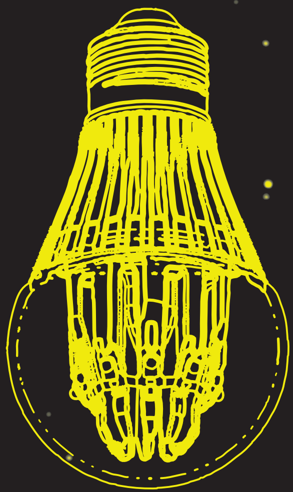
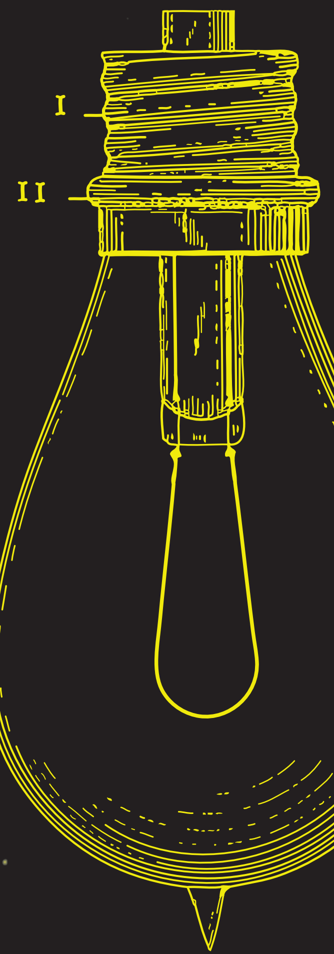
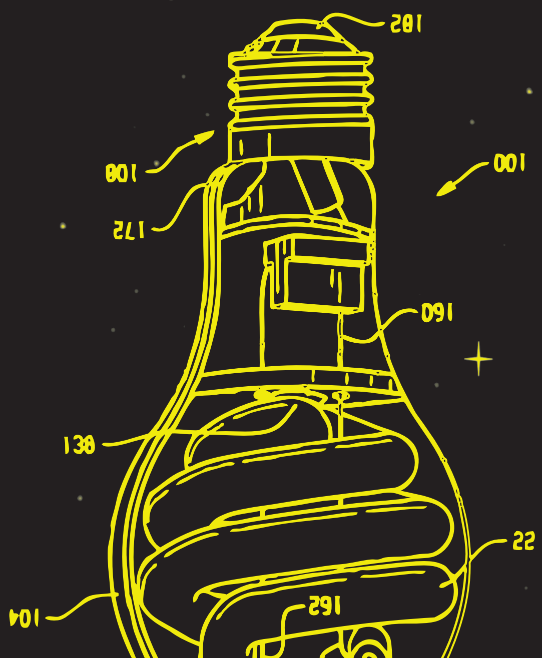
PRODUCT EVOLUTION

How new (types of) products come about & develop over time into families of advanced versions







HUUB EHLHARDT

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HOW NEW (TYPES OF) PRODUCTS COME ABOUT & DEVELOP
OVER TIME INTO FAMILIES OF ADVANCED VERSIONS

PROEFSCHRIFT

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Preface

0

"As far as I am concerned, you are already on the way", said Professor Arthur Eger to encourage me to take up the research project that resulted in this thesis. It has been a journey that has largely met my expectations. However, it has turned out to take longer than assumed at the start and, as befits a good adventure, I quite often left the beaten track and have trodden side paths, which has brought me to explore to places I could not have foreseen. I want to use this preface to explain how this research project came about and also thank a number of people for their support and contributions, without which this thesis would not have been conceived. This preface is much longer than is normal for this type of publication. The reason for this lies in the fact that the study described in this thesis was preceded by a decade of knowledge acquisition and idea development. This period produced a number of ideas and insights that are included in the section 'Evolution and Innovation'. These ideas and insights contributed to the starting point of this research. However, they are not formally part of this thesis and have, therefore, been included here in the non-scientific part of this thesis.

0.1 What preceded this thesis

Since a young age I have been fascinated by technology. Around the age of four I started taking products apart out of curiosity to find out how they functioned and had been constructed. A defective washing machine was one of my first significant subjects of investigation. A few years later, my fascination made me want to become an inventor one day. During my youth my technology-minded father, who had studied mechanical engineering, supported me in my technical explorations by providing me with more defective products for post-mortem examinations. My father also introduced me to the basic ideas on evolution. Indeed, in my early youth my father built a boat that he named 'The Beagle' after the ship on which Charles Darwin once sailed around the world on a voyage that was crucial for Darwin's thinking on evolution. During secondary school one of my favourite subjects was biology. However, at the age of 18 I abandoned biology and went to study Industrial Design Engineering at a technical university.

I did my Master's project at Philips, a Dutch electronics manufacturer, where my assignment was to design a multi-functional appliance to control the climate in baby rooms in a way that made them as comfortable as incubators. As part of the desk research for this project, I used information from all the consumer guides I could get my hands on in the library of the Dutch Consumers' Association Consumentenbond, which was still open to the public at that time. This desk research led to an observation about a feature once introduced in fan heaters, namely the thermostat used to control the temperature. In older test reviews the thermostat was uncommon while, in later reviews, it became more or less standard. This observation made me ponder whether these products could perhaps undergo a sort of evolution where features that brought the product more of a competitive advantage would spread through the population similarly to the way traits do in biological species.

After finishing my Master's degree, I continued working at Philips in predevelopment. This is where I became a sort of 'inventor' although, I have to admit, not a particularly gifted one. Seven years and a handful of not very influential patents later, I left Philips to work for the Dutch contract research organisation TNO. I had learned that I did not want to pursue a lifetime career as product designer, nor inventor because my work as a predevelopment engineer had dispelled any romantic notion that I might have had about the job of inventor, which I had dreamed about during my youth. It occurred to me that sufficiently skilled hardworking development engineers would come across inventions as a standard part of their work. Though the fascination for the process of establishing new technologies or products remained, the focus of my interest shifted towards one that looks at how these innovations actually happen in companies and other arenas. Hence, my fascination for technology had evolved into a professional interest in the process of innovation. During my work at TNO the observation from my master's project resurfaced in my mind and I became intrigued by the question of whether this could lead to an interesting and possibly new perspective on innovation. I realised that this would require substantial familiarity with both biology and innovation literature. Obviously, my knowledge of biological evolution had not yet developed beyond that provided by the biology curriculum of my secondary school. I therefore set out to acquire more knowledge on this topic and started reading books on evolution. After about four years my career at TNO ended due to a reorganisation. Just before that point I had written down ideas developed in the four preceding years in a draft paper titled 'Evolution and Innovation' of which a summary is included below. The inevitable change in working environment made it necessary to rethink my professional development. The draft paper was translated into a first presentation which I held in the Spring of 2005 to a diverse audience at a meeting organised by Innovaders, a company run by friends from university. Stimulated by the positive responses I set out to investigate whether a PhD position was feasible as a means to continue exploring my fascination for evolution and innovation. The PhD project I had in mind seemed to be an ideal opportunity to focus my efforts on interesting topics, literature and people. Ultimately, this could also nudge my further career in an interesting direction. It soon transpired that the topic of my fascination was not quite mainstream and that appropriate PhD positions were therefore not available.

Secondly, I was not enamoured by the pay I would receive in a PhD position, which was well below what I had become used to. At that time I applied for a position in a management-consulting firm and was subsequently hired. My enthusiastic story on innovation and evolution was welcomed. However, management consulting turned out not to be the ideal place for the type of intellectual exploration I was looking for.

At the end of 2009, former TNO colleague Erik Tempelman brought me into contact with Arthur Eger, professor of industrial design engineering at the University of Twente. Arthur obtained his PhD in 2007 based on a thesis entitled ‘Evolutionary Product Development’. The first meeting with Arthur took place in January 2010. During the third meeting Arthur made the remark stated in the first sentence of this preface. It appeared I had already started my research project and that all that was required was a formal start. This came as a surprise and I have to admit, a bit of a shock, as it required me to step-up alongside other substantial changes in my life.

At the end of January 2010 I had proposed to my beloved future wife Wyp de Jong. Preparations for the wedding in July were already on-going. Nevertheless, I realized that this was probably a once-in-a-lifetime opportunity for a non-mainstream PhD research project into a subject I was fascinated by and should not, therefore, be thwarted by other events. Consequently, I wrote down a short description of what I intended to investigate and named the research project ‘Technological Innovation as an Evolutionary Process’.

It soon transpired that Wyp was pregnant and that was something we made public during our wedding party on 10 July 2010. It was a hectic time as the consulting job required long working weeks and near constant assignments abroad. Wyp’s growing ‘bump’ made me realize I was going to be needed at home during the coming years. I therefore decided to return to a job close to home which did not require constant travel and work hours commonly associated with consulting jobs. Luckily, I was able to secure a job at Philips again and started there just two weeks after our daughter Yfke was born. This signalled the start of an intensive period of hard work during which I combined a young family, a daytime job at Philips and weekend PhD study. Sadly, it was during this period that my father became ill and subsequently passed away and did not live to enjoy the fruits of my labour that lies before you now, that is a thesis entitled ‘Product Evolution’.

In the following section, I will introduce the reader to my thoughts that preceded the start of this project. As the title of this research project suggests (Technological Innovation as an Evolutionary Process, see also section 1.1) the aim is to explore whether, and to what extent, technological innovation can be described as an evolutionary process.

0.2 Evolution and Innovation

Prior to this research project I read a great deal of literature on innovation and biological evolution, seemingly two fairly unrelated fields. In 2005 this resulted in a first presentation on the subject. The ideas put forward were also laid down in an unpublished paper entitled 'Evolution and Innovation'. The paper describes the thoughts that eventually made me explore the ideas laid down in this thesis. However, they are not considered conform the scientific standards to which this thesis is to comply. Therefore this 'introduction' has been placed in the preface, the non-scientific part of this thesis. This paper described how the stone hand axe appeared as a 'first tool'. Over time, ever more advanced and complex tools have been produced, with the smartphone being a key example of a very new type of product. In this I noticed a similarity in biological life that started out as something simple and evolved over time to acquire more diversity and complexity. Biological life on earth started out as low complex life forms and complexity increased over time. Today we not only have more complex forms of life, but also very simple forms (viruses) that did not yet exist in prehistoric times (Figure 0.1). Remarkably, the most commonly occurring life forms have always had a low level of complexity, both now and in the early days of life. Stephen J. Gould (1996) beautifully described why complexity is distributed in this way in his book 'Full House' in which he introduces the idea of a 'left wall of minimal complexity' (Figure 0.1) that functions

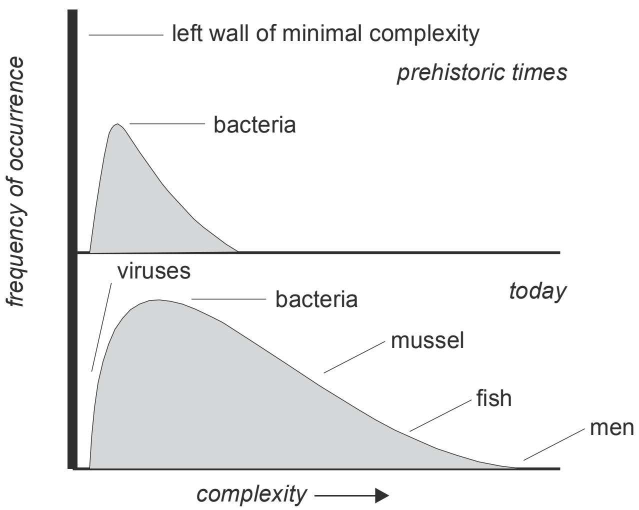


Figure 0.1. Distribution of complexity in life (Gould, 1996).

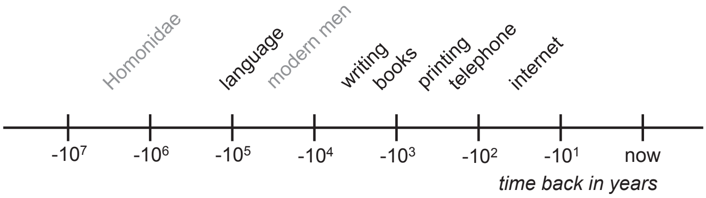


Figure 0.2. Punctuations in the evolution of human communication (source: the author).

as a border for the types of life with the lowest degree of complexity. On the right, there is no defined border for complexity but the frequency of occurrence rapidly drops as it approaches an asymptote.

