology, as well as in regulations, but these incremental innovations did not come up in the interviews. Apparently the NDT community does not consider incremental innovations noteworthy until they show up in services.

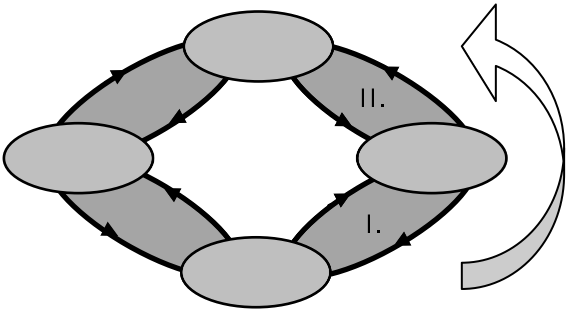

Figure 26: Schematic representation of incremental innovations in NDT services.

I. Most issues get resolved in the service delivery cycle (lower right) by writing new examination procedures and work instructions, with existing tools and technology

II. Some situations require small changes to equipment like manipulators and software interfaces; they are carried out in the engineering cycle

7.2.2. Radical NDT innovation in the construction stage

The innovations discussed in chapter 4 and in the interviews show that in situations where the NDT service changes radically, the technological change in the NDT method is linked to the introduction of a new construction method e.g. the use of a new material or a new way of joining materials. For this section, the Rotoscan innovation will be used to illustrate the mapping of the innovation trajectory onto CIM, but the findings in this section are equally true for e.g. ToFD (section 4.4) and Direct Digital Radiography of Weld (int10 and int13).

In the Rotoscan case, the new NDT method was linked to two new construction methods: the use of Gas Metal Arc Welding (GMAW) and the application of high strength steel (called X65 steel in the industry) to pipelines. As a response, a new ultrasonic technique was implemented. It should be noted that both the new construction method and the ultrasonic technique both had existed for some time prior to what happened in the actual case. While the history of the construction method was not studied in this thesis, literature shows that GMAW welding was developed prior to WWII and became available for commercial use in the 50s (Sapp, 2011). This is around the same time that RTD started experimenting with Rotoscan. In other words, science and technology (upper left quadrant of CIM) of both the application (pipeline welding) and the inspection solution (Rotoscan) progressed isolated from each other. The innovation started when it became clear that the new construction method required a new inspection solution. This is strongly linked to developments in the lower right quadrant of CIM; client and government regulators not being satisfied with the level of safety associated with the new construction method. In the Rotoscan case this is obvious from the fact that next to the client, the regulatory organizations were intimately involved in the first true applications of the technology in Canada.

As the first real field application was performed, some additional developments were started. These are no longer linked to changing the basic workings of the technology, but at making it reliable and usable in practical situation. In the Rotoscan case, this was the development of new displaying methods for the data, and the development of scanner carriages that could run on the same guide bands as the welding machine. This kind of developments is characteristic of the upper right quadrant of CIM.

The final stage of development before commercial breakthrough was the development of standards to go with the new inspection methods, and the development of non technical aspects of the product. In the Rotoscan case, the most important standard was the development of acceptance criterions based on Engineering Critical Assessment, which allowed the inspection methods to become commercially viable. One of the non technical developments of the product was the development of a project management structure and business model to go with this new NDT application. These developments are characteristic of the lower right quadrant of CIM, and have a strong connection back to the lower-left quadrant. Standards and work processes need to meet the requirements for reliability and safety that started the innovation process.

Summing up; Even though technologies are available on the shelf, the innovation truly starts when the requirements for NDT change, i.e. in the lower left quadrant of CIM. Innovation then proceeds clockwise, and is completed when the connection back to the requirements is made, in the lower right quadrant. A schematic representation of this process can be found in Figure 27.

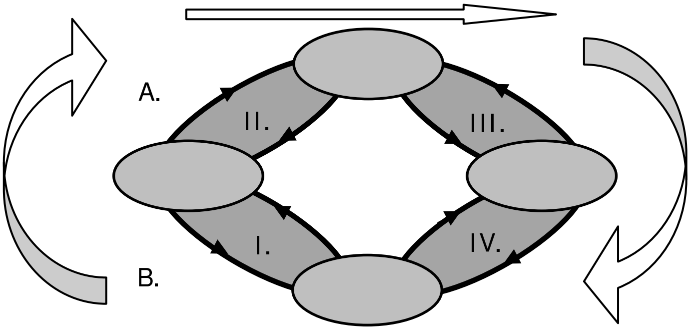

Figure 27: Schematic representation of radical NDT innovation in the construction stage of assets.

A. Prior to the innovation process, a new NDT technology was already developed, but disconnected from the application.

B. Prior to the innovation process, a new construction process lacked a method to ensure reliable construction.

I. End-user and regulatory organizations demand a higher level of safety and reliability.

II. The new NDT method is developed to match the requirements of the new construction method.

III. Modification to the technology are made to make it fit for purpose and suited for field conditions.

IV. Linking the new NDT service to the regulatory requirements: writing standards and acceptance criterions.

7.2.3. Radical NDT innovation in the in-service stage

In the operating phase of the asset, when NDT is performed as a maintenance or compliance activity we notice the following pattern. In this section, the MFL case will be used to illustrate the process, but the process equally applies to cases like Guided Waves and Pulsed Eddy Current, and the inspection of support corrosion discussed in a number of interviews (int12, int14 and int16).

Similar to the construction stage innovation discussed in the last section, the technology for the innovation had been available for some time, but it was not in any way connected to the integrity issue which it was aimed for. The interviews with for example Frits Dijkstra (int1), Hugo van Merriënboer (int4) and Raman Patel (int15), as well as cases like MFL (section 4.1) and Guided Waves (section

4.5), show that an issue with respect to a particular kind of degradation was typically known for some time as well.

The integrity issue would be brought up between the asset operator and his service provider and may also be flagged by the regulator (int15), but since nothing has gone really badly (i.e. no serious accident has happened), the priority of solving this problem is not high, and the regulator has no grounds to force the duty holder to do something, and no funding will be made available to create an industry wide solution. In CIM, these activities take place in the lower right-hand corner. In other words, and with reference to the section on incremental innovations above, the industry tries to solve the issue with incremental innovations.

Once a serious accident happens, the general public and the regulator will demand that action be taken. The problem solving activities in the lower right-hand corner will continue, but new activities in the lower left-hand corner will be added (Clear examples can again be found in the MFL case and in the interviews with Sieger Terpstra (int5)). The asset operator will contact his in-house research capabilities, and contact knowledge institutes and universities. In-house research capable inspection groups such as Shell Global Solutions and BASF Technical and Engineering Services do not have the capacity to develop solutions from scratch, and will use external research groups to aid them. In the MFL case, BP approached AEA technology to solve the problem for them. The public discussion on regulations is a typical lower left quadrant activity, and the research projects are upper left quadrant activities. The characteristic time in the right hand and left hand side are completely different. Where the service provider is expected to come up with a solution within days, the typical time for developing new regulations and performing research is many years. For example, the process for developing a new ISO standard has a timeline of approximately three years.

Once the research organizations have come up with a solution they will start trying to valorise the solution. In the interviews with Arno Volker (int2), Steve Burch (int14) and Gert Dobmann (int11) a number of options for bringing the new solution to the market have been discussed. None of these research organizations has the ambition to become a service provider, but they clearly have the ambition to make some money with new technologies. In the examples discussed, ESR (int14) teamed up with a service company, where they offer software solutions, and the inspection companies themselves take care of the instrumentation. IZFP (int11) had examples where they themselves produce and sell the inspection equipment, as well as working with regional investment grants to develop systems together with service providers, and dedicated companies being formed around the technology and resulting in a close link between this company and the research organization. With TNO (int2) a Joint Industry project with multiple companies, each taking a different market segment and role was discussed. From the discussion with each of the research organizations it is clear that such activities cannot be undertaken with just any service provider. The service provider needs to have some technology and development capabilities itself. This favours companies like Applus RTD, Sonovation and Sonomatic, compared to e.g. SGS which does not have its own engineering capabilities in NDT, and has to rely on equipment providers to develop solutions. These activities take place in the upper right-hand corner. The characteristic timescale for these projects is one to two years. For service providers this is experienced as being too long (int3). A fairly recent development is that equipment manufacturers are getting involved in this kind of projects. While in the past equipment suppliers were not considered to be innovation participants (int1, int3), this has changed both for ESR through the HOIS group (int14, int15) which now has multiple equipment providers in its membership and TNO (int2) which is now cooperating with GE (int7).

The next phase of innovation is in the lower right-hand corner of CIM. This is where the new NDT service gets tied back to the integrity issue. In the case of NDT, this has to do with development of a system of procedures and personnel certification around the technology. According to Zeelenberg (Zeelenberg, 2008) an NDT product is complete to the market once a number of processes have been developed: personnel certification, inspection procedures, the link to the product standard (often called a recommended practice), and the acceptance criterions for dealing with the indications found with the NDT technique. This final phase is typically performed by national committees of engineering societies, consisting of representatives of both end users, service providers and the organizations that researched and developed the technologies.

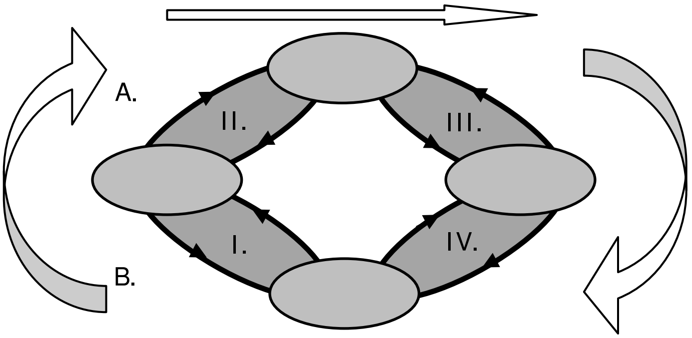

Figure 28: Schematic representation of radical NDT innovation in the in-service stage of assets.

A. Prior to the innovation process, the technology was already developed, but disconnected for the application.

B. Prior to the innovation process, the integrity issue to be tested, was already known to asset owners, but it did not get priority.

I. An accident happens, causing regulators and the general public to demand better inspection.

II. Asset owners and governments start to sponsor research.

III. Research is valorised with service companies.

IV. The new NDT service is formally linked to the integrity issue by means of standards and recommended practices.

When mapped onto CIM it appears that the innovation process in the in-service stage and the construction stage are not that different. The technology and the issue to be inspected were already present when a process in the lower left quadrant of CIM starts the innovation process. The innovation process then progresses clockwise until the cycle is closed.

7.3. CIM as a knowledge model

In chapter 4, the year in which these kinds of knowledge were made public for several NDT cases, was presented. This table (7) is repeated here for convenience (Table 24). In general the dates in this table support what was found in the previous section where CIM was used as a model of innovator roles.

Table 24: Repeated from chapter 4; years in which milestones for NDT cases where reached.