I imagined a similar idea could be applied to artefacts from prehistoric times, with the stone tools being the equivalent of early life forms. These days the complexity distribution curve stretches towards more complexity to include products like an aircraft carrier or smartphones. Similar, as in the biological realm, the complexity distribution curve for artefacts now also contains products like paperclips and clamps which have a complexity that is arguably lower than that of earliest products.

I also noticed that the pace of the introduction of new, more advanced and complex products dramatically increased over time. Stone hand axes, commonly referred to as the first tools, were first produced several million years ago (see also Chapter 4). About two hundred thousand years ago our own species *Homo sapiens* evolved from our ancestral species. Then, about ten thousand years ago, people started to live in more complex societies where agriculture, the first towns, clay tablet writing and specialisation of labour were the innovations that advanced the way they lived. People quickly started to make more advanced and complex products, which were made possible by specialisation of labour, amongst other things. At the same time the efficacy of knowledge accumulation and sharing rapidly increased because of more advanced language, which included writing. I noticed that a number of punctuations in how we share information (Figure 0.2) probably coincide with increases in diversity and complexity in products[1]. These information-sharing punctuations started with human language (probably more than a hundred thousand years ago) and then produced the first pictograms on clay tablets (4000 BC), Syllabic script on clay tablets (2500 BC), woodblock printing (200 AD), moveable type printing (1040 AD), the mechanical printing press (1440), Morse code (1836), telephone (1876) and

1 I have not explored events that describe major downturns in diversity and complexity of artefacts or products. A probable cause of such downturns can be found in the collapse and disappearance of societies. Jared Diamond described such downturns in his book Collapse (Diamond, 2005)

finally Internet (~1980). I found interesting information on this issue in a publication called 'The Evolution of the Book' where seven punctuations in the evolution of books are described (Kilgour, 1998, p.5). The information-sharing punctuations appeared to me to coincide with punctuations in complexity and diversity of products. Also, these information-sharing punctuations succeed each other at ever-smaller intervals.

While contemplating the evolution of artefacts, I came across the idea of the meme[2] (Dawkins, 1976) that was postulated as an analogy to the gene. Dawkins' idea was further elaborated by various authors (Brodie, 1996; Blackmore, 1999; Aunger, 2000, 2002). These works inspired me to think about how evolution of man-made things could be described. In archaeological works, such man-made things are referred to as artefacts. Literature on memetics suggests that memes mutually interact a lot, or cross-fertilise assuming emphasis on exchange in a pool (horizontal). This might resemble genetic interaction amongst types of single celled life, referred to as Prokaryota[3], which are known for horizontal transfer of genes, or exchange of genetic material without clear parent-offspring relations. This contrasts with sexual reproduction in biological evolution where there is a clear parent-offspring relationship (from one generation to a next, or vertical in a traditional family tree) and the pace of interaction is much lower. For complex life forms, like vertebrates, the time between generations is measured in weeks to many years. This is exactly where I have to be careful given that I am not a trained biologist but an engineer. Even being an engineer, I should note here that sexual reproduction is not the norm if diversity of life forms is taken into account. However, this perspective came about less than half a century ago (see also Figure 5.3 right side). To be precise I should say that the parent-offspring relationship is at least clear for multicellular life, as we know in Eukaryota[4], especially in case of sexual reproduction.

Contemplating differences between genetic and artefactual evolution led me to draw two different tree-like diagrams depicting how earlier and later forms of Eukaryotic (or more complex) life versus artefacts relate to each

2 Memes are defined as units of cultural information and are used to communicate and share ideas. The word meme is based on the Ancient Greek word mīmēma, meaning 'something imitated'. Ideas on memes developed further into a field of study called memetics in the 1990s to explore the concepts and transmission of memes in terms of an evolutionary model.

3 Prokaryota are microscopic single-celled organisms, which have neither a distinct nucleus with a membrane nor other specialized organelles, including the bacteria and cyanobacteria.

4 Eukaryotes belong to the taxon Eukarya or Eukaryota. The defining feature that sets eukaryotic cells apart from prokaryotic cells (Bacteria and Archaea) is that they have membrane-bound organelles, especially the nucleus, which contains the genetic material and is enclosed by the nuclear envelope.

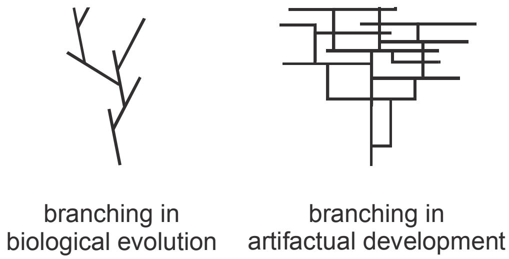


Figure 0.3. Two different types of tree structures depicting lineage relationships (source: the author).

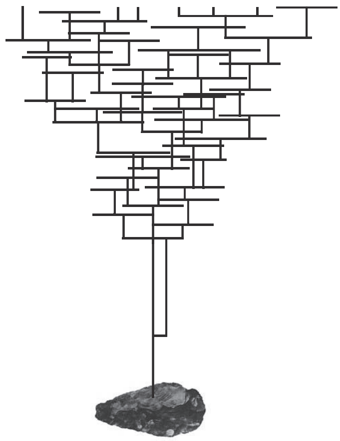


Figure 0.4. A tree of artefacts starting from the oldest tool, the stone hand axe (source: the author).

other (Figure 0.3 left side). Admittedly this figure with tree-like branching is biased by the tree of life based on the Linnaean classification (see also Chapter 5). Figure 0.3 right side assumes that memes are involved in artefact evolution. As memes do not have unambiguous parent-offspring relations as found in complex life, and because there is allegedly an emphasis on cross-fertilisation in a certain generation, memes and thus artefacts appear predominantly to exchange their information horizontally as represented mainly by horizontal lines.

Further extending this idea to products or artefacts caused me to draw a tree structure with the stone hand axe as a first node. Somehow a 'tree of artefacts' should begin with a first stone tool[5], and then grow over time into more complex artefacts. This tree of artefacts should then show an emphasis on horizontal exchange, assuming that artefactual evolution is based on memes as a carrier of information.

Inductive reasoning led me to the idea that the observed punctuations in the evolution of human communication or information sharing (Figure 0.2) probably led to punctuations in complexity and diversity of artefacts. Figure 0.5 pictures a tree of artefacts where roughly four huge punctuations in information sharing (language, writing, printing, internet) coincide with punctuations in complexity and diversity of artefacts and so, in abstract, represents the evolution of artefacts. It means that every time there was a huge improvement in information sharing, this allowed for a faster and

5 Note. The stone hand axe pictured here is by no means the oldest stone tool. However, it is used in this picture because this type of hand axe is easily recognised as a stone tool.

more reliable exchange of ideas (memes) that, in turn, enabled more complex and diverse artefacts to evolve. This also implies that there is a link between earlier and later artefacts, similar to lineage in biological life depicted by the family tree.

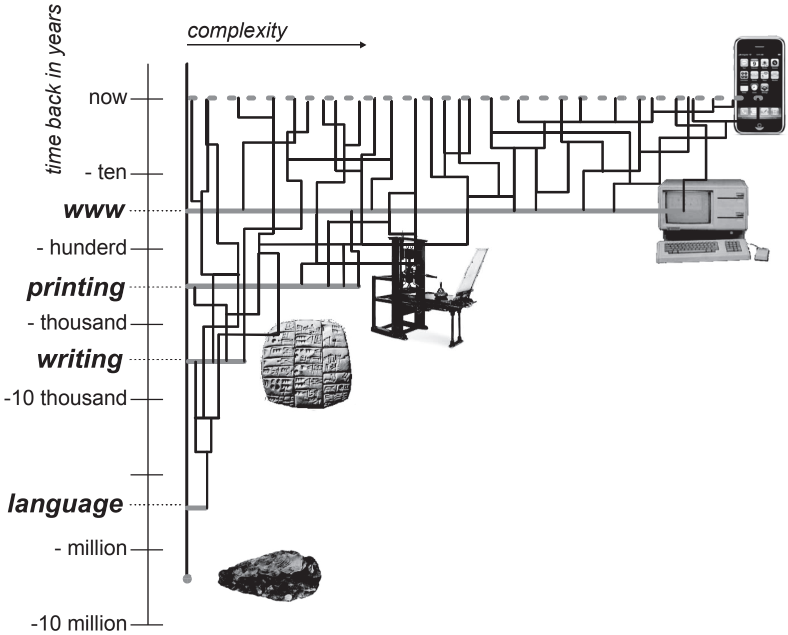


Figure 0.5. Evolution in artefacts (source: the author).

This picture marks the end of the first phase of my journey. Obviously this picture represents a figment of my own imagination for which there is no concrete proof, let alone any scientific underpinning. I realised that, if I were to take this any further, I would need a practical way to explore how evolution in artefacts takes place, if it could be described in such terms at all. I therefore set myself a challenge, namely to explore what is available on this topic in scholarly articles, investigate how some products evolved over time, explore whether the evolutionary analogy makes sense when describing this evolution, and determine how best to picture such evolutionary relations.

0.3 What does this thesis deliver?

First of all this thesis, like any other, lays down the results of a PhD project. Secondly it aims to provide a new perspective on the questions 'can technological innovation be described as an evolutionary process?', 'how can one describe it, and what insights does it provide?', and 'how do new types of products originate?'. Fortunately, it turned out that many authors have

already published work on this theme. I am therefore grateful to be able to continue building on their publications.
Thirdly this research project attempts to contribute insights from other disciplines like the so-called Science and Technology Studies (STS) or Science Policy and Innovation Studies (SPIS) to the realm of Industrial Design Engineers and others involved in New Product Development. To a large extent the education of Industrial Design Engineers is based on a mix of engineering and craftsmanship. Students of Industrial Design Engineering are not given any formal introduction to schools of thought on how innovation takes shape at an aggregate level. Consequently, they get to know the process of innovation from an ant's perspective[6], while the bird's-eye view stays out of reach. This produces engineers who can work very well on demarcated product development tasks but who are not familiar with the bigger picture of how these products come about. Assuming that a better understanding of the way new types of products come about or emerge leads to better product development, it seems relevant to contribute to this better understanding and incorporate it into education.

Studies like that of Eger (2007a) show products to start out at a crude level with, as yet, unrefined functionality and a relatively high price. If a product is successful on the market, it will develop into numerous versions created by many different designers and manufacturers. All these cycles of design-manufacturing-sales-use provide a variation, selection and retention process that shapes new versions of the product, similarly to how biological evolution has shaped life. Consequently, the products designers work on, are temporary embodiments in product families that evolve over time. This is a rather different perspective on products and their development than commonly taken by designers and design students. Thus far I have experienced this introduction to new schools of thought as an enrichment of my perspective on innovation in general. In particular it has provided me with a new way of looking at how new types of products emerge from pre-existing technology and then further develop over the course of time. Subsequently these products become a source of new technology development providing roots for other new types of products. What is more, they may have had unforeseen consequences that fuel the development of new products or technologies[7].

6 Although a worm's perspective is also used as opposite of a bird's perspective, being an engineer myself I prefer to use the ant's perspective here. Ants being social insects construct complex structures however without consciously doing so and having no consciousness. As will be argued in this thesis, individual inventors or engineers might perceive their inventive work as targeted, observed over many decades they are mere ants.

7 For example, the rise of car ownership has a causal relation to emergence of car-safety-problems inciting the development of car safety technologies such as safety belts used by adults. Subsequently, the till then latent needs for child passenger safety evolved and manifested into child safety seats (see also Section 7.1).

I hope I have provided two distinct additions to the field of industrial design engineering. First, the product evolution diagram that can be used to depict how products evolve over time. This diagram has been used and tested as analytical framework in education (see also Chapter 8). Second, this research has necessitated the shaping and sharpening of some definitions used to discuss the topic of research (i.e. products). The need for this vocabulary update became clear to me in the last part of this project when, among other things, I realized that I lacked clear, concise and unambiguous definitions. I am humbled to notice, at the end of this project, that it is remarkable how a long quest can lead to such a simple result.

0.4 I would like to thank the following people for their support

Wyp my dear, thank you for your endless support, in a turbulent phase of our lives. I had just come into contact with Arthur Eger when we decided to marry. While I had barely started this research project, we experienced a breakthrough in our other more significant project, the result of which we named Yfke. Yfke has also shown that she 'won the race' and finished her first steps in life, including being able to write, well before I finished this PhD. I would like to promise both of you that Sundays will now be for us to share, given that I have now completed this academic challenge and have a burning desire to focus on our 'quality time' together.

I would like to thank my parents for providing me with the start in life that made this possible and for the encouragement and support as I took up the educational path that has prepared me for this challenge.

I would like to thank Arthur Eger for encouraging me to take up this research project and for supporting me on the way towards its completion. I would especially like to thank him for the opportunity to co-author the book *On the Origin of Products,* which has been a very stimulating experience and accelerated the last stage of the project towards writing this thesis. Receiving the pass-through book (Mechanization Takes Command) during your valedictory speech was also a huge honour and one, I have to admit, that left me 'speechless'.

Erik Tempelman first engaged me in stimulating discussions on evolution and innovation during our time at TNO. Eventually Erik put me in touch with Arthur Eger and latterly supported me during my PhD project with many reviews reflections and other contributions that further stimulated my thoughts. Erik, thanks for being this catalyst!

Howard Turner, my former neighbour provided me with enduring language support and moral distraction. Despite your turbulent life, you have supported me in this PhD from start to finish. Howard, thanks for this!

Sera Kooijman, thank you for providing proofreading support at the end of this journey. This has been a great help in making this thesis more readable.

Janna Bathoorn en Jan Alwin de Jong (Studio Stedum), thank you for your contribution in the final phase of this project helping to make this thesis is ready to be printed and providing it with this beautiful appearance!

Looking back, the first act was a presentation at Innovaders, a company that aimed to contribute to a sustainable world through projects, products and services. I would like to thank Pepik Henneman, Jeroen Weijs, Gernout Erens and Arno Wayenburg (the Innovaders founders) for providing me that first opportunity to present my ideas.

Last but not least I have enjoyed the privilege of not having to disrupt my career during this PhD research project. Soon after commencing the project, I was hired by Philips in a construction that allowed me to study on Fridays (and Sundays). I am grateful to two line managers, Ian Rendle and Robrecht Maes, who allowed me to develop within a management position in the Procurement department of Philips Innovation Services on those days I was not working on my research project. This too turned out to be a journey with an unforeseeable course, but successful results. May many more journeys follow!

Introduction

1

1.0 Introduction

Since the dawn of mankind, we have been making tools. The stone hand axe has become known as the archetypal first tool. Initially the rate of development was very slow and, for hundreds of thousands of years, the hand axe did not change much at all. It was then that people started to write, live in cities and various labour specialisations came into being. The ever-increasing speed of development of new and more and more advanced types of tools has since characterized our technological history. Obviously the more complex and advanced tools could only be 'invented' by building on the knowledge developed by earlier inventors. This knowledge and skills accumulation process led to highly complex tools such as the Saturn V rocket that brought men to the moon and, more recently, the smartphone. The evolution of technology (Basalla, 1988) has been used as a metaphor to describe how particular inventions build on each other.

The products surrounding us have become more abundant and advanced over time. Technological transitions, like the introduction of electricity at the end of the 19^{th} century, caused a rapid increase in complexity and diversity of products. To date, a similar transition now driven by data is again responsible for a rapid increase in the complexity and diversity of products. There appears to be no significant explanation as to how these products emerge and relate to each other. The current levels of diversity and complexity seem to be taken for granted. Commonly, there has been a focus on increasing our economic prosperity by means of an elixer called innovation. For the last few decades a lot of attention has been paid to explaining this process of innovation. Many schools of thought have contributed to the body of literature on innovation and these have generally emphasised the discontinuous and disruptive character of innovation. Whole industries come and go, taking with them employment and economic prosperity. The evolutionary metaphor has also been used to explain the process of innovation to underline its gradual and continuous character. These evolutionary explanations for innovation focussed mainly on economics and technology, instead of products, which are one of our main units of consumption.

Until the industrial revolution, product design and manufacture was literally 'in the hands' of craftsmen. Knowledge on how to make products, and what products to make was part and parcel of craftsmanship that was maintained in craftsmen-communities, organised into guilds. The industrial revolution caused production to become 'industrialised' and, with that, its design and development process. By and large the idea is that, since then, each of these products has been 'intentionally designed' by (teams of) inventors and or

engineers. However, the design and development of all these products is, to a large extent, not a process in which all inventors, engineers and the like coordinated their efforts over industries and time to achieve a common goal of ever more refined and affordable versions of their products. Instead, they commonly competed against each other, sometimes aligning efforts into cartels to exclude others, all with the aim of maximising market share and/or profits. Nevertheless, we can identify families of products that came about and advanced through phases (Eger, 2007a).
Above all it has become clear that these inventors and engineers are only some of the many actors that influence how products change over time, selecting some to become the basis of subsequent next versions, and others to be discontinued. Other authors have already described how technology evolves (Basalla, 1988; Anderson & Tushman, 1990; Murmann & Frenken, 2006). It has become evident that, during this process, social groups play a large role, to the extent that it has been argued (by sociologists) that rather than technology determining human action, human action actually shapes technology. This perspective has become referred to as the Social Construction of Technology (Pinch and Bijker, 1984). It has also been argued that technology transitions drive innovations as an evolutionary reconfiguration process that takes places at different levels (Geels, 2002) incubating new products in niches and eventually causing societal change. Unfortunately, it appears that these views on innovation continue to be held by different schools of thought and are not commonly presented as a cohesive view to those who engage in the development of new products. Besides, it should be noted that most literature referred to above targets technology in general, rather than products specifically. It appears that there is not yet a *'Theory of Product Evolution'* that explains how products emerge. Finally, using the maxim that products *"are both the means and the ends of technol*ogy*"* (Basalla, 1988; p.30), this thesis takes a product centric perspective.

1.1 Technological Innovation as an Evolutionary Process

At the University Twente a series of lectures entitled 'Evolutionary Product Development' was given from 2005 to 2015 to students who were asked to map the development history of a certain product using the 'theory of product phases' (Eger, 2007a; 2007b). Subsequently the students were asked to design an evolutionary next version of the product. The analytical part of these assignments was executed by mapping ten characteristics of a particular product that are representative for six product phases. The exercise was not given any theoretical embedding in existing literature or theories on innovation mechanisms.

This PhD research project took off in 2010 with a rather broad ambition, namely to investigate how one can describe *Technological Innovation as an Evolutionary Process*. While investigating case studies and contributing to lectures on Evolutionary Product Development, it became apparent that students lacked a practical framework for analysing the causes and mechanisms that explain the historical development of products. En route it became evident that scientific contributions, particularly from disciplines like the so-called Science and Technology Studies (STS) or Science Policy and Innovation Studies (SPIS), could help provide explanations for the way products evolved over time.

Gradually, the goal of this research project developed towards providing students of industrial design engineering with a theoretical background and a practical analytical framework that would allow them to analyse systematically how products evolve and, during the process, identify mechanisms that are associated with changes in the product design that are relevant to product designers. This should provide both designers and others involved in the development of new products with more academic background and ultimately lead to a better understanding of the way new products come about or emerge from pre-existing technology and whose development is co-shaped by the context in which they are used.

Towards the end of this PhD research project, the ideas and insights developed converged in the book *On the Origin of Products* (Eger and Ehlhardt, 2017). The first sentence of this book summarizes how the research question has evolved. It reads as follows: *"This book addresses the question how new (types of) products come about and develop through time into a family of more advanced versions"*.

1.1.1 Information Sources

The book 'Evolutionaire productontwikkeling' (Eger, 2007a), which is used as reference for the Evolutionary Product Development lecture, can be considered the formal point of departure of this study. Besides this, a wide body of literature on innovation as well as evolution was consulted. Most of these were journal papers supplemented by a series of books.

Given the ambition to investigate some cases of evolving consumer products, and the experience gained from a Master's project for which consumer guides had been used, this research project started investigating how *Consumentengids*, the Dutch consumer guide, could be used as source and historical archive of consumer products to be investigated in case studies. Whereas, in the past, the *Consumentenbond* (the Dutch consumer organisation that publishes Consumentengids) used to have a freely accessible library, this was no longer the case at the start of this project. However, it transpired that second-hand volumes of Consumentengids were readily available up until the 1970s. These volumes were therefore acquired. The gap up to the first issues that appeared in 1959 was filled using copies from the national library. See also Chapter 9 for background information on using consumer guides as a primary source for investigating the historical development of consumer products.

During the research on case studies it became apparent that a wide range of information sources were needed in addition to consumer guides, in the form of books and scientific papers, to explore the historical development of products. Patents have been widely used to identify inventors, dates of filing of inventions as well as figures which describe them. In addition, a wide range of reports by different authorities and Internet resources, including Wikipedia, proved necessary to provide information required to conduct this research.

1.1.2 Selection of Case Studies

At the start of this PhD project in the spring of 2010, a complete collection of all the volumes of Consumentengids was established as a research archive. Subsequently, an index of all product tests published since 1959 was built in order to select those products which were most suitable for further investigation in case studies. The following criteria were used to identify suitability; 1) the timespan covered by tests published needed to cover at least two decades, 2) at least 10 tests had to have been published. Based on these criteria, Child Restraint Systems (CRSs) and Compact Fluorescent Lamps (CFLs) were selected for further research in case studies. See also Chapter 9 for a further discussion on the use of Consumentengids, the relevance of the products investigated, geographical coverage, etcetera.

1.2 Product Phases

It is commonly agreed that radical, new innovations imply both a promise of potentially high returns and a substantial risk of failure and loss of money. In reality, most innovations or new products come about on the basis of incremental steps, a strategy that greatly reduces risk.
Professor Dr ir. Arthur O. Eger, who used to run a design company named 'van Dijk/Eger/Associates', noticed that product properties depend on the 'maturity' of the product. Very new/young products typically do not yet perform very well as regards their basic function. Over time the performance of functions improves, production is improved and this leads to lower prices. These observations were successfully used to guide projects executed by van Dijk/Eger/Associates. A first publication (Eger, 1987) on

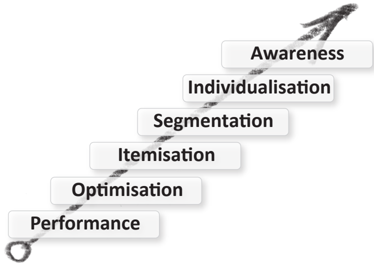


Figure 1.1. The six product phases, first version as used from 1993 (Eger, 2007b).

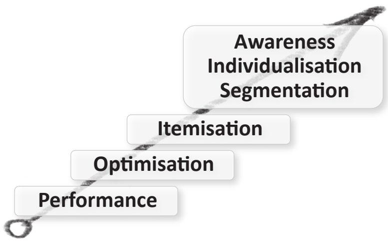


Figure 1.2. The six product phases, last three occur simultaneously (Eger and Drukker, 2012).

this observation was eventually followed by a thesis named 'Evolutionaire productontwikkeling' which translates as 'Evolutionary Product Development' (EPD) in 2007.

EPD is a low-risk, new product development (NPD) strategy that defines step-by-step product development or innovation strategies based on the product phases theory. The current 'phase' is defined by positioning the product according to a number of product characteristics. Each phase is defined by ten characteristics, of which five are product-related (newness, functionality, ergonomics, product development, styling), while the others concern its market, production technology, promotion, service and ethics. The six product phases are performance, optimisation, itemisation, segmentation, individualization and awareness. Initially, the phases postulated were assumed to appear sequentially (Figure 1.1). A recent study (Eger and Drukker, 2012) defined three sequential phases plus another three that appear to co-exist as a fourth phase as shown in Figure 1.2.

The product phases are described as follows.

- Performance: The product is new to the market, the performance is initially poor and there is hardly any competition from the small number of suppliers. Development is intended to improve performance, while the price is relatively high and production and assembly often manual.
- Optimisation: Development is carried out in order to improve performance, reliability, ergonomics and safety. The price may still be relatively high, although the number of suppliers starts growing slowly.
- Itemisation: Product's functionality and reliability are good. The product is usually safe and ergonomically acceptable. Development efforts are intended to add extra features and accessories. Prices start falling and the level of competition grows.
- Segmentation: Almost the complete target group has heard of the product and the product range offered is wide. Development efforts are aimed at reaching specific target groups through different trade channels and

special editions. Styling becomes more expressive and addresses emotional benefits. There are a lot of competitors and market penetration is high.