	MFL Floor-scanner	**Roto-scan**	**PEC / Incotest**	**ToFD**	**Guided Waves**	**Computed Radio-graphy**	**Phased Array**
Physical principle	Magnetic flux leakage (1868)	Ultra-sonic testing (1794)	Eddy currents (1851)	Diffraction (1815)	Lamb Waves (1917)	Radio-graphy (1895)	Huygens principle (1690) Array technology (1905)
Prior use in other sectors	Oil exploration		Geo-physics	Neutron physics		Medical	Medical
First patent in NDT	1963	1952	1989	n.a.	1994	1975	1954
Start of development project	1982	1956	1987	1974	1992	1983	1969
First commercial offering in NDT	1988	1989	1996	1983	1999	2001	2000
First codification	1991	1994	2002	1993	2006	2005	1999
Commercial break-through	1994	1996	none	Differs per country UK 1993 USA 1999 Dld 2004	2006	2006	2005

It is difficult to determine at what moment the theory underlying NDT methods has to be considered to be known. In many cases, the scientific principle has been known for a very long time before it was considered for testing purposes. Besides that, the measurement principle was typically developed for a similar purpose in a different industry before it was used in NDT. In depth analysis of this research prior to the use of scientific theories for NDT is not part of this thesis.

Additionally, there is evidence in a number of cases that the person who did the technological research for the NDT methods was not, or only partly, aware of the scientific research in the area. Good examples are the INCOTEST cases (section 4.3), where the main researcher was not aware of previous research into pulsed eddy currents, and the MFL cases, where the researchers at AEA did not seem to be aware of an almost identical technology already in use at Tuboscope (4.1). This fits with the observation, made in the interview section (6.9), that NDT technologists do not have a very broad knowledge of the scientific research in their field. For the analysis in this chapter it is therefore assumed that basic physics principles are known prior to the innovation, but details of developments by others are not. This is important, as the innovation cases could not be studied in isolation otherwise.

The moments of a first patent and of a first product offering are readily identified for almost every case. The date of a first standard for the NDT method is less clear again. Although a standard has been identified in each of the cases, there are several kinds of standards (section 3.2). Ginzel and Lozev (2000) make a distinction between guides which only give recommendations, and standards which give mandatory prescriptions. They consider an NDT method to be fully acceptable if the later has been published. Zeelenberg makes a distinction between method descriptions, personnel certification and acceptance criterions (Zeelenberg, 2008, Zeelenberg, 2010). The description of Ginzel and Lozev is more appropriate to the US market, and the description of Zeelenberg to the European market (the European standards system does not use prescription the way the US system does). The distinctions they make address the same issue however, which is that rejection levels for flaws are made binding in both the “standard” as described by Ginzel and Lozev, and the “acceptance criterion” as described by Zeelenberg. As Ginzel and Lozev state, this distinction is not sufficiently made in NDT at present, leading to the final step towards acceptance limits not being taken, or being taken very late, as was the case in ToFD.

When considering market transition in the context of CIM, acceptance criterions are the type of standardization which relates closest to acceptance by the market. In chapter 4, these distinctions are not considered. The year of any first inspection standards is considered to be the year in which the “for whom?” market transition knowledge became public knowledge.

When looking at these cases in the framework of CIM, the upper left hand process takes place independently, as general research unrelated to the eventual NDT method. This research yields a patent that remains unused for considerable time, even though some development work might be done. Once a practical problem (new construction) or public pressure related to accidents (in-service) triggers the product development (the upper right hand process in CIM) a product offering is reached in a fairly short period of several years. In the cases of chapter 4, the length of the period is between 2 and 7 years. This explains why e.g. Rost and Hecht (int10.) were surprised about the long length of the innovation process found in the case study. From their end user point of view, they would only see this 6 to 8 year process (7.6 years on average, see Table 8) as the innovation proper, and not what happened before, as scientific exploration does not concern them in their work.

Commercial success is linked to acceptance of the new NDT method in codes and standards. This is apparent from the close match between the year of commercial success and the year of first codification. There is however no causal relationship between the two. Rather, regulatory developments and product development appear to happen in interaction.

7.4. CIM as model of actors in the innovation process

CIM has been previously used to map the activities of participants in the innovation process (Sommen et al., 2005). This can also be done for NDT. As CIM is a scale free model this can be done at several aggregation levels. The role of the respondent may be different when looking at a different level; (1) the person that was interviewed, (2) the department or business unit the person is working in, and (3) the main activity of the companies the respondents work for. It is even possible for the respondent to have multiple roles.

When looking at the primary activities of the companies for which cases were described, and at which interviews were taken, they can be categorized according to the role NDT plays for their business (Figure 29). Descriptions of these companies can be found in Appendix A.

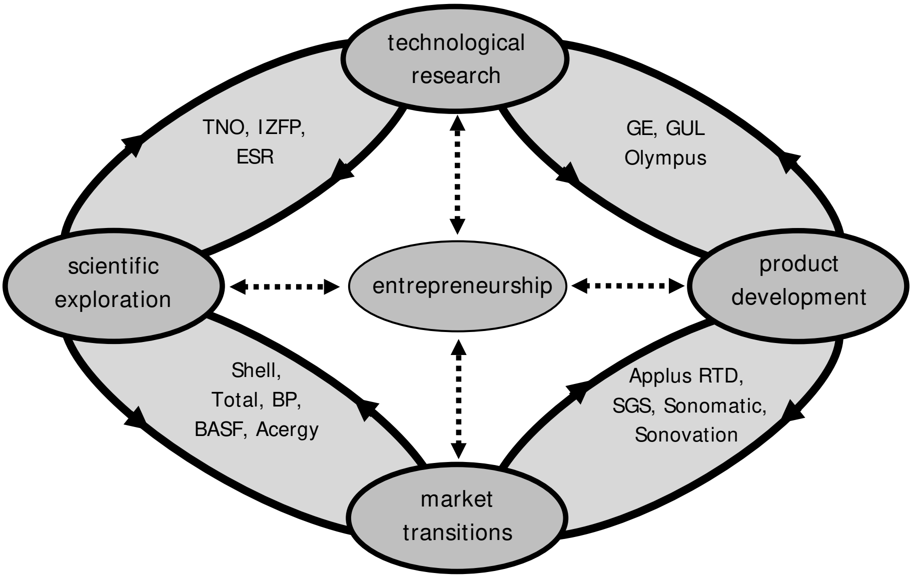

Figure 29: The organization featured in this thesis mapped onto CIM

The picture becomes a bit more complicated when other activities that are also performed at the companies are also considered, or when the activities of the person interviewed are considered (Table 25).

In Table 26, the information about the roles performed in the companies is displayed in a different ways. For this table, only the data on four service providers (Applus RTD, Sonomatic, Sonovation and SGS), three equipment providers (GUL, Olympus and GE), three scientific institutes (IZFP, ESRT and TNO) and four asset operators (Shell, Total, BASF and BP) are displayed. First notice that none of the service providing companies and none of the research institutes has a secondary asset operator role. Secondly, from Table 26 it can be seen that nearly every company in the set performs the technology (equipment development) role.

Table 25: Overview of the primary (P) and secondary (S) activities of companies which were discussed in the cases and interviews. Activities have been classified as primary if they correspond to the main activity of the company classified. Activities have been classified as secondary if they are performed by department or individual in the company but are not corresponding to the main activity of the company classified.

	Scientific exploration	Product development	Service provider	Client / regulator
Applus RTD	S	S	P	
SGS			P	
Sonovation		S	P	
Sonomatic	S	S	P	
GE	S	P	S	S
Olympus	S	P		
Total				P
Shell	S	S		P
BP		S		P
BASF		S	S	P
TNO	P	S		
IZFP	P	S	S	
LR – Stoomwezen			S	P
HSE	S			P
Acergy				P
Guided Ultrasonics (GUL)	S	P		
ESRT	P	S	S	

Table 26: Number of companies performing each CIM role for each type of company. Please see text for full explanation

	Upper Left role (science)	Upper right role (technology)	Lower right role (service)	Lower left role (client)	Total number in data set
Research institutes	3	3	2	0	3
Equipment providers	3	3	1	1	3
Service providers	2	3	4	0	4
Asset operators	1	2	1	4	4

When the figures in Table 26 are compared to the interview results, some of the findings can be understood more clearly. In section 6.6 it was noted that equipment suppliers are perceived as innovation partners very infrequently. It can now be concluded that the reason for this is, that most companies do not need an innovation partner to perform this role, as they can perform it themselves.

In the section 6.6 nearly every respondent mentions service providers and asset operators as innovation partners. It can be concluded that these companies are needed as an innovation partner, as this role cannot be performed inside the companies themselves.

The conclusion of this analysis is, that innovation partnerships across companies are only looked for, if the innovation role cannot be sufficiently performed inside the company itself. This creates a paradox; to be innovative some knowledge of other innovation roles is needed in order to be able to receive and absorb the new knowledge generated by a different role in the innovation process, but if too much of the role is performed inside an organization, the organization will perform a “not invented here” attitude, stop looking for partnerships and close down its innovation process (as opposed to having an open innovation process).

7.5. The entrepreneurship and regulatory role

One of the features of CIM is the entrepreneurship role, which acts as a catalyst to the innovation process; making sure the value and contribution of each of the innovation roles is understood across the whole cycle. In principle this role can be taken up by any organization that is already participating in the innovation process.

In section 7.1 a number of innovation trajectories were discussed. Innovation in construction NDT is mainly driven by requirements resulting from new construction processes, and innovation in in-service NDT is mainly driven by public pressure over industrial incidents. In both of these, regulators play an important role. In the construction stage it is notified bodies, classification companies and insurance companies who demand the structure to be tested before being put into service. In the in service stage it is appointed bodies and government inspectors looking after the safety of industrial installations.

Also from the interviews it is clear that in many cases, the industry is waiting for the regulator or the government to drive innovation. In other words; the NDT community expects of the government to take up the entrepreneurship role.

Given the existing regulatory structure however it is unrealistic to expect either the government or the regulator to perform this role. A regulator has a normative role, and will therefore be reluctant to propose changes. The role of a regulator is to point out deviations from the norm. Changing the norm while doing so would be disruptive. Industry is expected to write its own standards and is ultimately itself responsible for safety of its installations. There could however be a very important role for the government in stimulating entrepreneurship (vs. performing entrepreneurship). This will be further discussed in the next chapter.

A worrying development is that under the Pressure Equipment Directive much of the regulation of NDT is privatized. The part of regulation which will be performed by a certification company will now be performed in a situation where the regulator is paid by the asset operator. At the same time several interview respondents state that the quality of conventional NDT (i.e. one of the big 4 NDT methods, see section 3.1.1) is below standards. This has also been a subject presented in conferences (Zeelenberg, 2010). One respondent states that hardly any conventional NDT inspection conforms to the requirements of regulations. Combined with the comment that regulators get regularly asked to approve regardless of the no-conformity creates a situation where regulators could be pressured with the threat of giving the certification contract to another company. For innovation the main impact is the double standard this creates for new technologies, which are much more strictly regulated.

Table 27: Companies taking up the entrepreneurship role in the cases in chapter 4

Case	**Section of thesis**	**Most Entrepreneurial Companies**	**Primary role of entrepreneurial companies**
MFL	4.1	AEA	Research institute
Rotoscan	4.2	TCPL and RTD	Asset operator and Service provider
INCOTEST	4.3	ARCO	Asset operator
ToFD	4.4	AEA and Sonomatic/Sonovation	Research institute and Service provider
Guided Waves	4.5	Plant integrity and Guided Ultrasonics	Equipment provider (both)
Computed Radiography	4.6	OREX, AGFA and GE	Equipment providers
Phased Array	4.7	R/D tech	Equipment provider

Table 27 shows which companies performed the entrepreneurship role in the cases described in chapter 4. A company is considered to be entrepreneurial in this sense if it was involved in coordinating the innovation process, bringing together companies in the various roles and being involved in standard writing. From the data presented in the table it can be concluded that indeed any participant in the innovation process may take up the entrepreneurship role. It should be noted however that in every case, the most entrepreneurial company also was involved in developing the (prototype) equipment. This is a very remarkable result given the fact that equipment suppliers are observed to have a low participation in innovation projects earlier in this thesis.

Given the fact that many respondents expect most value of the innovation to be received by the asset operator (section 6.7) and the asset operator is the role active in most innovation project (section 6.6), a more central role of asset operators could be expected. The fact that this is not observed can be explained from the responses of the interview respondents: NDT is just one of many low priority services performed in industry. In other words: NDT is just not important enough for large oil, gas and chemical companies to be a target for innovation.

The observation that the entrepreneurship role is performed by the company developing the equipment can be explained from the issues around intellectual property. In an industry where secrecy is important as a means of appropriating intellectual property, an important way to guard development is to keep equipment developments proprietary. In other words: the capability of developing equipment is a way to capture the benefits of innovations. Technology, in the shape of equipment and software, is the element in innovation which is easiest to guard from copying by competitors.

7.6. Why is innovation in NDT slow?

The interview respondents (in section 6.8) gave a number of different responses to the question; “why is innovation in NDT slow”? When these are combined with the insights gained by analysing innovation in NDT with the Cyclic Innovation Model (CIM) conclusions can be drawn on the structure of the NDT innovation system.

Berkhout suggests that innovation systems can have a number of characteristic flaws (Berkhout, 2007). One is a disconnection between the left (academic) and the right (practical) side, which identifies a society in which science works in isolation from industry. The two worlds make their own choices and plans, and throw results over the fence to the other side.

The other is a disconnection between the upper (technological) and the lower (market) side, which identifies a society in which new technological designs are pushed into the social community without attention being paid to the value of these technologies for society.

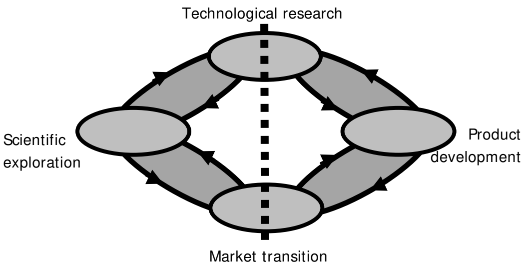

Figure 30: Characteristic flaw in the innovation system where science and practitioners have become isolated

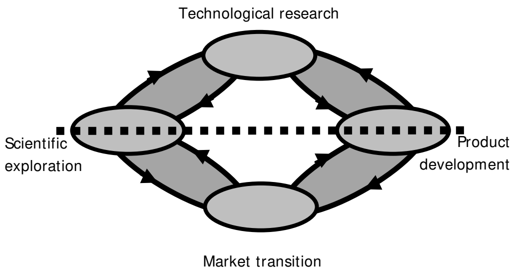

Figure 31: Characteristic flaw in the innovation system where technology has become isolated from the market

Looking at the different issues presented in this thesis, both these characteristic flaws appear to be at work in NDT, but not at the same time in the implementation of a singular new NDT innovation.

7.6.1. Isolation of technology from the market

The starting point for many NDT innovations is a situation where a problem has existed for some time in the industry. In the construction stage of assets this is typically related to a new construction method: for example the advent of welding as a construction method required new technology for testing the weld. In the in-service stage of the asset this is typically related to a corrosion or degradation problem. For example: corrosion of the floor plates of storage tanks needed new technology to test these plates for corrosion.

At the same time a potential solutions to the problem also exists in the shape of a shelved technology or a technology that is already used in other sectors or for another problem. In the welding case above, this was radiography (x-ray testing) which was already used in the medical sector, and in the tank floor case above this was the Magnetic Flux Leakage technique which was already in use for pipeline inspection.

In other words, the problem in the market is not connected to an existing technological solution. This situation clearly corresponds to the flaw depicted in Figure 31, i.e. a disconnection between the technological and the market side.

This flaw is especially at work at the time when a new technology has been invented but where it is not linked to a suitable application. This time corresponds to the time between the first milestone (invention) and the second milestone (introduction) in the method used to analyse the innovation cases (see section

4.8.1). If the right connection between issue and solution are made, this will result in the introduction of a first commercial product.

A number of the reasons given by interview respondents (see section 6.8) can be linked to this flaw in the innovation system. These are depicted in Figure 32.

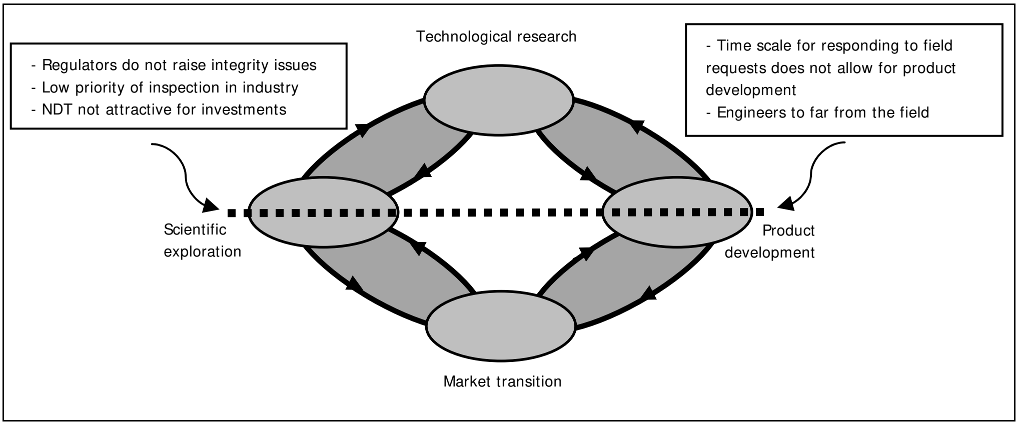

Figure 32: Isolation of technology from the market, and the reason why this occurs in the innovation system

Figure 32 shows a number of reasons for the problem in the market not to be connected to the technological solutions. The regulators that were interviewed expressed that even though they know about problems in the industry, they feel restricted in raising the issue with industry unless something serious happened. The demand to solve the issue typically comes as a result of public and parliamentary pressure as a result of an accident or demands of a powerful interest group (in the tank floor case; a storage tank collapse leading to the evacuation of a school).

On the side of industry, testing is typically not a very high priority. Testing and inspection is primarily seen as a cost that is incurred to comply with regulations. The tendency is to try to reduce this cost. Adding a new inspection would increase budgets that have targets for reduction. Additionally this would bring the risk of finding flaws, leading to more investigations, repairs and more cost.

The lack of industrial priority and public attention also makes NDT an unattractive area to invest in. Finding funding for research and development is hard when the government does not allocate resource because it is unaware of the issue (and therefore allocates funds to more popular causes) and the industry does not give it priority either. At the same time, the scale of many NDT companies is insufficient to fund innovation themselves.

Still, many of the people in the field try to find solutions with existing technologies. These however will need to fit in operational timescales and budgets. The result is that solutions are being requested in the field on a case by case and plant by plant level, and are expected to be delivered in weeks or months. This is a very different timescale from the time needed to research a solution, which might take years. Finally the engineers that might have ideas to solve the issue are working in labs, too far from the field to suggest the solution or try to solve it with a quick prototype.

The problem could be solved if the industry would recognise the issue to be occurring on a wider scale than on the one plant trying to find a solution. On the aggregated level of a whole industry or even all the plant of one multi-national, the problem is more likely to be identified as a serious issue, and investments are more likely to be made available for solving it. Similarly the problem could be solved if the timescale for finding solutions would be adjusted. Many of the industrial assets inspected with NDT have lifetimes of 25 to 40 years. A solution will still be valid in a few years.

When worded in term of the dimension of innovation (found in paragraph 1.2.2), these conclusions become:

- Disconnection between top and bottom half of CIM results in looking at problems at the wrong level of aggregation and at the wrong time scale.

Once the industrial issue is perceived on the right aggregation level (in many cases; on a world level), and on the right time scale (the lifetime of the asset, often 25-40 years), the issue of attention and investment capacity is no longer valid. If the integrity problem, for which the NDT innovation was originally proposed, is real then at some point an accident will happen, and the general public will demand that the issue will be looked into and solved.

7.6.2. Isolation of science from practice

The isolation of scientists from practitioners was mentioned in a lot of interviews (see section 6.9). The problem was particularly linked in the interviews to the time where a new NDT solution needs to be validated and accepted for use in the market. A good example is the slow acceptance of Time of Flight Diffraction testing, which had to be demonstrated before use many time, while clients were complaining that the method was oversold and not enough was published about it. This situation clearly corresponds to the flaw depicted in Figure 30, i.e. a disconnection between the scientific and product side.

This flaw is at work especially when a new technology is available in the market, but is not fully accepted. This time corresponds to the time between the second milestone (introduction) and the third milestone (diffusion of a standard product) in the method used to analyse the innovation cases (see section 4.8.1).

A number of the reasons given by interview respondents (see section 6.8) can be linked to this flaw in the innovation system. These are depicted in Figure 33.

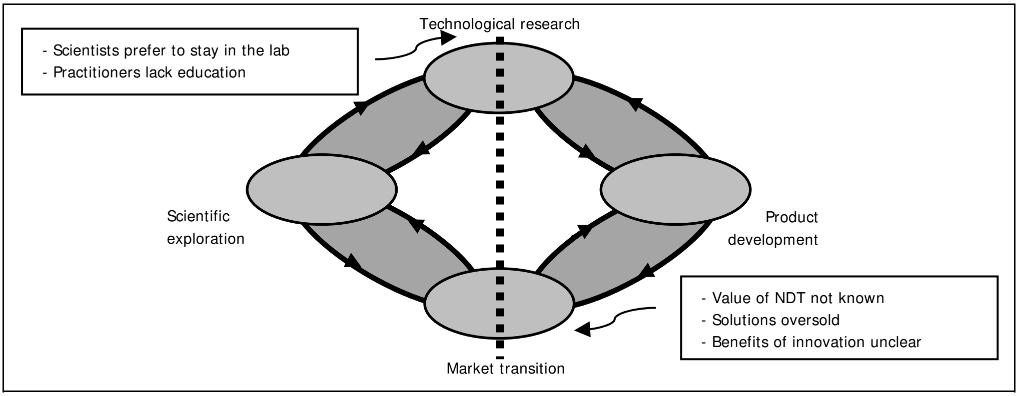

Figure 33: Isolation of science from practice and the reason why this occurs in the innovation system.