- Individualisation. Product development is aimed at mass customisation or co-creation. Prices have dropped, but may increase due to customisation. Production and assembly have become highly automated.
- Awareness. Product development is aimed at minimizing the impact on environment or society. The styling might become sober to emphasise the low impact characteristic and, for some products, new ways to offer the functionality are introduced that change ownership models, such as product sharing and product service systems.

1.3 Research Objective and Research Questions

The previous sections described the starting points that have led to this study. Firstly, this study was motivated by a deep-rooted curiosity for innovation in general and, more specifically, the process that leads to emergence of new products and their subsequent development over time.

Secondly, this study was conducted as part of the research programme entitled *'Product & Service Design'* under the theme of *'Understanding Product Success, Inspiring Product Design'*. Prof. Dr ir. A.O. Eger gave a course entitled Evolutionary Product Development, which was based on extensive practical experience in the field of industrial design engineering and a PhD study into patterns in developing products that produced the 'product phases theory'. The product phases theory and the associated course in Evolutionary Product Development were not yet connected to the scholarly world of Science Policy and Innovation Studies (SPIS). In general, the world of SPIS is, as yet, not that well connected with the world of those involved in engineering and new product development. Although SPIS provides conceptual frameworks used to analyse innovation, they are not yet part of the education of those who later become involved in the development of new products or design and engineering. This research project aims to develop a better understanding of the way in which new (types of) products come about and develop over time into families of more advanced versions and as such directly contributes to above mentioned research program theme.

Thirdly, as happened to many a man, a Master's project finished years ago provided observations and aroused a curiosity that has now been satisfied by this research project. To quote a scholar who investigated how future actions can be explained by earlier events *"one damn thing follows another"* (David, 1985; p.332).

The research objective of this study is to contribute to the understanding of *how new (types of) products come about and develop through time into a family of more advanced versions*. To that end it aims to provide an analytical framework that can be used to study how particular products develop over time. The analytical framework was built on insights from various schools of thought and complements the product phases theory by providing an instrument for mapping the development history of products. The product phases theory is used to provide guidance to product developers with a low risk strategy for new product development.

Building on the research objectives, the following research questions are posed:

1. How do new (types of) products come about or emerge? To what extent does the genius of the inventor play a decisive role in these events?
2. Can technological innovation be described as an evolutionary process?
   - To what extent can the biological evolution metaphor be used when describing innovation in products?
   - How can we describe a (evolutionary) relationship between the first product and the most recent products? How can we operationalize such relationship?
   - To what extent does context[1] influence how new types of products come about?
   - Does memetics provide useful clues on how to analyse evolution in products?
   - Can the evolutionary metaphor be used to develop a better understanding amongst product developers of the way products typically evolve?
3. Can we provide tools to help a) those who study the history of technology, or b) those who develop new products?

These research questions have been reformulated in the following propositions;

P1: Technological innovation can be described as an evolutionary process.

1 Speciation, the evolutionary process by which new species come about, distinguishes four modes based on different contexts or geographic conditions that influence the extent to which populations are isolated from each other. The four modes of speciation are allopatric, peripatric, parapatric and sympatric. In allopatric speciation a barrier splits populations into two geographically isolated populations. In peripatric speciation a small population enters an ecological niche and becomes isolated from the main population. In parapatric speciation there is only partial isolation where a population adjacent zones. In sympatric speciation the population remains in the same geographic location, and speciation is driven by other conditions (like preference for specific food sources).

P2: The emergence of new types of products, and their subsequent development into families of advanced types, can be described as an evolutionary process.
P3: Evolution in products can be visualised as a Product Family Tree.
P4: The influences of a context on the evolution of a product can be mapped as an ecosystem.
P5: To understand how products evolve, one needs to analyse the interaction between a product family and an ecosystem over time.

1.4 Reliability and Validity

The reliability of research relates to the consistency of data collected. The validity of data relates to the reliability and relevance of data used in research. For the research project laid down in this thesis this section will reflect on the reliability and validity of three topics: 1) the theoretical framework used, 2) the Product Evolution Diagram and 3) the case studies.

The theoretical framework used for this study is based on leading publications from diverse schools of thought and is described in Chapter 3. At time of writing there is not a single scientific theory that explains how new types of products emerge. This thesis brings together deliberately different perspectives and conceptual models that more or less use evolutionary metaphors to describe patterns and mechanisms of innovation. The patterns and mechanisms described in Section 3.1 are derived from the field of economics (creative destruction, path dependence and lock-in) and in Section 3.2 sociology (diffusion of innovation and social construct of technology) and are some of the leading ideas on innovation. The patterns and mechanisms described in Section 3.3 are identified by Martin (2012) as belonging to the key publications over a period of 50 years leading to the development of the field of science policy and innovation studies (SPIS). This publication by Martin forms the most significant substantiation that the patterns and mechanisms described in Section 3.3 should indeed be regarded as some of the most significant in their field. The fact remains that there are more patterns and mechanisms that can be used to describe innovation then have been included in this thesis. As such, the literature described in Chapter 3 forms the lens through which the researcher established his analytical framework and investigated his cases.
The theory of evolution has provided a paradigm shift with regard to the way we think about the origin of species and remains uncontested in validity. Nevertheless, the concepts described in Section 3.4, referred to as universal Darwinism, are more general in nature than those described in Sections 3.1 to 3.3 and, as a result, did not lead to a final conclusion regarding their validity. Consequently, the author of this thesis cannot claim

universal validity of the evolutionary metaphor as regards the origin of new types of products. However, given that the author did not find any better explanations nor any evidence that refutes their validity, this thesis uses the evolutionary metaphor to explore the origins of new types of products. The researcher notes that the theory of product phases (Sections 1.2 and 3.5.1) forms a point of departure for the research project described in this thesis and, at time of writing, does not (yet) form part of the standard theoretical background commonly used by industrial design engineers or related professional groups.

The Product Evolution Diagram is suggested as a framework to analyse how products developed over time. The Product Evolution Diagram uses two elements, namely the Product Family Tree and the Ecosystem. The Product Family Tree as used in this thesis does not claim to map the only and correct lineage relations between products. The reservation that is made in this thesis describes that, contrary to the phylogenetic trees used in biology, it is not possible to unambiguously map lineage relationships for the world of made given the fact it lacks a clear unit of heredity that can be measured similar to the gene. Therefore, the Product Family Tree should be regarded as a mere visual aid to map relations between products as they appear from the research. In a similar fashion the Ecosystem is mapped using the PEST method which is commonly used by others in strategy studies (Chapman, 2006) and has been used successfully by the author (see also Section 6.2). Although it is not claimed here that general validity can be claimed for the Product Evolution Diagram as a visual tool for mapping how new (types of) products come about, it has successfully been used in education. As shown in Chapter 8 and Appendix A, students of Industrial Design Engineering at the University of Twente have successfully used the Product Evolution Diagram to map the development history of a wide range of products. Based on their work, that can be regarded as a form of 'member checking' (Creswell & Miller, 2000), it can be concluded that the Product Evolution Diagram provides a useful tool. In addition, the Product Evolution Diagram as a framework for investigating the historical development of products has been presented in the academic arena at a conference (Ehlhardt, 2013) and in a peer-reviewed journal (Ehlhardt, 2012). On both occasions, here used as an 'audit trail' (Creswell & Miller, 2000) no arguments were presented that refuted the applicability of the Product Evolution Diagram for the intended purpose.

This thesis describes two case studies, which are examples of reflective research. The first case concerns the development of Child Restraint Systems (CRSs) and was also published in a peer-reviewed journal (Ehlhardt, 2012). This case study made extensive use of Consumentengids, a publication of the Dutch consumer organization Consumentenbond, as a source of information on the performance of CRSs and time of availability on the market. Subsequently the case was again investigated by a student (Reigersman, 2014a), which provided additional information, in particular on the early development of CRSs in the USA based on, among others, historic Sears catalogues. The case study on CRSs included in this thesis is a revised version that included information provided by Reigersman, as well as quantified information on the development of car ownership in both USA and Europe between 1900 and 2010.

The second case study included in this thesis concerns the development of General Lighting Solutions (GLS) and the Compact Fluorescent Lamp (CFL). This case also used Consumentengids as source of information. Particular for this case it appeared possible to map the development of price and performance of CFL over time. Performance data found in Consumentengids was crosschecked with data found in other independent sources (publications by the US Department of Energy (DOE, 2011b) and the International Energy Agency (Waide & Tanishima, 2006), (Waide, 2010) and various other papers) and found consistent on performance metrics and as such is used as a form of 'triangulation' (Creswell & Miller, 2000). However, price information prices could not be crosschecked as the level of detail found in product prices published in Consumentengids has not been found in other publications.
As concluded in Chapter 9 on the use of consumer magazines for this research project it is not possible to reconstruct the development of products over time based solely on information found in consumer guides. Chapter 9 contains an extensive overview of advantages and limitations of the use of Consumentengids (as the only consumer guide reviewed in detail) for this type of research.

1.5 Structure

This thesis commences with a preface that, among other things, introduces the reader to the chain of events and ideas that eventually lead to this research project. Chapter 1 describes the actual start of this project, the information sources used, the relationship to the product phases theory, as well as the research objectives and questions.
Chapter 2 describes definitions used in this thesis that need to be included to be unambiguous in the thesis. It appears that a small but dedicated vocabulary is needed to explain how products evolve.
Chapter 3 provides a concise overview of literature. Individually, the schools of thought referred to do not provide integrative perspectives on the evolution of products. Therefore, the intention here is not to be complete or

to provide summaries, but rather to show how different schools of thought, which I assume to be most relevant here, provide connected perspectives on this topic.
This is followed by Chapter 4 which describes how this thesis explains how technological innovation can be perceived as an evolutionary process.
Chapter 5 explains how tree diagrams were used in biology to depict hereditary relations and explores how similar diagrams are being used to depict lineage in human culture.
Chapter 6 elaborates on the product evolution diagram. This diagram provides an analytical framework that can be used to depict how a particular family of products evolved over time, and what external influences shaped it.
Chapter 7 elaborates two case studies of consumer products, namely the child restraint system (CRS) and the compact fluorescent lamp (CFL).
Chapter 8 includes some results from education. Over the course of four years, many students have shown that they are capable of using the PED as an analytical tool in EPD. This chapter contains some interesting examples of work by students are included and reflected upon.
Chapter 9 elaborates on the source that provided the cases studied in this research project, namely the Dutch consumer guide or ‘Consumentengids’. It also includes an overview of the advantages, limitations and background of the guide used, and its positioning amongst other consumer guides.
Finally, Chapter 10 provides conclusions and recommendations for finalising this research project.

Definitions

2

2.0 Introduction

Words can have many different meanings. The terms ‘product development’, ‘innovation’, ‘design’, ‘styling’, ‘industrial design engineering’ and ‘functionality’ are used across various disciplines, and in everyday language. Often they are used with a different meaning. Some only use ‘product development’ in relation to the development of a new or improved product. For others it has a much wider meaning and includes the search that precedes the design of the new product, the development of production methods and the preparation for the product launch.

The term ‘design’ is used in an even wider context. Whereas some fashion boutiques may sell ‘designer dresses’, the dresses sold in a department store have also have been ‘designed’. An engineer who defines the wiring for an airplane, or a programmer who writes code will also refer to their work as a ‘design’. In order to be unambiguous and avoid misunderstandings about the meaning of these terms, the definitions used in this thesis are defined at the very beginning. Most of the time ‘product’ refers to a physical object that performs a function. However, in this thesis a ‘product’ can also be software, a service or combinations of these elements, meaning that products are not only bicycles or shavers, but also word-processing software, electric toothbrushes with apps on smartphones, holidays or bank services. The definitions below are also presented in the book *On the Origin of Products* (Eger and Ehlhardt, 2017*)* as a) a set of terms that are commonly used and for which the specific meaning is defined and b) a set of newly defined terms. The section below entitled ‘thesis specific’ contains definitions that are either new, or can be regarded as specific for the topic presented here. This is followed by a ‘literature’ section, which presents definitions used in various knowledge domains such as Innovation Studies or Engineering. Finally a ‘general’ section lists a set of more generic definitions used in common language, that nevertheless require definition to make this publication unambiguous to the reader. It is assumed here that these definitions provide a nomenclature that contributes to the general understanding of the way in which new (types of) products come about.