The first issue mentioned in interviews is, that even though new NDT techniques are demonstrated (i.e. show that they can find a flaw), they are often not validated (i.e. show that flaws can be found reliably). Validation requires knowledge of statistics and experiment design. These are skills that NDT technicians typically do not have. The people in NDT that have these skills are typically scientists who hardly ever visit the field. Also technicians have no access to, and no awareness of scientific literature. It is therefore not surprising that the results of any statistically relevant test that was done in the field, does not get published. The lack of involvement of scientists in the field also prevents these scientists from seeing that there is still much to be improved about their new technique.

Clients who used the technology will often resist publication of result, in order to avoid helping competitors. Clients who did not use the technology before will not be able to find much about the application of new NDT techniques in literature, and will have to go on what is told to them by service providers. These service providers than misinterpret the need for information of clients. Where clients are in need of information on validation of the technique, NDT service providers interpret this as a need for awareness of new techniques, and send the client glossy brochures. As a result the technology gets oversold.

Another serious issue is that the value of new NDT is unclear. There are many good stories of NDT solutions saving millions. These savings however are not on the NDT but instead on prevented downtime of installations, reduced cost of parts that would otherwise have to be repaired and reduced cost of work preparation (for example: less scaffolding needed). Clients therefore find it hard to assign savings to good NDT.

Another reason for the lack of visible benefits of NDT innovation is, that NDT is perceived as a cost incurred for complying with regulations, rather than a reduction of risk for accidents and downtime. New NDT techniques are usually not in the regulations yet. In order for NDT techniques to be performed in a regulatory framework it is necessary that it is known what the results of an NDT test mean in the context of the regulation. The criterions for acceptation of rejection of an object being tested will need to be captured in a standard for this purpose.

These issues could be solved if innovation was not perceived as a linear process where scientists throw a solution over the fence to field technicians. If scientist would be involved in validation and standardization, field technicians could at the same time help them improve the technique with practical insights. This however needs both sides to be open and to acknowledge their own weaknesses.

At present, the NDT sector is very technology oriented. More attention to non technical issues, such as the commercial issue of the value of a test, is needed to improve the innovativeness of the sector.

When worded in term of the dimension of innovation (found in paragraph 1.2.2), these conclusions become:

- Disconnection between left and right side of CIM results in looking at innovation as a linear process revolving only around technological knowledge.

Once innovation is perceived as a cyclical process, it is logical for scientist to remain in the process for the improvements steps of the technology and help to establish acceptance criterions and interpretation of the measurement results with field technicians.

7.7. Innovation system flaws in innovation literature

In the previous two paragraphs it was concluded that the flaws in the innovation system result in looking at the issues of innovation in a way that harms the speed of innovation. These have been formulated in term of the dimensions of innovation as found in paragraph 1.2.2. and are summarized in Table 28.

Table 28: Flawed perception of the innovation process in NDT which leads to slow innovation

Perception of the innovation	**Perception in the NDT community which harms innovation**	**Alternative perception which would support innovation**
At the wrong aggregation level	At plant or project level	At industry level
On the wrong time scale	Weeks or month	Several years
As a linear process	First time right technologies	Multiple iterations and improvements
As a purely technological process	Innovation revolves around defect detection	Innovation includes: • Economic value • Safety and risk reduction • Social acceptance of the new technology

This flawed perception harms the speed of innovation as innovation will be perceived to be unsuccessful or unfeasible. Because of this the next steps in the innovation process will be delayed. The importance of perceiving innovation as being successful, for further investments has been described by Arthur in his studies of increased attractiveness caused by adoption (Arthur, 2009).

Perceiving innovation on a low aggregation level will lead to the perception of innovation being an unattractive investment. Perception at the wrong timescale will lead to innovation being expected to be too late for the market. Perception of innovation as a linear process will lead to the innovation being kept in the lab environment until the research is cancelled or the technology is perfect. Perception of innovation as a purely technological process will lead to the innovation missing essential elements and failing in practice.

Each of these perception flaws can be found in literature, although they have not been presented as a set before.

The time scale on which innovation happens has been studying extensively. A good example of the expectation of these timescale being different than what happens in reality can be found in the Minnesota studies on innovation (Van de

Ven, 1999, Van de Ven et al., 2000). This project started out with research groups joining team that were actively trying to innovate, with the intention of following these projects until completion. This turned out to be very difficult as these projects took much longer that originally expected. Marchetti (Marchetti, 1980), following the work of Mensch (Mensch, 1975) also studied the time needed for innovation and remarks, that the expectation that innovation is much longer than commonly thought.

The perception that innovation is a linear process is very common, and has become embedded in industry policy (Bush, 1990) and in the stage gate process by which many companies manage innovation (Cooper, 2008, Cooper and Kleinschmidt, 1986). Rosenberg (Rosenberg, 1982) showed that in many cases technological progress precedes scientific research, and that technological progress itself happens in combination with trial and error experimentation by practitioners who do not understand what they are doing. Ortt and Dedehayir (Ortt and Dedehayir, 2010) addressed the fact that research is expected to take place before large scale diffusion of the new product, but that in fact most product research is performed after the innovation has started large scale diffusion, as funding for product improvement has become available at this point.

The fact that innovation is often wrongly perceived as a purely technical process has been addressed with the emergence of 3rd generation innovation processes (Rothwell, 1994, Rothwell, 1992). A good example of an early innovation description which includes non technical aspects of innovation can be found with Rothwell and Zegveld (Rothwell and Zegveld, 1985).

The issue of studying innovation at the right aggregation level has not been extensively researched by itself, as most innovation research starts out with a fixed perception of the unit of analysis which should be studied. The fact that this is not sufficient to understand innovation is however well known. Hekkert (Hekkert et al., 2007b) for example identifies this issue and has modified the Innovation System approach to reflect this.

7.8. The complete picture

In this chapter the innovation system of the NDT sector was analysed using the Cyclic Innovation Model. This analysis showed that incremental innovations and radical innovation each have a different progress of activities. Incremental innovations stay within one or two quadrants of CIM. Interview respondents put emphasis on incremental innovations taking place between the asset owner and the NDT service provider.

At a first glance radical innovations aimed at new construction NDT have a different innovation trajectory than radical innovation aimed at assets that are in use. When mapped onto CIM however they follow the same sequence of involvement of the different roles distinguished in CIM. Before the innovation takes place, both the integrity issue and the new NDT capability are developing independently from each other. A change in regulatory requirements matches the two, and starts the process of developing the new capability into equipment, and a field deployable service. Finally the new NDT service is written into codes and standards to link the new service to the new regulatory requirements the innovation started with.

Once this sequence was established, the factors that were discovered to slow innovation in NDT were expressed as flaws in the innovation system. These flaws were shown to arise at different times in the innovation process. Together they span all the factors that were identified in the interviews. The next chapter will touch on fixing these flaws.

8. Conclusion

NDT refers to the set of activities that is used to determine the condition of objects or installation without destroying or damaging them. Many of the technologies used in NDT are also used in medical diagnosis, for example X-Ray photos and ultrasonic echoes. The pace of innovation in Non-Destructive Testing (NDT) is slow compared to other sectors. The time it takes for new testing methods to become a commercially successful service that is available to the industry is much longer than for most hi-tech services, including the medical sector, which itself is known for being a slow innovator. In several cases, technologies are already well-established in the medical or geosciences fields before they start being introduced to NDT.

The aim of this thesis is to analyse the innovation system of NDT, and to find out why innovation is slow and how the existing process can be improved. In this chapter, the most important findings of this thesis are discussed, with special attention to what can be done to increase both the amount of innovations and the speed of innovation.

To analyse the NDT innovation system, we used the Cyclic Innovation Model (CIM), a relatively new innovation model that treats innovation as a holistic and cyclical process. CIM identifies four roles in the innovation system: scientific exploration, technological research, product development and market transition, which are connected by four feed-forward and feedback relationships. A fifth role, the entrepreneur, is created as a driver and coordinator in the innovation process.

CIM based on a set of requirements derived from a preliminary investigation of innovation cases in NDT. The main investigation was conducted via interviews with people in a variety of roles related to innovation in NDT. Three different approaches to CIM were used to cross reference results. In the interview process, CIM was used as (1) a model of roles in the innovation process, (2) a model of actors in the innovation process, and (3) as a model of knowledge in the innovation process. Based on this approach, the results of the interview could be validated across the different interpretations of the model. The interview results were analysed in two different ways: by tabulation of results and with methods out of grounded theory.

Although NDT is a relatively small but important sector for industrial safety, the insights generated by this thesis can be used to help other sectors as well, as we will discuss below.

8.1. The Innovation process in NDT

Chapters 4, 6 and 7 presented steps towards a better understanding of innovation in NDT. In chapter 4, it was concluded that there are several innovation trajectories that can be distinguished. NDT innovations show a typical progression of the activities and the kind of companies involved, and in particular the conditions under which innovations can be successful. These trajectories are particular to the life cycle stage of the asset involved, specifically with regard to the construction stage and the stage where the asset is being used (called the in-service stage in NDT).

It is confirmed that the time it takes to bring a new invention from idea to a successful new product is indeed long: 30 years on average. The conditions that need to be met for an NDT invention to become an innovation are that it has to be associated with an industrial problem and that it needs to be captured in codes and/or standards up to the point where the interpretation of inspection results (acceptance criteria) is regulated. Furthermore, it was observed that small start-up companies are often more successful in this area than large established NDT companies.

Chapter 6 shows that innovation is usually seen as a process between an NDT service provider (the company or person performing the test) and an asset owner (the client of the NDT service), with a remarkable lack of participation from the companies that manufacture and supply NDT equipment. The reason for this limited participation is that most of the other participants in the innovation network have the capability to develop equipment themselves.

When asked about the benefits of innovation and who receives the benefits, the respondents gave three different characteristic responses. Some respondents said that most of the benefits go to the owner of the asset (the company owning and operating the object to be inspected, and the client of the NDT service), while others said it is unclear who benefits or assumed that NDT is performed for the safety of the general public, which therefore is the beneficiary. Together, these perceptions pointed to the conclusion that the economic value of NDT innovation is mostly unexpressed, as NDT is mostly seen as an activity that is performed to comply with regulations. Examples show, however, that NDT innovation can generate a huge value for all the parties involved. An issue remaining is to express this value.

Chapter 6 also shows that the NDT sector has a problem when it comes to cooperation between the scientists developing new NDT techniques and the practitioners who have to use them. Scientists are criticized for not concerning themselves enough with the practical issues related to the application of their invention, while practitioners often lack the background and education to work with new technologies. Service providers and asset operators, however, rely mostly on practitioners to take innovations to the final step of implementation.

In chapter 7, the findings of chapter 6 were interpreted using CIM as a framework. The innovation trajectories were conceptualized, using CIM as a model of innovator roles. Next, the order of the steps in the innovation process was confirmed using CIM as a knowledge model, and finally, the actors in the innovation process were mapped onto CIM. These three ways of using CIM together provide a good indication of the flaws in the NDT innovation system.

The major innovations studied in this thesis start off with an integrity issue or new construction capability known in the client industry that cannot be adequately tested. At the same time a technological solution exists for this testing problem that is known by NDT technologist but that is not associated with the issue. In other words, the development of technology is disconnected from market requirements.

Once the connection between the issue and the new technological solution has been made, a new NDT service product is developed and becomes available. For the new service to become accepted, validation programs are needed in which the reliability of the new service is proven. It has been observed that scientists and practitioners do not cooperate well at this stage, which is a second flaw in the NDT innovation system.

8.2. Managerial implications - Faster innovation in NDT

Today innovation is no longer an activity that is performed by a dedicated department in a company, or left to knowledge institutes. Being innovative is now one of the core competences of successful companies, which needs to be directed from the board room. Companies that are not innovative will be replaced by cheap labour solutions, or will be replaced by innovative ones. In the NDT sector this is no different. In other words: non innovators will perish.

As it was argued in the introduction to this thesis, based on the recent paper by Booz and Company (Jaruzelski and Dehoff, 2010), at the core of innovation are products that clients want to pay for. Clients buy NDT services for two reasons:

- They are forced to perform inspections based on standards enforced by a regulator
- The service saves them money in some other part of their business by e.g. improving the reliability and increasing the up-time of installations, or protects them for a substantial risk

These are two very different drivers for innovation, which have not been distinguished in the sector. If inspection is enforced by regulators, the intended beneficiary of innovation is the general public. The general public will benefit from more safety and less pollution (release of hazardous materials). Since the industry in which the new NDT is performed will be paying for the inspection, it is understandable that the industry will resist the innovation, unless the government provides him with a level playing field, i.e. by forcing industry actors to perform the inspections and not just one company. This is the main reason why NDT technology needs to be standardized for innovation to be accepted faster.

If the intended benefit of a new service is saving money on some other process, it should at least be clear what these savings are and how big they are. The most common of these savings are reduction of the amount of scaffolding and cleaning needed, or a reduction on the amount of maintenance needed. In the investigation performed for this thesis, no evidence was found of a structured effort to make the benefits clear to clients. One exception to this was the in house inspection department of BASF, which tracked the savings realised with new NDT services (int10).

Although the two possible reasons for buying new NDT services could be at work independently, in a healthy economic situation, they should both apply together. On the one hand, government has a moral obligation not to force the industry to perform inspections which are ineffective (i.e. which cost more than they benefit the general public). On the other hand, industry should have the moral obligation to work as safely as possible and perform any inspection that improves safety, if there is no financial burden. Even though realizing a cost or risk reduction is a reward in itself, the cost and benefits of inspection rarely coincide. Standardization can prevent the dilemma where a rogue company saves cost in the short term and outperforms its competitors by not performing inspection, while running risks in the future. In other words: NDT should be an integral part of the Corporate Social Responsibility of companies.

For innovation, the benefits of a new NDT service should be clear and the solution should be standardized. As we have shown, however, it takes a long time to reach these goals, when following the process that is now commonly used to innovate.

8.2.1. Fixing the innovation process

As a result of the flaws in the innovation system described in section 7.6, new NDT technologies are not applied on a large scale, and innovation is not achieved. Clients are simply not willing to pay for new NDT techniques if they are not validated, the value is unclear and the results are not accepted in a regulatory context. If industry wants faster innovation in NDT, the flaws in the innovation system need to be bridged. In terms of CIM; someone needs to take up the entrepreneurship role. This can be done in a number of ways.

The entrepreneurship role in CIM is defined differently than entrepreneurship is commonly understood. In CIM the main role of the entrepreneur is to drive and coordinate the activities of the actors in the innovation circle and if necessary perform the activities of missing or failing actors or create new actors for these roles. Additionally he carries the risk of the new venture, and endeavours to benefit from the innovation. The role of the entrepreneur in CIM is to be the circle captain.

The visionary role played by Steve Jobs at Apple is a good example: although Apple is renowned as an innovator it was not very active in technological research and instead got most of its original ideas from the PARC labs of Xerox and has been accused of getting many more recent ideas at competitors. Apple has been able to combine these ideas in appealing product designs (e.g. iMac and iPod), with new ways of delivery (e.g. iTunes and Apps). The key competence however has been to identify exactly what clients are willing to pay for. All four quadrants of the CIM innovation circle are engaged in the innovation process.

In NDT an entrepreneur should coordinate scientific exploration in measurement physics, equipment development, development of new delivery models for services (i.e. new business models) as well as the inventory of threats in the industry, for the detection of which clients are willing to pay.

8.2.2. The role of government and regulator

The participants in the NDT innovation network position the government in the entrepreneurship role. Historically, the government has forced the industry to innovate in response to accidents. Two common misunderstanding further cause the expectation for the government to drive innovation; regulators are confused with the government, and the role of standards is confused with the role of the laws. As a result, it is assumed by the sector that the government is responsible for codes and standards. In reality this is the industry. In most cases it is not government controlled laws that need to be changed in order to innovate in NDT, but instead the standards that are controlled by industry.

One way to overcome the flaws in the innovation system would be for the government to give the regulator a mandate and funding, to be pro-active in innovation. This new regulator role would be to identify integrity threats that need to be addressed, commission research for finding ways to inspect for these issues and enforce regulations that oblige asset operators to use the latest inspection and testing technology. This has been the practice in the nuclear industry, which has an obligation to look for inspection solutions beyond current technical knowledge (int11). As a result, the nuclear industry has been a source of NDT innovation. It does not seem likely however, in the current political climate that politicians would decide on a similar regulatory arrangement for e.g. the oil and gas industry unless some very serious accidents would happen. The development of ToFD in the nuclear sector (section 4.4) is an example of this kind of innovation.

A much more likely way for the government to participate in innovation is by stimulating entrepreneurship, and funding those parts of the innovation process of which the intellectual property cannot be protected easily. NDT innovators now use secrecy, surrounding their equipment and software, to protect their Intellectual Property (IP). Protecting the IP in equipment is relatively easy. The other parts of the innovation process should be stimulated. The most important ones are related to the flaws in the innovation system; connecting integrity issues in industry to promising new technologies, and stimulating the scientific validation of new testing services.

The role of the regulator will need to be strengthened. Under the new regulatory structure resulting from European harmonization, several regulatory government functions have been privatised. These functions are now being executed by certification companies, acting as contractors to asset operators. These companies have expressed concerns about the quality of the existing NDT practice, but lack the power to intervene unless an accident happens. New NDT techniques are judged by a much more demanding standard than old NDT techniques. Notified and appointed bodies (certification companies that execute regulations) will need to access new and old NDT techniques by the same quality standard. This will only be achieved if regulators are financially independent.

8.2.3. Performing the entrepreneurship role

Each of the other roles however can take up the entrepreneurship role, and the information from the cases discussed in chapter 4 gives some indication as to what that would look like. In section 4.8.3 it was concluded that small start-up companies are more successful in exploiting new innovative inspection solutions. When looking at these examples they clearly show entrepreneurship behaviour in the sense of CIM. Taking Guided Ultrasonics ltd. as an example (section 4.5), research scientists formed their own company and went into the field themselves with inspection companies to learn about practical problems, improving their product through feedback from users, and teaching field technicians to properly use the new technology. Their company has been consistent in declaring that they are not a service company, but will help field technicians in every way possible. Additionally, they have been active in producing codes and standards and personnel certification schemes for their technology. Other examples of this kind of entrepreneurship are the company 'NDT systems', that was created by employees of IZFP, and the company Physical Acoustics (now Mistras group) that was created by researchers of Stanford University.

It is not just scientists and employees of research organizations innovating this way. The case of Phased Array (section 4.7) shows people from R/D tech (an equipment supplier) actively acquiring high tech knowledge on Phased Array technology to produce better equipment, and eventually becoming a leading equipment manufacturer. The people of R/D tech have consistently worked with service providers and end-users of NDT services to find new areas to apply their equipment, and have subsequently worked on scientific literature, standards and technician training for their equipment.

The cases of INCOTEST (section 4.3) shows someone working at an asset operating company (ARCO) developing new technology and looking for a service company to commercialize the technology.

Powerful clients could use their scale to bring NDT innovation to the right level of aggregation. Most of the client industries for NDT already operated on a global scale. It will have big benefits for them to have their integrity issue solved on a global scale as well.

To service providers the recommendation is to realize that it is relying on people without sufficient knowledge and understanding of new technologies to make the final step in innovation: getting NDT technology standardized and accepted by clients. The best way to achieve faster innovation results is to keep development scientist involved in new products longer. At least until a standard exists that includes acceptance criterions. This will included sending these people into the field and accepting that this is more costly than using under-educated people. The benefits of innovation should be sufficient to cover this, if the recommendations in the next two paragraphs are followed.

In the NDT sector relatively small service companies find themselves caught between large and powerful clients (oil, gas and chemical corporations) on the one hand and large and powerful suppliers on the other. In recent years, the service providers have become larger, due to a wave of mergers and acquisitions (Weyers, 2010). This has the added benefit that NDT service providers will be getting more market power, and will thus be better able to appropriate the benefits of innovation. In order to do this, service providers should also organize themselves. At the moment, the NDT trade organizations have membership from all the roles in the innovation process (end users, equipment providers, scientists and service providers). As a result, there is no trade organization looking after the interests of service providers exclusively. Service provider should together work on a shared vision for the sector, and through organizing themselves create the market power needed to perform innovation.

Service providers should also become more aware of the non-technical aspects of their services. Lessons could be learned from earlier innovations. It was shown in this thesis, that start-ups are often more successful in innovating than established NDT companies. One of the important aspects is that these start-ups are running a completely different business model than the large inspection organizations. Starts-ups are typically a mix of experienced field personnel and university educated innovators, who build up the knowledge to implement new technology at their clients around the world. A local office serving the local plant will never build up this kind of specialist knowledge, and will probably not even be able to bear the cost of equipment investments needed. The most straight forward way for existing service companies to capture the opportunities of new technology is to establish their own start-ups, separated strictly from regional offices. This solution is close to the way Christensen describes the start of innovative businesses (Christensen, 1997).

Another non-technical aspect of services is the value that is created with innovation. It would be helpful to the commercial processes if the value of new NDT services to clients would be investigated.

It is important to realize that in each of these ways in which the entrepreneurship role is implemented, the participation of clients is important. In practical NDT, the asset owner and construction companies, the clients of the NDT services, are both paying for the service and make the final decision on how the inspection is performed. Additionally regulations are written by the industry (and not by the government, which is a common misconception).

8.2.4. Collaborative solutions

Alternatively the entrepreneurship role could be performed collectively, implemented in industry societies and associations. These would need to follow a process where a collective vision of the future is created, and projects are formulated toward the fulfilment of this vision. For NDT, the certainties of the future are clear: industrial assets and infrastructure are aging. Several new materials (composites, ceramics) have been introduced in the past few years as construction materials, for which new NDT techniques will need to be created. Technical labour is going short, and tasks like NDT are now performed in a way which is too labour intensive. Safety will become an important component of corporate responsibility. Any new vision will need to propose solutions for these issues.

If these issues are perceived on the right aggregation level (the industrialized world) it is clear that a good market will exist for solutions. Producing these will however take time. The MFL case (section 4.1) is a good example of the minimum time needed for kind of innovation. An asset owner (BP), research institute (AEA) and a service provider (RTD) together produced an inspection solution and together worked on regulations. (The equipment development role was share by RTD and AEA). The project was started in 1983 and first field services were performed in 1991. In this time three generations of equipment were produced, tested in the field and improved. In my opinion, the length of this process (8 years) is a good estimate of what should be expected for this kind of developments.