2.1 Thesis specific

Artefact: An artefact (from Latin phrase arte factum, from *ars* = skill + *facere* = to make) is something made by a human being, typically of cultural or scientific interest, such as a tool or a work of art.

Product: A construct designed to realise a specific basic function. Products can be tangible (e.g. a lamp, car, or chair) as well as intangible (e.g. word processor, package holiday). Some products can function independently (e.g. a chair), while other products are typically nested within other products (e.g. a navigation system in a car). Some products (e.g. a telephone) are elements of larger technological systems (telephone networks). In this thesis we refer to products that are 'produced' in series, or mass produced and offered for sale.

Products are a specific type of artefacts intended to realize a specific basic function, resulting from accumulated know-how (to make) and know-what (function to realize), and are generally produced in series, or mass, and offered for sale. This thesis excludes from the scope of products those artefacts that are not intended to realise a specific basic function and/or are considered works of art, such as a painting or a piece of music. The reason for this exclusion lies in the importance that is attributed here to 'function' and 'production', which leads to a clear distinction in technology cycles (see also section 3.3) between 'application-based products intended to be used for a basic function and need to be efficiently produced' and those regarded as 'art'. Without dismissing art, this thesis inclines towards engineering because of the utilitarian character of the products it produces.

New type of product: A construct that provides a new basic function, or an existing basic function in a fundamentally different way that commands a decisive performance, cost, or quality advantage over previous products.

New types of products commonly originate from technological discontinuities and become well established and recognisable once a dominant design has been achieved. Typically, new types of products initially fulfil their basic function poorly against relative high costs. Over time products mature through the product phases, improving in basic function performance, against lower cost, and differentiating into embodiments that serve different segments of the market.

One example is the incandescent lamp which was a new type of product that originated at the end of the 19th century and provided a basic function (providing light) in such a way that it had clear performance-, cost- and quality advantages over previous products which fulfilled the same basic function (e.g. a candle, paraffin lamp, gas lamp, or arc lamp).

Product Class: A group or range of products that, from a functional perspective, may serve as a substitute for another, depending on how wide or narrow the definition used for product class is. A product class is a functional classification designating products with the same basic function. Products within a class compete with each other in the market place but need not belong to the same product family, i.e. they do not share a common root or ancestral product and use the same or similar architecture and technology.

For example, the General Lighting Service (GLS) product class originated as a designation for an incandescent lamp standard also known as the standard ‘incandescent light bulb’. Currently GLS bulbs might use incandescence, gas discharge or LED technology. They all belong to the same product class providing the same basic function. However, they belong to different product families as they descend from different ancestral products and are based on different technologies. A narrow product class for ‘lighting’ would include incandescent lamps, halogen incandescent lamps, tube lamps and LED bulbs, while a broad product class would include candles and paraffin lamps. An adjective can be used to narrow a product class down (e.g. electric lighting or GLS lamps).

Product Family: A series of (the same) type of products that is designed to realise the same basic function, and use the same technical principles to achieve their function. These products share a common root or ancestral product and commonly use the same or similar architecture. The branches in a family are separated by differences in user segments to which their designs and architectures are optimised. A young product family typically consists of product variants in the performance or optimisation phase. Once a product family matures to the segmentation phase, it consists of variants that have evolved to serve specific segments of the market and commonly apply architectures that are optimized for the type of use or users that define the segment.

For example, an incandescent lamp bulb type-A and a halogen incandescent lamp of the PAR type (including a parabolic reflector) belong to the same product family because they are derived from the same historical product. However, the GLS incandescent and GLS LED bulb are not in the same product family as they apply different technical principles to generate light, despite having the same or similar appearance. The GLS incandescent and GLS LED bulb do belong to the same product class because they provide the same basic function and are often used as substitutes. Having the same producer, being made from the same material, or providing the same function does not define a product family either.

Product Evolution Diagram (PED): An analytical framework that graphically relates evolving products to a context of factors influencing that particular evolution. Using a timeline, it combines a Product Family Tree with an ecosystem. The graphical narrative provided by the PED visualizes the complex relationship between technological developments and their context.

Product Family Tree (PFT): A mapping technique to visualise the evolution of a product family through time by relating inventions, dominant designs (standards) and discontinued products. A PFT emerges from a single node, a first-of-a-kind product, and then branches out into different designs that exist in parallel and cater to different segments or types of use. Some branches are discontinued as certain technologies, designs or product architectures become out-dated.

Ecosystem: 1 (biology). A community of living organisms in conjunction with the non-living components of their environment (things like air, water and mineral soil), interacting as a system. 2 (thesis specific). Context in which a product is used and its evolution is influenced by contextual factors. Used to map influences on the development of a Product Family in a Product Evolution Diagram.

Context: 1 (general). The situation in which something exists or happens, and that can help explain it. 2 (thesis specific). The whole of factors or circumstances that influence how a product evolves. This thesis refers to Political, Economic, Social and Technological factors (abbreviated as PEST) as an example of typical factors that influence product evolution.

Knowledge: Umbrella term for facts, information and skills acquired by a person through experience or education. It covers more specific designations such as 'know-how', 'know-what', 'know-why' etc. Knowledge can be transferred via imitation, verbal exchange or by writing and reading. More recent knowledge transfer means include audio and video.

Know-how: 1 (general). A term for practical knowledge on how to accomplish something, as opposed to 'know-what' (facts), 'know-why' (science), or 'know-who' (communication). Know-how is often tacit knowledge, which means that it is difficult to transfer to another person by writing it down or verbalising it. 2 (thesis specific). Knowledge on how to manufacture a product. Know-how may be protected as 'intellectual property' by patents. Often know-how is not formally disclosed and kept as a trade secret.

Know-what: 1 (general). A term referring to facts, or factual knowledge. 2 (thesis specific). Knowledge on what to manufacture. Commonly referred to as the 'spec', which is short for 'product-specification' and describes a product in terms of functionality, features, dimensions, material and all other properties that distinguish a specific product.

2.2 Literature

Path dependency: A concept used to explain how a certain state (e.g. the design of a product, or a standard) is explained by the preceding course of events. Path dependence is most likely to arise in 'network' industries, where the benefits of adopting a particular design, standard or technology depend on choices made by others. At a certain point a *lock-in* is achieved, making the choice for the particular design, standard or technology quasi irreversible. Path dependence and lock-in are commonly associated.

Lock-in: A situation where a particular design, standard or technology becomes dominant, despite other potentially more economic alternatives being around. Lock-in may occur either because of sunk cost, or because of external economies and a lack of coordination mechanisms that prevent individuals from switching to another (potentially superior) design, standard or technology. Path dependence and lock-in are commonly associated.

Dominant design: 1. A design that is widely adopted and which changed the nature of competition in the corresponding industry (Murmann & Frenken, 2006). 2. A single configuration or narrow range of configurations that accounted for over 50% of new product sales or new process installations and maintained a 50% market share for at least 4 years (Anderson and Tushman, 1990, p. 620).

Dominant designs are associated with change in industry dynamics. However, scholars differ on whether a dominant design is the cause or the consequence of these changing competitive dynamics. Dominant designs remain in their position until a disruption causes new designs to evolve, which then compete with the incumbent until a new dominant design is established.

The term dominant design is used on different levels of analysis. Most commonly it is used to define a configuration on product (or system) level. The term dominant design is also used for subsystems e.g. like landing gear in airplanes (Tushman & Murmann, 1998). Products (or systems) can then be described as complex artefacts composed of a nested hierarchy of different levels of subsystems and ultimately components in each of which dominant designs occur.

In this thesis the term dominant design is used for both products, systems and subsystems. We also distinguish between dominant designs in a product family (e.g. CFL lamps) and in a product class (e.g. GLS lamps).

Function: The natural or characteristic action performed by a product (SAVE, 2015).

Basic function: The primary purpose, or most important action performed by a product. The basic function must always exist, although methods to achieve it may vary (SAVE, 2015).

Function Analysis System Technique (*FAST):* A method developed to systematically analyse the functionality of products (Bytheway, 1965). Functions are described using a verb and a noun. FAST distinguishes between basic and secondary functions and their subsets. The FAST method uses a diagram to map functions from the WHY on the left (highest order function or output) to the HOW on the right (lowest order function or input). FAST is a tool used in Value Engineering, a systematic method to improve the 'value' of goods or products and services by using an examination of function (SAVE, 2015).

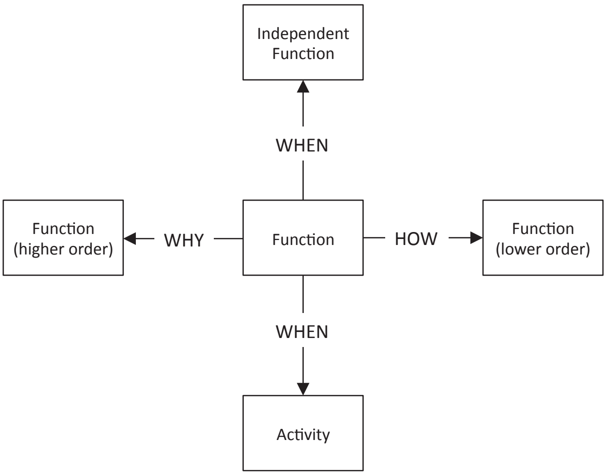


Figure 2.1 The schematic logic in a FAST diagram used to perform function analysis (Bytheway, 1965).

Functionality: In this study the word functionality relates to the technical performance of a product. Does the product function – in a technological way – as the user expects? According to this definition the functionality can be good while, for instance, the comfort, safety and user friendliness of the product are unsatisfactory. Consequently, this functionality is sometimes referred to as technological functionality. Wherever this study refers to another kind of performance, this will be stated, for example in the case of ergonomic or economic functionality.

Product phase: A phase in the marketing product life cycle (M-PLC) of a product that has distinguishing features defined by product characteristics (Levitt, 1965).

Product (phase) characteristic: A feature of a product phase that is characteristic for this phase. Product characteristics may concern the functionality, emotional benefits, price, market, product development, production, ethics, etcetera.

2.3 General

Design (verb): The process of purposely developing ideas into e.g. a construction, engineering drawings etc.

Design (noun): The arrangement or scheme to which a product is made, intended to accomplish a goal by satisfying a set of requirements.

Design (adjective): The appearance of the whole or part of a product, including any pattern or texture applied to its surface.

Evolution: 1 (biology). The process by which life forms change over time. 2 (general). The process of gradual change and development.

Evolution (from the Latin verb *evolvere* = unrolling) was first used in the early 17th century in general writing, medicine and mathematics meaning "to unroll, unfold, open out" especially of books. Charles Lyell first used the word in 1832 in relation to species and biology. Charles Darwin only used the word once in a closing paragraph of "The Origin of Species" (1859) preferring the term "descent with modification". Others later popularized the current meaning in biological context.

Industrial design engineering: The design and engineering of functional objects that can be produced in series or that can be mass-produced.

Innovation: 1. The act of innovating. The introduction of a new idea into the marketplace in the form of a new product or service, or an improvement in organization or (production) process. 2. A change effected by innovating.

Niche: 1 (biology / ecology). The specific area where an organism inhabits in an ecosystem (affecting its survival as a species). 2 (general) A special segment of the market.

Product development: The activity of dealing with the design, creation, production and marketing of new products, also referred to as new product development (NPD).

Styling: A distinctive manner or way of form giving, e.g. a unique decoration or an expressive shape.