8.2.5. Industry associations

There are a number of current examples in the NDT sector of collaborative entrepreneurship in industry associations. Associations like PRCI (Pipeline Research Council International) and HOIS offer membership to asset owners, service providers and equipment suppliers and spend the membership fees on collaborative projects. In both associations several tiers of membership exist to allow less wealthy companies like service providers to participate. Projects are selected in a voting and ranking process in which the asset owners have priority votes. Codes and standard organizations could also perform this role, although at present they have very limited involvement in innovation.

On the more scientific side, RCNDE in the UK and CNDE in the USA are similar associations for more fundamental research. These also offer membership and perform collaborative research. Where RCNDE and CNDE focus mostly on university research, PRCI and HOIS focus mostly on field validation and adaptation of existing technology. It could be very beneficial if these two groups of associations would start cooperating. Together they would spam the whole innovation process as described by CIM. At present this is not realized and results from projects remain isolated.

8.3. Generalization of the results

The managerial implication with respect to NDT can be generalized in a number of ways. First of all, NDT is a highly regulated sector and the innovation process to a large extent depends on the regulatory process. It should be possible to generalize the results toward other sectors that depend heavily on regulation. After the financial crisis, innovation in the banking system comes to mind. Using CIM, it should be possible to standardize banking and insurance sector regulation in such a way as to ensure that that their products are safe to the public, and still innovative. The medical sector, which is also highly regulated, is another sector highly regulated sector which might benefit from results obtained with CIM.

Secondly, NDT is a sector that witnessed recent large-scale outsourcing, privatization and consolidation. There are other sectors in which similar developments are taking place, for example the mail and the utility sectors. The results of this thesis can almost certainly be applied to other technical service providers active in the oil and gas sector, as well as to services like cleaning, nursing care and road logistics. These sectors will probably be experiencing a split between lowly educated and conservative practitioners, and more highly educated innovators, who have a problem commercializing their inventions. Investigating innovation in these sectors using CIM would most likely prove worthwhile.

8.4. Theoretical implication

This thesis used CIM to analyze innovation in the NDT sector. CIM was used in three different ways (1) as an model of roles (2) as a model of knowledge and (3) as a model of actors. In this thesis, methodological tools were presented and applied to the NDT sector. The main use of this methodology was in structuring the interview presented in chapter 6.

CIM was selected by assessing three innovation models, selected from a much larger set, against a number of requirements. Each of the ways of using CIM provided new insights into the innovation process. After having used CIM this way, we can now look at the requirements that were originally used to select CIM:

1. Possibility to model on different aggregation levels
2. Possibility to model relationships inside and outside of a company (open innovation)
3. Possibility to model both industrial and societal developments in interaction
4. Possibility to model the creation of knowledge and intellectual property
5. Possibility to model development over time, and including feedback processed (dynamic model)

8.4.1. Aggregation levels

CIM was used on different aggregation level when it was used as a model of innovation actors. This turned out to be useful as it allowed companies to be evaluated not just on their primary objective, but also on the extent to which they are able to perform other roles in the innovation process. For NDT it was shown that it is important to be able to perform some of the other roles, but that being able to perform the role completely may also lead to closed innovation behaviour and a 'not invented here' attitude. It is recommended in this thesis to further investigate the importance of being able to perform additional roles, to innovation behaviour.

The importance of studying the aggregation level was also evident in the discussion on the flaws in the innovation system (section 7.6): when an innovation system addresses innovation on the wrong aggregation level, the issue do not get solved.

8.4.2. Relationships inside and outside of a company

Relationships inside and outside companies were shown using CIM as model of innovation actors. In the interviews it was clear if respondents chose an internal or external innovation perspective, and if they had an open or closed innovation mindset.

8.4.3. Link between public/political processes and corporate behaviour

It was more difficult to model both industrial and societal developments with CIM. Although both are certainly possible, both clients of NDT services and regulators ended up together in the lower-left hand quadrant of CIM, making distinction less straight forward. CIM as used in this thesis turned out to have a bias to being used as a model of industrial processes. Making use of some of the concepts of the functions of innovation system model of Hekkert could improve CIM.

8.4.4. Intellectual property

CIM was used as a knowledge model, and very naturally adapted to analysis of knowledge creation and intellectual property. It is recommended in this thesis to further explore the link between CIM and other similar knowledge models like the engaged scholarship model of Van de Ven. A better understanding of how knowledge is used to create economically valuable activities may lead to a new level of understanding of innovation as a process, and may have very general and far reaching applications.

8.4.5. Dynamic behaviour

Dynamic behaviour was modelled both using CIM as an innovation process model, and using CIM as a knowledge model. Feedback behaviour, in the sense that innovation was shown to be an iterative process where it is not only important to pass knowledge on, but also receive back the results of using this knowledge in the next stage of innovation was observed in many cases.

In this thesis, the characteristic time of the processes in each of the CIM cycles was not investigated. This is recommended for future research. Some of the interview results, as well as the results of using CIM as a knowledge model (Table 24) give clear indications as to the possibilities of using CIM for this kind of analysis.

8.5. Recommendations for further development of CIM

The methodology developed in this thesis, in particular the three ways of using CIM (role model, actor model and knowledge model) can be deployed to analyse the innovation performance of companies and industrial sectors. The methodology could be developed into a new type of innovation audit.

On the theoretical side, the dimensions of innovation which were used in the process of selecting CIM as the model for this research should be further developed. The dimensions: (1) Scale of aggregation (2) Time dependent behaviour and feedback processes (3) Actor and network dependency and (4) Knowledge generating processes could be complete set of dimensions spanning all relevant aspects of innovation. These dimensions were based on a limited literature review. Still, the result has the promise of providing a more fundamental basis for studying innovation issues.

A limitation of CIM is the fact that the role of a regulator or government is not explicitly modelled. Although the creation of laws and regulations could itself be studied using CIM (with as 4 nodes: science of lawmaking, technology of law making, practical laws and the reception of laws by the general public), this would be a CIM model by itself.

Two options for expanding CIM with a government role have been proposed elsewhere. Van der Duin (2010) has suggested the combination of CIM with the Function of Innovation systems model of Hekkert (Hekkert et al., 2007b), which is itself more focussed on institutional factors than on the private sector. Berkhout has worked on expanding CIM to have an additional polar relationship representing conservative and progressive forces. These poles could represent the regulatory and government dimension of the innovation process (Figure 34).

A final possible improvement of CIM would be to model the dynamic behaviour of the feedback and feed forward processes using techniques from System Dynamics. The most famous example of the use of systems dynamics is the 'The limits to growth' report. In fact, the innovation model that was created by Forrester (the founder of System Dynamics) has a number features that are similar to CIM (Forrester, 1980, Forrester et al., 1976). This model was shown to be able to simulate business cycle behaviour. Expanding CIM this way would however mean that a fixed level of aggregation has to be chosen while modelling, taking one of the strength of the model away.

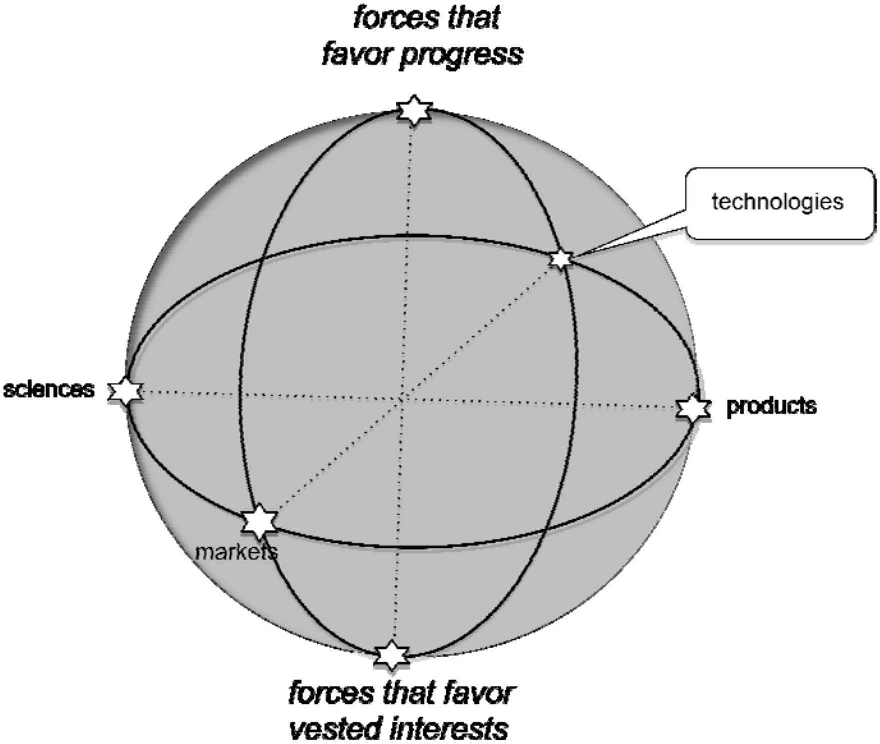

Figure 34: CIM expanded with a third dimension modelling forces that favour progress and forces of vested interests

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Appendix A. Company profiles

This appendix contains company profiles of the companies that the interview respondents work with. For each company a short description has been made of their activities, their origins and their relationship with NDT. These descriptions are adaptations of public information about these companies.

Applus RTD

Applus RTD is the market leader in Non-Destructive Testing in the Benelux, Germany and the UK. Worldwide it has over 4000 employees working in Non-Destructive Testing in 33 countries.

RTD was founded in 1937 as Röntgen Technische Dienst in Overschie (now Rotterdam). Founder Ouwerkerk was a welding foreman at a shipyard. He started the company with investments from Mr. Van Beuningen, a local shipping tycoon, and Mr. Phillips of Phillips electronics. The company grew due to the growth of the petroleum harbour in Rotterdam, the building of the gas transmission network in the Netherlands and construction inspections of nuclear plants in Germany.

Until 2003 RTD was owned by Lloyds Register and was sold to ABN AMRO Participations at that time. This started a period of international expansion. In 2006 the company was bought by Applus, and Spanish inspection, verification and testing group.

SGS

SGS is the world's largest inspection, verification, testing and certification company. SGS employs over 59,000 people and operate a network of more than 1, 000 offices and laboratories around the world.

SGS provides services in the area of quality, safety, performance and efficiency for the following industries: Agricultural, Automotive, Consumer Testing, Environmental, Industrial, Life Science, Minerals, Oil, Gas & Chemicals, Systems & Services Certification, Governments & Institutions.

Established in 1878, SGS started by offering agricultural inspection services to grain traders in Europe. From those early beginnings, SGS grew in size and scope as their agricultural inspection services spread around the world. During the mid 20th century, SGS began to diversify and started offering inspection, testing and verification services across a variety of sectors, including industrial, minerals and oil, gas and chemicals among others. In 1981, the company went public.

SGS delivers NDT services in more than 30 counties, including the Benelux from the SGS office in Spijkenisse, which also serves as the hub for advanced NDT services, and Germany from subsidiary SGS Gottfeld.

TNO Science and Industry

TNO is an independent Dutch research organization that contributes to the competitiveness of companies, organization and the economy and quality of life as a whole. It tries to do this by doing scientific research, and offing its expertise to clients. TNO is organized into 30 institutes around 5 core themes. Additionally TNO has a group of 54 companies to exploit its knowledge. In total over 4400 professionals work at TNO. TNO get 1/3 of its funding from the Dutch government.

TNO has research into NDT and NDT related subjects in several institutes, including Defense and Safety in The Hague and Science and Industry in Delft. Recent activities include the development of UMASIS ultrasonic simulation software and a corrosion monitoring system. TNO has a history of running joint industry project together with the Dutch national welding institute (NIL) and the Dutch national NDT society (KINT) and companies from the industry.

BASF Technical and Engineering Services

BASF technical and engineering services, part of the BASF group, delivers a wide range of technologies and services. The main activity is supporting the BASF chemical site in Ludwigshafen, the largest chemical industry site in the world, stretching across 10 km2 and employing over 30000 people. Services include high pressure technologies, surface treatment, chemical analysis, automation and robotics and machining services. BASF Technical and Engineering Services also performs services to other sites of BASF, and to other companies.

In the materials engineering group, BASF technical and engineering services has a Non-Destructive Testing department. This department serves as the in-house NDT service provider for BASF Ludwigshafen and as an expert group for this and other sites. The department is not capable of performing all services themselves, neither all technologies nor the complete volume of inspections. For this purpose the NDT department also has a role in identifying companies that could perform these services for the larger organization.

Sonovation

Sonovation is an internationally operating specialist NDT company. Sonovation has its head office in Oosterhout, the Netherlands and offices in The United Kingdom, Germany, Belgium and Saudi Arabia.

Sonovation started as the Dutch branch office of Sonomatic in 1988. Sonomatic is a company building and delivering services with automated ultrasonic inspection systems, and renowned for being a pioneer of the Time of Flight Diffraction (ToFD) technique. Sonomatic was bought by AEA Technology in the 90s.

Jan Verkooijen bought out the Dutch branch office of AEA Sonomatic in 2000, making it an independent company named Sonovation. Sonovation is now itself known for being a specialist supplier of ToFD, Phased Array, Corrosion Mapping mechanized Pulse-Echo, and Long Range UT. Sonovation also offers the Pulsed Eddy Current (PEC) technique, a technique for quick corrosion screening under insulation (CUI) and corrosion monitoring.

Besides delivering services, Sonovation also develops and sells its own ultrasonic inspection system (Sonovision) and inspection software. Additionally Sonovation gives training courses for both its own personnel and other companies involved in specialist NDT.

In 2011 Sonovation announced that it was being acquired by TÜV Rheinland.

Total E&P Nederland

Total E&P Nederland is a subsidiary of Total S.A., which is engaged in all aspects of the oil and gas industry, including upstream operations (oil and gas exploration, development and production, LNG) and downstream operations (refining, marketing and the trading and shipping of crude oil and petroleum products).

Total E&P Nederland has been engaged in the exploration and production of natural gas in the Netherlands and the North Sea Continental Shelf since 1964. In the Dutch sector of the North Sea, gas is produced from 21 platforms and two subsea production installations. Most of the platforms are unmanned and remotely operated; four have gas treatment facilities. After treatment, the gas flows through a network of pipelines to GasTerra (the former Gasunie Trade & Supply) onshore. The offshore production centers are located between 80 and 150 kilometers northwest of Den Helder. The Central Control Room in the head office in The Hague monitors the process of all the installations and is manned 24 hours a day. Helicopters and supply vessels are used to transport personnel and goods.

The company is a major gas producer in the Netherlands, with an annual production of approximately 6 billion m3, or around 13% of Dutch domestic consumption. Total E&P Nederland has 273 permanent employees and indirectly provides work for at least a further 800 people.

As part of its responsibility to operate and maintain its installations responsibly, Total E&P Nederland performs regular NDT and inspections. These activities are coordinated from the office in The Hague.

History

1964 Company established under the name Petroland N.V.

1971 Start of onshore gas production

1973 First gas discoveries on the Dutch Continental Shelf.

1977 Start of offshore gas.

2001 Merger with Total Oil and Gas Nederland B.V. to become TotalFinaElf E & P Nederland B.V.

Shell Global Solutions

Shell Global Solutions originates from Shell research laboratories. Shell Global Solutions, part of Royal Dutch Shell, delivers technology and consultancy to the energy and processing industries. Shell Global Solutions draws on its corporate heritage as the owner and operator of large plants around the world to provide clients in the oil and gas, petrochemical production and other processing industries with energy technology, catalysts, R&D expertise and business and operational consulting services.

Shell Global Solutions licenses cutting-edge technologies as well as providing business and operational consultancy to help customers improve the capacity and performance of existing units; integrate new process units into existing refinery operations; incorporate advanced catalyst systems and reactor internals; and build new refineries.

Shell Global Solutions has more than 5,000 professionals, many of whom have operational and technical experience across a broad range of petrochemical processing and production industries. Shell Global Solutions has around 125 engineers working on materials and inspection issues, in three locations (Houston, Amsterdam and Singapore). Work in this area includes issues related to materials selection, welding, corrosion and inspection technology.

GE sensing and inspection

GE Sensing & Inspection Technologies is an affiliate business of General Electric specializing in the design and manufacture of sensing elements, devices, instruments, and systems that enable customers to monitor, protect, control, and validate the safety of their critical processes and applications.

GE Inspection Technologies incorporates a number of originally independent companies that are each leaders in a particular field of NDT instrumentation. The group was formed in a number of subsequent mergers and acquisitions.

In 1999 Agfa X-ray systems part of the AGFA-Gevaert group and leader in the area of radiographic film and processing materials bought RADview, leader in the area of digital x-ray

In 2000 Agfa bought Krautkrämer the leading company in ultrasonic equipment.

In 2001 Agfa added the Seifert and Pantak businesses to the group. Both are leading companies in the area of X-ray tubes

In 2004 Agfa NDT was acquired by GE Aircraft Engines as part of the movement of GE to be involved in the servicing of their products.

GE continued adding companies to the group: among others Everest VIT in remote video inspection (2005) and Phoenix|X-ray in X-ray tomography (2007)

In 2006 GE sensing and GE Inspection Technologies were merged

In addition to merging these companies to a group, GE started to transfer technologies from its medical equipment business to the area of NDT. One of these development is the development of Rhythm; an NDT data management software solution which was derived from a medical patient data management system.

Acergy

Acergy S.A. was an international offshore seabed to surface engineering and construction company previously known as Stolt Offshore and Stolt Nielsen Seaway and was part of the Stolt-Nielsen Group until 2005. In 2011 the firm merged with Cayman Islands-based Subsea 7, Inc. to create Subsea 7 S.A.

The company started as the Haugesund based Stolt Nielsen Seaway and offered divers for the exploration of the North Sea in 1970. The company was part of the Stolt-Nielsen Group. In 1989 the company expanded to Aberdeen and in 1992 the company acquired the French diving company Comex Services. In 1997 the company won its first ultra-deepwater contract off West Africa, resulting in the acquisition of Houston based Ceanic Corporation, Danish NKT Flexibles and ETPM of France.

In 2000 the company changed its name to Stolt Offshore. But poor management forced the company to narrow its focus and a new management was introduced in 2003. In 2005 the Stolt-Nielsen Group sold its ownership in the company and listed it on the Oslo Stock Exchange and NASDAQ. As of 1 March 2006 the company changed its name to Acergy.

Acergy / Subsea 7 has extensive experience in deepwater Subsea, Umbilical, Riser and Flowline (SURF) and Life-of-Field projects has made it a preferred contractor and trusted partner for national and international energy companies. Acergy / Subsea 7 provides integrated services and plans, designs and manages the delivery of complex projects in harsh and challenging environments. To deliver these services, Subsea 7 operates a fleet of around 40 ocean going ships.

The services of Acergy / Subsea 7 have to comply with many national and international regulations. These often require the Subsea pipelines (and other structures) to be inspected with Non-Destructive Testing.

ESR technology

ESR Technology was previously the engineering, safety and risk division of AEA Technology. This division was a part of the commercial arm of the UK Atomic Energy Authority. This heritage means that we have many years experience of the application of engineering excellence to demanding projects worldwide. ESR has in-depth experience of working with customers across many sectors, including oil and gas, rail, utilities, aviation and space.

ESR Technology hosts and manages five internationally renowned Centres of Excellence that ensure that we deliver the best possible solutions to help customers improve and enhance the performance, safety, reliability of their capital assets. The Centres are:

- European Space Tribology Laboratory
- National Centre of Tribology
- National Non-Destructive Testing Centre
- Pump Centre

In 2011 ESR was acquired by Hyder consulting. Hyder is one of the world’s longest established engineering consultancies, with a heritage of over 150 years. It operates from offices in Europe, the Middle East, Germany, Australia and East Asia.

Hyder offers a full range of advisory and design services that deliver market leading infrastructure and property solutions. Hyder has designed some of the world’s most instantly recognisable landmarks including London’s Tower Bridge, Sydney Harbour Bridge and the Burj Khalifa - the world’s tallest building.

HOIS

Managed by ESR Technology, HOIS is a prime industry forum for discussing inspection issues and utilising improved inspection technology for applications in oil and gas industry. HOIS’s main aim is to achieve more reliable and cost effective Non-Destructive Testing techniques in the oil and gas industry and hence improve operational safety.

This is achieved by:

- Developing improved procedures and recommended practices
- Performing independent evaluation trials to assess techniques and understand benefits and limitations
- Development of inspection techniques and inspection technology

- Provision of an internet accessible source of information on inspection techniques both advanced and conventional

HOIS operates as a membership based organization. Among the members are many of the major Oil and Gas companies active in off-shore exploration, their NDT and inspection service providers and many of the companies producing and marketing NDT equipment.

HSE

The Health and Safety Executive (HSE) is a non-departmental public body in the United Kingdom. It is the body responsible for the encouragement, regulation and enforcement of workplace health, safety and welfare, and for research into occupational risks in England and Wales and Scotland. The HSE was created by the Health and Safety at Work etc. Act 1974, and has since absorbed earlier regulatory bodies such as the Factory Inspectorate and the Railway Inspectorate though the Railway Inspectorate was transferred to the Office of Rail Regulation in April 2006. The HSE is sponsored by the Department for Work and Pensions. As part of its work HSE investigates industrial accidents, small and large, including major incidents such as the explosion and fire at Buncefield in 2005. Though it formerly reported to the Health and Safety Commission, on 1 April 2008, the two bodies merged.

The Executive's duties are to:

- Assist and encourage persons concerned with matters relevant to the operation of the objectives of the Health and Safety at Work etc. Act 1974.
- Make arrangements for and encourage research and publication, training and information in connection with its work.
- Make arrangements for securing government departments, employers, employees, their respective representative organisations, and other persons are provided with an information and advisory service and are kept informed of, and adequately advised on such matters.
- Propose regulations.