Overview of Literature:
Patterns and Mechanisms of Innovation

3

3.0 Introduction

Many authors have discussed patterns and mechanisms of innovation and provided analytical tools to investigate them (Schumpeter, 1942; Rogers, 1962; Abernathy & Utterback, 1975; Dosi, 1982; David, 1985; Abernathy & Clark, 1985; Anderson & Tushman, 1990; Von Hippel, 2005). Evolutionary metaphors have been used by several authors in this context (Nelson & Winter, 1982; Basalla, 1985; Mokyr, 1996; Geels, 2002; Murmann & Frenken, 2006; Dosi & Nelson, 2013). This thesis extends on this work, originating from a wide range of disciplines such as economics, sociology, science policy, innovation studies, evolutionary models and industrial design engineering, with the aim being to expand the descriptive and predictive power of the evolutionary paradigm as applied to technological innovation in general and the emergence of new (types of) products in particular. Since the evolutionary metaphor is central to the formulation of the research questions formulated in Chapter 1, the next section summarizes, in particular, those major perspectives and conceptual models used to describe patterns and mechanisms of innovation that fit the chosen perspective.

3.1 Economics

3.1.1 Creative Destruction

Being key to economic advancement, innovation is the subject of the study of economics. The observation by Schumpeter (1942) that innovation is associated with creative destruction is a well-known comment. When new products, processes or technologies are introduced that outperform earlier versions, the incumbent is ousted. The creative force of innovation destroys that what it improves upon.

Neo-classical economic theory assumes that actors' behaviour is based on supply-and-demand relations and set prices for goods. It assumes stable prices once supply-and-demand are in equilibrium. However, it became clear that the economic process is a dynamic process and that innovations disturb equilibriums.

Nelson and Winter (1982) developed an evolutionary theory on economic change, which they based on continuous change to overcome limitations in conventional neoclassical economics that do not really explain the economic process of change or renewal.

Instead, evolutionary economics describes the process of change along trajectories, based on the argument that economies grow because they are fuelled by technical advancement. Nelson and Winter refer to all regular and predictable behavioural patterns within firms as ‘routines’. Put simply, the term ‘routines’ encompasses all ‘know-how’ and ‘know-what’ those firms apply in their processes and these can range from hiring personnel to research and development. Firms compete on the basis of the fitness of their routines that evolve over time, based on the premise of continuous change.

The economic historian Mokyr (1996; 1998; 1999; 2000a; b) proposed an evolutionary theory of technological change, according to which it is more useful to analyse the change in techniques rather than the change in the artefacts based on those techniques. The argument is that a lot of techniques do not involve artefacts and that a lot of artefacts only acquire meaning once ‘how-to’ instructions are included.

3.1.2 Path Dependence and Lock-in

Path dependence is a concept used to explain how a certain state, for example the design of a product, is explained by the preceding course of events. A broad and generic interpretation of path dependence is that ‘history matters’. However, this is regarded as trivial. A narrower interpretation of the concept holds that small events are a disproportionate cause of later events.

By its theoretical definition path dependence has implications for the evolution of products. It is used to argue how a historical course of events can explain the outcome of the particular development. This course of events leads to a certain outcome, which is not a predefined equilibrium. A different course of events leads to a different outcome. It also suggests that a design that becomes dominant is not necessarily superior to other possible designs. Instead, small events in the course of history can make certain designs more viable in a market which leads to self-reinforcing mechanisms that provide it with a continuing dominance, or lock-in. Based on this reasoning the potentially superior design cannot develop sufficient momentum, or is locked-out from the market, and therefore becomes unviable. The evolutionary race continues along the ‘lock-in’ path until a next dominant design is set. In retrospect, the moments at which these paths are defined become important nodes in the evolution of products.

The concept of path dependence was developed by economists to explain how technology adoption and evolution of industries take place. Since then the concept has also been applied to other fields. David (1985) described path dependence in his iconic paper on QWERTY. Since then QWERTY has become adopted as the paradigm case of path dependence. In his paper David argues how this particular keyboard layout became dominant over the course of time. Although the case and the arguments used are criticized by authors who distinguish different types of path dependence (Liebowitz & Margolis, 1990), the idea that development processes are path dependent is commonly accepted. The QWERTY case became one of the most influential articles in social sciences and developed into a polemic. Kay (2013) argues that, if one were to rerun the tape of history, QWERTY would always win. Basic probability theory is used to showcase *"the probability of having the seven letters that make up 'typewriter' finish up on top row is one in 5000"* (Kay, 2013, p. 1177). In plain English, it is highly probable that these letters were arranged in this way on purpose to allow salesmen to impress potential customers by rapidly typing the word typewriter. In addition, probability arguments have been put forward that the Dvorak Simplified Keyboard (DSK) layout has letter pairs prone to jamming which appear 16 times more frequently than in QWERTY. Hence, this layout would not have outcompeted QWERTY if it had been around at the beginning of the typewriter evolution. Kay argues that DSK did not win the competition with QWERTY because it is inferior. What is more, DSK was patented 69 years after QWERTY.

Another reflection on the topic of path dependence by Vergne (2013) argues that although the theoretical concept itself cannot be disputed, empirical evidence for path dependence cannot be provided *ex post* case studies like that of David. For the record, Vergne notes that David did not claim evidence of path dependence but described QWERTY as a rather intriguing case, believing that many more similar cases were around which we do not fully perceive or understand. Vergne argues that, as is the case with most case study research, path dependence theory is not falsifiable. To illustrate his point Vergne provides an overview of different research methods including simulation and laboratory experiments, and evaluates their strengths and weaknesses. He closes with a remark that scholars have so far done a poor job as regards empirically exploring path dependence. Higher quality research is required or the concept will continue to be a trendy catchall phrase to explain virtually every sequence of historically important events.

A well-known, more recent example of path dependence is the triumph of VHS over other videotape formats. The VHS format was not superior to Betamax. On the contrary. The greater availability of VHS tapes compelled consumers to buy matching equipment. This network effect reinforced itself and eventually led to a triumph for VHS. Standards or standardization are often associated with path dependence. Standards can be coordinated through agreements set in industry bodies, as was the case with JPEG, which was defined as file format for compressed digital pictures by the Joint Photographic Experts Group. In other cases, standards are uncoordinated as an outcome of development processes, as was argued to be the case for the QWERTY keyboard layout.

Standardisation defines compatibility between various products and users that use the particular standard. It shifts the locus of the evolutionary battle from the interface design defined by the standard towards application of the particular standard. It is not so much the technical superiority of a particular standard at a certain point in time that defines its evolutionary fitness. Rather, the versatility of use of the standard greatly influences the extent to which it is used and therefore its economic success and with that, its evolutionary faith. An example of such a battle of standards at time of writing is between standards for interfaces used for data communication and connectors. FireWire, also known as the IEEE1394 standard, was developed by Apple in the late 1980s and early 1990s and first used in products in 1999. USB (Universal Serial Bus) was developed in the mid-1990s by a partnership of companies and quickly became more frequently used than FireWire. Both standards evolved through various versions that competed on the data bandwidth possible for communication as well as versatility of use. USB replaced a variety of earlier interfaces such as serial and parallel ports, as well as power chargers. USB acquired a greater market share and a larger diversity of types of use. FireWire declined in use and Apple replaced it with the Thunderbolt interface in 2013. The evolutionary race continues with new versions of standards being released every few years. USB released a Power Delivery (PD) specification in 2012 that enables up to 100 Watts to be provided, where as few as 10 Watts was previously possible, with the intention of bringing about uniform charging of electronic devices. Based on this new specification an interface named USB Type-C was developed, that prompted Apple to remove the connector used only for power delivery in their laptops released in 2015. The chances are that this new USB standard will open evolutionary paths to many new types of use and new types of products which were previously non viable.

3.2 Sociology

3.2.1 Diffusion of Innovation

One of the best-known models of innovation was developed by Rogers (1962) and describes how new products, methods or technologies become adopted or, in other words, diffused throughout a population. According to Rogers the acceptance of product introductions generally follows a well-defined pattern. The most important variation within this pattern is the amount of time it takes between the introduction and the moment of complete acceptance. This can vary from a few years to several centuries.

According to Rogers' definition a product is accepted if at least 90% of the potential users own it.

Rogers characterizes users according to their degree of willingness to adopt innovations. The users who are most eager to adopt particular innovations are referred to as innovators. They are followed by early adopters, early majority and late majority and finally laggards (Figure 3.1). Those users who are most sceptical and wait to adopt innovations are called laggards. The first three user types appear to have 'status' as an important motivator for adopting an innovation. The definitions devised by Rogers are commonly used in popular culture and became a staple in marketing literature. Rogers attributes five key characteristics that influence why potential adopters will consider using the innovation:

- Relative advantage, the advantage the innovation has over existing products.
- Compatibility, the compatibility with existing values, experiences and needs of potential users.
- Complexity, perceived ease of understanding and use.
- Trialability, the degree to which the innovation can be tried (first hand experience).
- Observability, the easier it is for potential users to see the result of the innovation, the better the chances that it will be adopted.

Although the characteristics are all rather rational, certain aspects such as emotional benefits, habits or status are not taken into consideration.

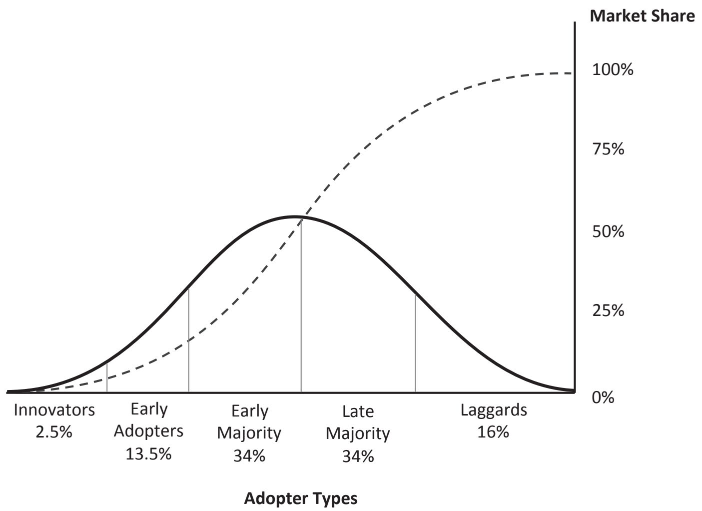


Figure 3.1. The diffusion of innovations and types of adopters associated with different adoption levels according to Rogers (1962).

3.2.2 Social Construct of Technology

Another influential sociological perspective on innovation, referred to as the Social Construct of Technology (SCOT), argues that *technology does not determine human action, but that rather, human action shapes technology*. SCOT (Bijker, Hughes, and Pinch, 1987) takes us away from the common technology centric view and underlines the forming pressures exerted by different social groups on innovating products and technologies. Bijker (1997) uses the SCOT perspective to describe, for example, how fluorescent lamp technology emerged and competed with incandescent bulbs. Fluorescent lamps were, from the outset, superior in efficacy terms. However this turned out to be insufficient to oust the incumbent incandescent lamps. According to Bijker, the struggle was not so much based on pure technical benefits for the end user. Rather Bijker argues that it was literally the power struggle between social groups that shaped the evolution of fluorescent lighting. Utilities that produced electricity wanted to continue to increase their revenue stream and rejected energy-saving technologies. Lamp manufacturers who competed with each other for market dominance feared losing market share and needed to cooperate with fixture manufacturers. Consumers were not a strong voice in this game. Hence, according to Bijker we need to understand how social groups such as producers of electricity, manufacturers of lamps and users interact to comprehend how, in this case, fluorescent light came about.

3.3 Innovation Studies

In this section an overview is provided of concepts used to describe patterns and mechanisms of innovation. Most of the concepts and authors described in Section 3.3 are listed in a publication by Martin (2012) according to which they constitute the field of Science Policy and Innovation Studies also abbreviated as SPIS.

3.3.1 Product Life Cycle

In the mid-1970s, Abernathy and Utterback (1975) proposed a model on innovation process characteristics that is currently known as the technology life cycle. Their model describes the relationship between innovation patterns for two distinct but complementary aspects, competitive strategy (what) and production process characteristics (how).

According to Abernathy and Utterback, the locus of innovation is first found in new insights on 'needs'. During this stage new products are conceptualized and new product specifications emerge. The technology life cycle model describes how the rate of 'product innovation' decreases after the introduction of the innovation (Figure 3.2). Product innovation refers to

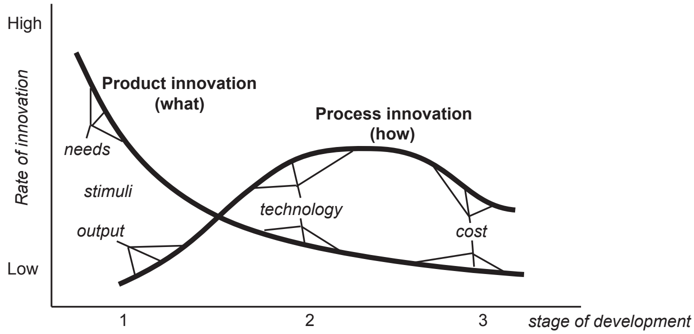


Figure 3.2. The Technology Life Cycle (Abernathy & Utterback, 1975).

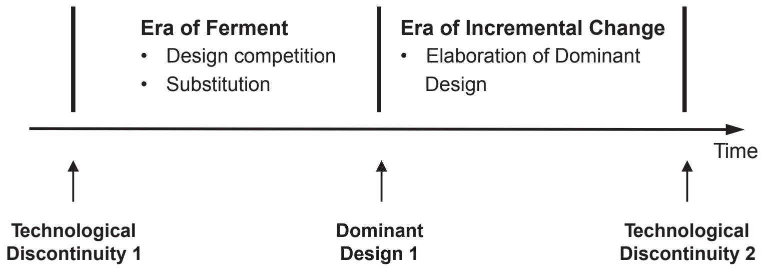


Figure 3.3. Technological discontinuities and dominant designs (Anderson & Tushman, 1990).

the 'what' that is innovated rather than a physical product. Improvement of the 'how' of a product or technology is called process innovation. The rate of innovation starts low in 'process innovation' and then increases to a certain point and subsequently decreases. Process innovation includes both technology to fabricate a product and details in the design (of a product), with the aim being to improve its manufacturability. In the first stage, product innovation (design or specification changes / improvements) is focused on maximizing performance while process innovation is at a low rate.

In the second stage 'technology' serves as the main stimulus for innovation. Innovation in the product is targeted at sales maximization. Here the locus of innovation is found in better ways of (re)producing. Production systems are increasingly designed for efficiency. Some sub processes become highly automated while others are essentially manual or based on general-purpose equipment.

The third stage finds its main stimulus for innovation in 'cost' (reduction). Cost minimization is a dominant strategy (for changes in the product design or specification) and process innovations become systemic. According to Abernathy and Utterback, one can expect *"a greater degree of competition* *based on product differentiation with some product designs beginning to dominate"* when firms start focusing on maximizing sales (Abernathy & Utterback, 1975, p. 643-644). This notion is the first use of the concept 'dominant design' in literature.

3.3.2 Technological Discontinuities and Dominant Designs

Anderson and Tushman (1990) propose an evolutionary model of technological change. Their model (Figure 3.3) recognises that technology develops in cycles. Periods of fermentation and periods of incremental change alternate and are demarcated by technical discontinuities and dominant designs. The eras of fermentation are essentially *'trial and error phases'* characterised by intense technological variation and selection which culminates in one, sometimes a few, dominant design(s). Subsequently an era of incremental change starts, in which a dominant design is further elaborated until a new technological discontinuity punctuates the equilibrium. The model is called evolutionary as it recognises that the process of (technological) *'variation'* provides designs that compete, then *'selection'* amongst variants in the era of ferment finally produces a dominant design as outcome, and subsequent technological elaboration leads to *'retention'* of the dominant design. In Chapter 5 of this thesis, these dominant designs will be pictured as the successful branches in an evolutionary process that is visually displayed in a Product Family Tree. The designs that are substituted or outcompeted constitute the evolutionary dead-end twigs.

3.3.3 Technology Cycles and Dominant Designs as Nested Hierarchies

Tushman & Murmann (1998) recognise that products are composed of a nested hierarchy of subsystems and linking mechanisms (Figure 3.4). Not all subsystems are equally important. Some subsystems are core and are either tightly connected to other subsystems, or represent a strategic bottleneck. In contrast there are peripheral systems that are only weakly connected to other subsystems (Tushman & Murmann, 1998, p. 249).

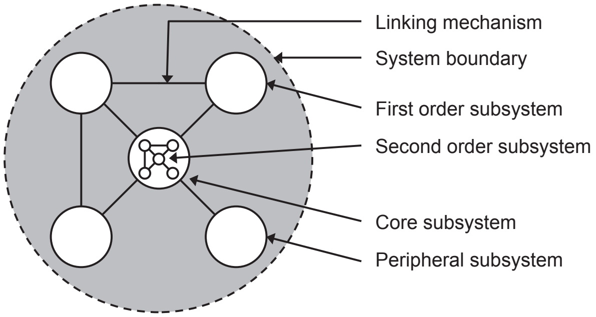


Figure 3.4. System composed of subsystems and linking mechanisms (free after Tushman & Murmann, 1998).

Without the complexity of linking mechanisms, these systems can also be depicted as a nested hierarchy with the system as highest level on top, cascading down via subsystems of various orders towards components (Figure 3.5). For example, a car can be considered a unit of analysis at system level. Cars contain a power train, which is a first-order subsystem that consists of second-order subsystems engine, transmission, driveshaft, differentials, etc. The engine can be implemented technically in different ways (e.g. as internal combustion engine, hybrid, or electric). A car with an internal combustion engine contains third order subsystems like the cylinder block, crankshaft and pistons. The piston is built up of components piston-head, piston ring, gudgeon pin, piston-rod, bolts and nuts.

According to Tushman and Murmann, each of these systems and subsystems go through technology cycles (Figure 3.6) that can be regarded as evolutionary sequences of variation, selection and retention. A first *'technical discontinuity'* (TD1) disturbs equilibrium and a series of competing design variations are produced during an *'era of ferment'* (EoF). Selection results in a first *'dominant design'* (DD1), which is subsequently refined during an era of incremental change (EoIC). These cycles succeed each other over time and so represent technological trajectories.

As complex systems constitute different subsystems - each of which is subject to its own technology cycles - the evolution of complex systems can again be described as a nested hierarchy of technology cycles (Figure 3.7).

3.3.4 Technological Paradigms and Trajectories

Dosi (1982) introduced the term technological paradigm in analogy with the scientific paradigm posed by Kuhn (1962). Dosi defined technological paradigm as *"a 'model' and a 'pattern' of solution of selected technological problems based on selected principles derived from natural sciences and on selected material technologies"* (Dosi, 1982, p.152). Subsequently, a technological trajectory is defined as *"the pattern of 'normal' problem solving activity (i.e. of 'progress') on the ground of a technological paradigm"* (Dosi, 1982, p.152). The technological trajectory is the direction of advance within a technological paradigm. The technological paradigm severely narrows the directions of technological change (solutions) pursued (investigated). It provides a framework that guides technological development. At the same time such a framework also prevents any investigation of alternative types of solutions. Thus, a technology paradigm has an exclusionary effect, blinding technologists and engineers for other technological possibilities. According to Dosi *"paradigms are an 'outlook' that focus the eye and the efforts of technologists and engineers in defined directions"* (Dosi, 1982, p.158).

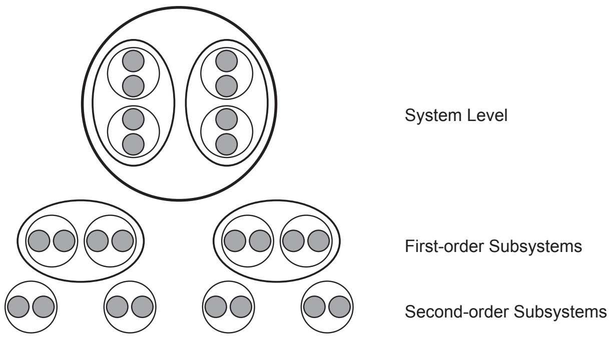


Figure 3.5. Illustration of a four-level nested hierarchy (Murmann & Frenken, 2006).

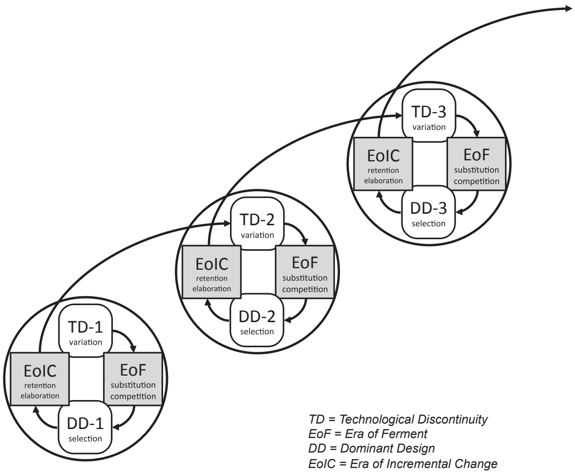


Figure 3.6. Technology cycles over time (free after Tushman & Murmann, 1998).

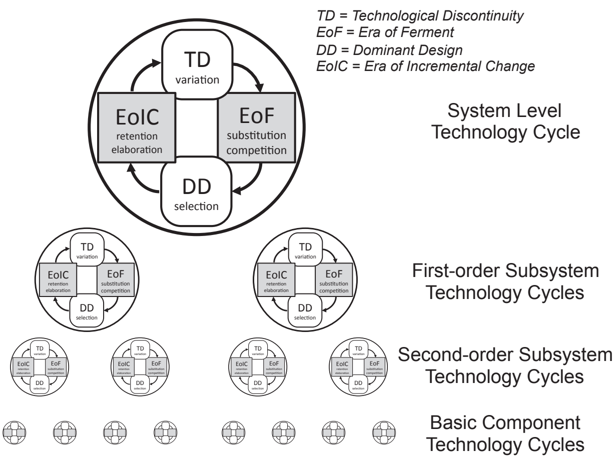


Figure 3.7. Nested hierarchy of technology cycles over time (free after Murmann & Frenken, 2006).

Dosi describes two different states of technological development, 'normal progress' and 'extraordinary innovative effort' or breakthroughs. During 'normal progress' technology develops along a path or trajectory that is framed or limited by the boundaries of the technological paradigm. This is also called 'continuous technological change'. Trajectories are disrupted by changes in the technological paradigm. When a technological paradigm changes, the problem solving activity starts almost again from the beginning. This type of technological change is referred to as 'discontinuous'. Often, the emergence of new technologies is characterized by new emerging firms.

Dosi describes two phases of technological change. First, in a 'trial and error' phase, institutions produce and direct the accumulation of knowledge, experience, etc. A multiplicity of risk-taking actors tries different technical and commercial solutions. Then a second phase starts: the oligopolistic maturity. In this phase the production, exploitation and commercial diffusion of innovations are commonly executed by a less diverse group of actors. Therefore, this phase is referred to as oligopolistic competition. Actors in this phase derive their oligopolistic power from the asymmetric capability to innovate successfully. Static entry barriers (such as economies of scale) protect the oligopolist from competition entering the market. This possibility for firms to enjoy oligopolistic positions is a strong economic incentive to innovate, as it provides them market and technological leadership.

3.3.5 Technological Transitions

Geels (2002) developed an analytical model to describe technological transitions, which are long-term and large-scale technological developments. Examples of technological transitions are the replacement of horse-based transportation by automobiles or the replacement of the current hydrocarbon-based energy systems by renewable energy. The model developed by Geels uses a so-called multi-level perspective (MLP) because it uses three analytical levels in its description of technological transitions: micro-level or the niche, the meso-level or socio technical regime and the macro level or landscape. The micro-level describes how radical innovations occur in small networks or niches. The meso-level describes a web of interlinking actors that together define so-called socio-technical regimes. The regime level slowly aligns with radical innovations that stabilize over time into dominant designs. A macro-level or landscape describes a broad range of factors such as social trends, economic pressure, or cultural values that together change even slower than the regimes. The three levels influence and interact together describing different actors and dynamics that collectively effectuate to long-term technological change or technological transitions. The multi-level perspective model recognises that technological transitions are multi-dimensional in nature with technological change being only one aspect of change alongside e.g. culture or industrial networks.

3.3.6 Disruptive and Sustaining Innovations

In his book 'The Innovator's Dilemma', Christenen (1997) makes a comparable distinction to that of Anderson and Tushman when he differentiates between disruptive and sustaining innovations. According to Christensen innovations are sustaining most of the time. A sustaining innovation is an innovation that fulfils a desire held by existing clients. Often this means improving the performance of the product. Sustaining innovations hardly ever lead to the failure of an organization. A sustaining innovation leads to an improved product with an immediate, positive result for the company. In the event of a disruptive innovation there is, according to Christensen, no improvement of the product that the existing relations are interested in. On the contrary, the present clients will not want the innovation. Disruptive innovations have to find their own, new market. The problem for the present organization comes later, after the product has been developed in more detail, and sometimes only after several years, when the disruptive innovation has been improved in such a way that it has become interesting to their clients. In many cases it is then too late. The new organization will have acquired such a strong position in the market that the existing organizations are unable to catch up.