Part of the duty of the HSE is being a regulator for the Oil and Gas industry, particularly in the area of safety and inspection. Part of this duty used to be the regulation of pressure vessel inspection, but this role has been discontinued after European harmonization of pressure vessel legislation in the Pressure Equipment Directive (PED). HSE retains a regulatory role for the nuclear and off-shore sectors.

Fraunhofer IZFP

Fraunhofer is Europe's largest application-oriented research organization. The research efforts are geared entirely to people's needs: health, security, communication, energy and the environment. The Fraunhofer-Gesellschaft undertakes applied research of direct utility to private and public enterprise and of wide benefit to society.

Research is carried out in more than 80 research units, including 60 Fraunhofer Institutes, at different locations in Germany. The majority of more than 18,000 staff are qualified scientists and engineers. The total annual research budget is €1.65 billion. Of this sum, €1.40 billion is generated through contract research. Two thirds of the research revenue is derived from contracts with industry and from publicly financed research projects. One third is contributed by the German federal and Länder governments in the form of institutional funding

The Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (IZFP) is one of the Fraunhofer institutes. It is located in Saarbrücken and Dresden and has around 300 employees, of which around 60 are scientists, and around 45 are engineers.

The Fraunhofer IZFP is engaged in research and development covering

- the physical principles of Non-Destructive Testing
- material characterization
- control and monitoring of production processes and industrial plants and components

The results achieved at the institute are used in industrial applications when quality assurance and/or proof of technical safety are required. The methodological expertise comprises the physical fundamentals, sensor technology, test instrument design and manufacturing, processing technologies, techniques for data evaluation and documentation, and, in addition, the qualification and validation of new inspection and testing procedures including instrument and system maintenance, staff training, and inspection and testing services.

Lloyd's Register Nederland

Lloyd's Register is a worldwide classification, certification and risk management company. Lloyd's Register was founded in the 17th century and became famous for publishing a Register of Ships, which gave investors in those ships an idea of the condition of the ship. This register, of virtually all commercial sea going ships, is still published annually.

To support this activity, Lloyds also started to publish Lloyd's Rules with standards for how a ship should be build. A ship is considered to be in a particular 'class' if it meets the minimum requirements of that class as stated in the rules. In many cases this is the condition that needs to be met in order to get insurance.

In the 20th century Lloyds register diversified into oil & gas, process industry and other activities. One of the acquisitions was the privatized Stoomwezen B.V. in 1994. Until that time Stoomwezen was the Dutch governmental inspection organization looking after the safety of pressure equipment. Today this activity is part of Lloyds Register Energy and is a Notified Body under the Pressure Equipment Directive (PED) and an Appointed Body for the inspection of pressure equipment that is in-service.

Appendix B. Interview protocol

A. Data on the respondent, his organization and the people he is involved with

1. Identification of respondent

	Person	Organisation	Industry
Name			
Position / role			
Responsibility / mission			

2. What do you consider to be Innovation? Please elaborate?

B. Relationships across the industry

3. Who are the stakeholders where innovation in NDT is concerned?
4. How often do you interact with each of these?
5. Who would benefit most from the innovation and why?
6. Which scientific organizations are you in contact with?
7. Which engineering, development and other technical organization are you in contact with?
8. Which operational NDT companies / NDT service providers are you in contact with?
9. Which asset owners / end users of the service are you in contact with?

C. Description of a typical project

10. When I would ask you for a typical innovation project in NDT, which product or service do you think of?
11. Please describe how that product / service was researched and developed
    11a. what was the original reason for researching this product
    11b. what activities were undertaken to develop this product? Who was involved at which stage?

    - 11c. what technological approach was taken? Who decided and who was involved?
    - 11d. how was market introduction organised? What was expected of the product?
    - 11e. what client was this product intended for? How was it received?

12. What was at stake for you, your organization, the industry?
13. Please indicate which of these answers a – e is typical, and which is not

D. Bottlenecks

14. Why is innovation in NDT slow?
15. What determines the speed of innovation in NDT?
16. What problems are usually encountered around a new product service?
17. Why is this problematic?
18. How are these things resolved?

E. Knowledge

19. Who has scientific knowledge in NDT
20. Who has engineering knowledge in NDT
21. Who has practical knowledge in NDT
22. Who has knowledge about the requirements for NDT

Appendix C. Concepts in innovation management

In order to get a good overview of the available concepts in innovation management, a literature review was made on the most influential concepts. This review was done by going through a number of textbooks on innovation management and listing which concepts these refer to. This review is not reported in the main thesis as it would deviate too much from the main subject, but was an important input for the model selection process described in chapter 5.

Concept pertaining to the general economy

Process	**Concept**	**Subject / perspective**	**Research question**	**Research method**	**Reference**
General Economy	Creative destruction	Macro economy	How does innovation influence the economy	Various (evolutionary economist)	(Schumpeter, 1947, Schumpeter and Opie, 1934)
	National and regional innovation systems	Regional economy	Which region is most innovative	Analyzing factors such as R&D and higher education spending	(Nelson, 1993), (Porter, 1990)
	Entrepreneur ship and Science parks (MIT model)	Regional economy	How to speed up the introduction of new technology	Comparison of number of startups and their success	(Roberts, 1991)

Concepts pertaining to innovation in operational management

Process	**Concept**	**Subject / perspective**	**Research question**	**Research method**	**Reference**
Operational management	TQM, Lean and 6 sigma	Corporate operations	How to improve performance and reduce cost	Statistical evaluation and benchmarking	Various
	Learning organization	Corporations	How can the dynamic processes in organizations be better understood	Simulations and modeling	(Senge, 2006)

Concepts pertaining to R&D and NDP project management

Process	Concept	Subject / perspective	Research question	Research method	Reference
R&D and NPD organization and project management	Generations of R&D models, Technology push v.s. market pull	Corporate departments (large companies)	What is the interaction between R&D, NPD and operations	Analyzing the flow of activities between departments	(Rothwell, 1992)
	Stage gate model & R&D Funnel	Corporate departments (large companies)	When should projects be abandoned	Evaluation of current projects and the prospective success of results	(Cooper, 2008)
	Skunk works and heavy innovation teams	Corporate departments (large companies)	How much interaction should there be between exiting activities and new development	Evaluation of past projects	(Clark and Fujimoto, 1991)
	New product marketing	Corporate departments	What factors differentiate successful innovators from unsuccessful ones	Research of markets and customer needs	Various

Concepts pertaining to discontinuous change in technology

Process	Concept	Subject / perspective	Research question	Research method	Reference
Discontinuous change in technology	Disruptive innovation	Large corporations	Why do some companies fail and others succeed with the same technology	Case studies of successful and unsuccessful companies	(Christensen, 1997)
	Technology trajectories / regimes	Economic sectors	What patterns does technological innovation take	Case studies on technologies	(Nelson and Winter, 1977), (Dosi, 1982)
	Dominant designs	Economic sectors		Case studies of technologies	(Utterback, 1996)
	S shaped performance models, sailing ship effect	Economic sectors		Case studies of technologies	(Foster, 1986)

Concepts pertaining to Appropriation, exploitation and protection of knowledge

Process	Concept	Subject / perspective	Research question	Research method	Reference
Appropriation, exploitation and protection of knowledge	Standards	Companies	Under what circumstance can an open standard benefit companies	Case studies of technologies	n.a.
	Open innovation	Large corporation	How can inventions out of in-house R&D be made profitable	Case studies of technologies	(Chesbrough, 2003)
	Innovation networks	Economic sector	What kind of contacts benefit innovation	Network models	Various
	IP protection	Companies	How can inventions be protected from imitation	Cases	n.a.
	Joint ventures and strategic alliances	Companies	n.a.	n.a.	n.a.
	New venture division	Companies	n.a.	Case studies of technologies	n.a.
	Business models	Companies	What kind of commercial organization can be used to exploit a technology	Case studies of technologies	(Chesbrough, 2006)
	Technology lifecycle	Technologies	How can a technology be best exploited given age	Market analyses	n.a.

Concepts pertaining to corporate strategy

Process	Concept	Subject / perspective	Research question	Research method	Reference
Corporate strategy	5 forces model and Value chain	Companies	What strategy could the company take given environment	Market analyses	(Porter, 1980, Porter, 1985)
	Core competences	Companies	What strategy could the company take given resources	Analyses of competences	(Prahalad and Hamel, 2006)
	Dynamic capabilities	Companies	What strategy could the company take given resources and environment	Analyses of market and competences	(Teece and Pisano, 1994, Teece, 2009)
	Product market combinations	Companies			(Porter, 1980), (Ansoff, 1957)
	Innovation audit	Companies	Is the organization innovative		(Tidd et al., 2005a)

Concepts pertaining to the interaction with users

Process	Concept	Subject / perspective	Research question	Research method	Reference
Interaction with the user of the innovation	Diffusion of innovations	Society	What social factors influence adoptation of innovations	Quantitative analyses of adopters	(Rogers, 1962)
	Crossing the chasm	Company	What social factors influence adoptation by later adopters	Cases	(Moore, 2002)
	Lead user innovation	Sectors	If and when does innovation start with users	Quantitative analyses of technologies in a sector	(Hippel, 1987)

Source works

Authors	Title	Year first/last ed.
Joe Tidd, John Bessant, Keith Pavitt	Managing Innovation: Integrating Technological, Market and Organizational Change (Tidd et al., 2005a)	1997 / 2005 (3rd)
Paul Trott	Innovation Management and New Product Development (Trott, 2008)	1998 / 2008 (4th)
Robert Burgelman, Clayton Christensen , Steven Wheelwright	Strategic Management of Technology and Innovation (Burgelman et al., 2009)	1988 / 2008 (5th)
John Howells	The Management of Innovation and Technology (Howells, 2005)	2005 (1st)
Michael L. Tushman & Philip C. Anderson	Managing Strategic Innovation And Change (Tushman and Anderson, 2004)	1997 / 2004 (2nd)

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On 23 October 2002, Niels Pörtzgen and I visited Guus Berkhout. During a project that I had worked on with Niels, the plan was born to get Niels started on PhD research. Niels succeeded and defended his thesis on 6 November 2007 with Dries Gisolf as his supervisor. Part of him getting started was visiting Guus Berkhout, who had laid the foundation for a number of the theories that Niels was going to adopt into NDT from Geophysics. The meeting went well, and Guus gave us his blessing. While we were about to leave, Guus gave me a book (Berkhout, 2000) and said: “maybe this is something for you to look at later”. That is how it all started.

In 2005, after having been part of the group management team of RTD for a short time, Cesar Buque was joining RTD and I had to hand over the leadership over the technology development at RTD to him. My own PhD project was created as a way to avoid us becoming two captains on one ship. It also gave me the opportunity to explore why so many promising technologies failed when handed over from the technology department to operations. This was a subject close to my heart after seeing the Guided Waves team, which Michiel Engel and I had built up, fall apart in operations. This brought me back to Guus Berkhout, his book and the Cyclic Innovation Model.

My first acknowledgement goes to Guus Berkhout, for sowing the first seed of this thesis, and being there all the way. When combining the work at RTD with PhD research became too hard, he arrange for me to work at the Civil Engineering and Geophysics faculty for a year, in which I performed the majority of the work in this book. He organised the funding for this through the Delphi consortium, for which I am very grateful. His drive and energy are an inspiration to me.

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