3.4 Universal Darwinism and Evolutionary Perspectives

3.4.1 Biological Evolution

Darwin published his book 'The Origin of Species' in 1859 to provide an explanation for how species originate and evolve by adaptation and selection. This process became known as biological evolution. Since Darwin, the bio-chemical process of evolution has been unravelled. The current prevailing thought is that life started very simply with some kind of replicating molecular structure, although the form of the first replicating units and their origin remains a mystery. Over billions of years more complex and advanced forms of life evolved, generally referred to as organisms. These organisms use a large helical molecule referred to as DNA[1] as storage medium for biological information. We call the smallest unit of

1. In the 20th century it was discovered that a large helical molecule named deoxyribonucleic acid, commonly abbreviated to DNA, plays a central role in evolution as carrier of biological information. DNA consists of different molecular building blocks, amongst which the so-called base pairs Adenine (A) Thymine (T), Cytosine (C) and Guanine (G) that constitute the coding units like the 0 and 1 in a bit. A region of DNA that influences a particular characteristic in an organism is called a gene and constitutes the unit of heredity. The complete set of genetic information of an organism is then referred to as the genome.

heredity information genes. The complex life forms appeared later in time as they could not have evolved without their less complex predecessors. The genetic information found in the genomes of current living organisms is the result of a process of accumulation of biological information that started with the origin of life on earth. This allows us to trace back how long ago and along which paths organisms evolved into different species (see also Chapter 5).

Biological evolution based on genes is often described in the following steps:
1. Variation: Random mutations are introduced by errors in the gene coping process.
2. Selection: Competition amongst organisms results in ousting those least adapted to an environment. Once a species dies off, the genetic information is irretrievably lost.
3. Retention: Those species best adapted to an environment survive and reproduce.

3.4.2 Evolution Applied in Other Fields

One and a half centuries after Darwin published his book, the potential explanatory value of the concept of evolution was still being explored in fields far beyond biology. Besides Innovation Studies described above, evolutionary ideas are now also applied to fields like economics, psychology, physics and computer sciences. Collectively this is referred to as universal Darwinism.

3.4.3 Cultural Evolution

In his book 'The Selfish Gene' Dawkins (1976) introduces a new concept, the meme: a unit for carrying cultural information that can be compared to the gene as a unit for carrying biological information. Memes are defined as units of cultural information and are assumed to play an elementary role in communication, and the sharing of ideas. A meme is postulated as a contagious information pattern that replicates by parasitically infecting human minds and altering their behaviour, causing them to propagate the pattern. Ideas – or memes – can be reproduced by various forms of communication: imitation, writing, video, etc. Memes have some important differences from genes. They spread fast, in a promiscuous manner, back and forth. This contrasts with genes in multicelled life, which are transmitted to a next generation (parent to off spring and not back again), which is therefore a relatively slow process.

Ideas evolve through memes via the following three steps:
1. Variation: Different ideas are generated by trial and error.

2. Selection: Competition amongst ideas leads to ousting of those least fit in a particular environment. Ideas are not killed as long as they can be retrieved.
3. Retention: Ideas are retained e.g. by imitation, orally transferring a story, printing books or producing products.

According to Edmonds (2005) memetics has not been very successful in providing 'explanatory leverage upon observed phenomena'. The huge number of publications in the first few years of this century quickly diminished and almost became non-existent after 2005. Studies into this unit of reproduction have not (yet) led to commonly accepted ideas on how to explain *innovation* in general or, as investigated in this thesis, *how new (types of) products come about and develop through time*. Therefore, memes and memetics will be parked here and considered a philosophical concept that at this point will not contribute to the research objective stated in this thesis.

3.4.4 Technological Evolution

Basalla (1988) uses *'the evolution of technology'* as a metaphor to describe how the process of technological innovation produces novel artefacts, and how society applies selective pressure on available artefacts. As a historian, Basalla refers to artefacts rather than products or technologies. He proposes the application of the theory of organic evolution to the technological world, although he warns for the *"vast differences between the world of the made and the world of the born"*. His theory of technological evolution is rooted in four broad concepts; diversity, continuity, novelty and selection.
"This diversity can be explained as the results of technological evolution because artifactual continuity exists; novelty is an integral part of the made world; and a selection process operates to choose novel artefacts for replication and addition to the stock of made things" (Basalla, 1988, p. 25).

His book is organised according to these four concepts and explores the evolution of many artefacts. Basalla states:
"(…) *continuity implies that novel artefacts can only arise from antecedent artefacts – that new kinds of made things are never pure creations of theory, ingenuity, or fancy. If technology is to evolve, then novelty must appear in the midst of the continuous"* (Basalla (1988, p. vii-viii).

Since the groundwork by Nelson & Winter (1982) and Basalla (1985) many authors have used the evolutionary metaphor to describe technological change. Rosenbloom (2010) provides examples of technological evolution and refers to many of these authors. According to Rosenbloom (2010; p. 9) *"technological evolution refers to changes in production processes or institutional arrangements that make it possible with a fixed set of resources to produce either*

(1) a greater quantity of a given product or service or (2) to produce new or qualitatively superior products or services".

3.4.5 Architecture and Design

For centuries, design solutions provided by biological evolution have served as a source of inspiration to architects and engineers. Steadman (1979) explores the many analogies that have been made between the evolution of organisms and human-designed objects. With his background in architecture, Steadman describes many interesting examples, not only of architects and designers but also philosophers and other theorists, that have looked to biology for inspiration. Although this work is extensive in the examples and references listed, it does not provide a clear explanation of how designers can benefit from the evolutionary analogy. There does not appear to be a method for design analogous to the process of growth and evolution in nature or at least not one that is easy to grasp.

Benyus (1977) describes 'biomimicry' as a new discipline using nature's best ideas as inspiration for design solutions. Among other things, such nature-inspired design perspective has received attention in the context of sustainable design (Tempelman e.a., 2015). Next to inspiration for designs, biological evolution has been used as explanation for certain evolutionary mechanisms in the world of made. Gould & Vrba (1982) introduced the term 'exaptation' for the process by which features acquire functions for which they where not originally adapted or selected. For example, feathers that most likely originally evolved for thermal insulation are now an indispensable trait for flying birds. An often-quoted example of functional shift in the world of made is the radar whose technology also proved useful in microwave ovens. Adriani & Cattani (2016) brought together several papers in a special section of a journal in an effort introduce the concept of exaptation to a broader audience and exposing it as a (possible) solution to questions about the emergence of man made novelty, particularly radical innovation.

3.4.6 Industrial Design Engineering

Industrial design engineering is a discipline involved in the design of industrially produced goods, often involving mass manufacturing.

This approach to design and manufacturing started with the industrial revolution. Since then designing has become increasingly technology-intensive. In order to support the diffusion of new technologies amongst industrial design engineers Poelman (2005) proposed a model of *'knowledge metabolism in development projects'* based on memes and analogies of cooperating organisms.

3.4.6.1 Product Phases

In the last decades of the 20th century, the process of developing new products was mastered and taught in various engineering courses. Eger (1987, 1993, 2007a) recognised that products develop through phases and proposed a step-by-step product development or innovation strategy named Evolutionary Product Development (EPD). Recognising that radical, new innovations imply both a promise of potential high returns and a substantial risk of failure and loss of money, Eger introduced Evolutionary Product Development as a strategy reducing risk in new product development.

EPD recognizes phases in the development of products. Each phase is defined by ten characteristics, of which five are product-related (newness, functionality, ergonomics, product development, styling), while the others relate to its market, production technology, promotion, service and ethics. The six product phases are performance, optimisation, itemisation, segmentation, individualization and awareness (see also Figure 1.1). In the first phase the product is new to the market, the performance often poor and few competitors offer the product at a relatively high price. Over time the product starts improving in reliability, ergonomics and safety. Competition increases and prices decrease. The product acquires more features and the market adoption rate increases to a high level. Initially the phases postulated were assumed to appear sequentially. A recent study (Eger, 2013) defined three sequential phases plus another three that appear to co-exist as a fourth phase (see also Figure 1.2).

3.5 Patterns and Mechanisms of Innovation Framed

The models discussed above describe different perspectives (social, economic, technological and evolutionary) on the process of innovation. Time is a common dimension and is used to route from earlier to later versions. Over time, periods with specific innovation dynamics are identified. Kuhn (1962) and Dosi (1982) describe how a specific regime or 'paradigm' defines a period characterized by one and the same 'frame of mind' in the first case of science-thinking and the second of technology-thinking.

Geels (2002) describes how the process of technology transitions is driven by interactions within and between different levels (micro/meso/macro). Longer time frames are typically assigned to technological trajectories and technological transitions. Radical innovations occur in niches (micro-level) on shorter time frames.

Utterback and Abernathy (1975), as well as Anderson and Tushman (1990), describe how technology cycles are defined by periods of rapid change alternated by periods of slower change. These technology cycles are associated with shorter time frames and are nested in a technology trajectory. Murmann and Frenken conceptualise products as complex artefacts that evolve in the form of nested technology cycles. Dominant designs are described as those designs that result from these technology cycles to become widely adopted and change the nature of competition in corresponding industries.

Eger (1987, 1993, 2007) describes how products evolve from a poor performance towards more advanced and refined versions.

The common feature of most of the above models is that they assume a sequence as well as a gradient (from course to finer) in the process that delivers new products referred to as innovation. However, an integrative perspective on how products come about, develop into families of related products over time as well as the causal link between new products and their predecessors, is generally absent in literature. An exception is the evolutionary theories. This thesis addresses the gap between sequential models and evolutionary models. Figure 3.8 contains an overview of a number of the models described.

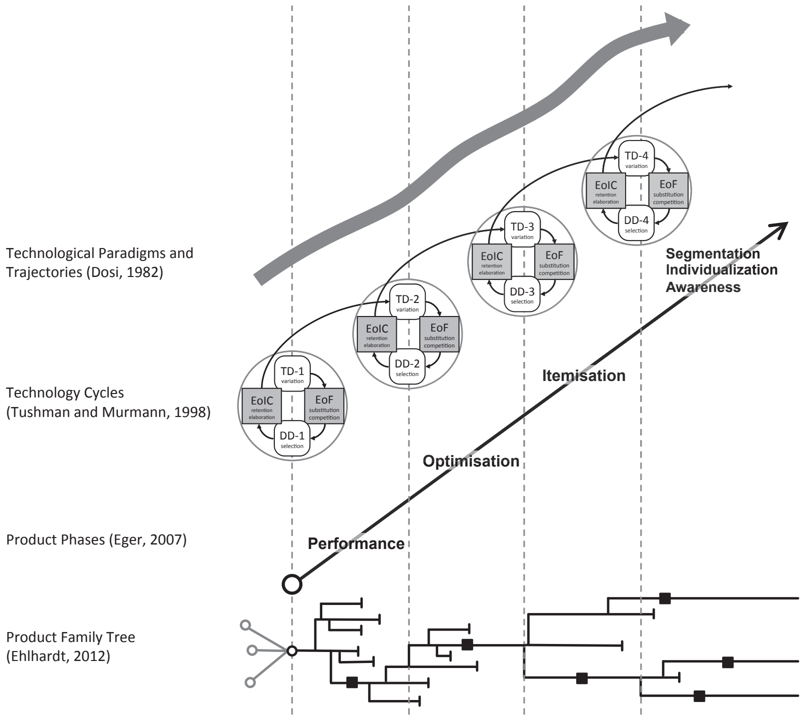


Figure 3.8. Patterns of Evolution in Products, based on some of the concepts presented in this chapter. The vertical dotted lines represent technological discontinuities. The black squares represent dominant designs.

3.6 Conclusion

Previous sections have provided an overview of literature on patterns and mechanisms of innovation. It appears that a range of disciplines have produced perspectives on patterns and mechanisms of innovation. In general, these are rather different perspectives.

Two behavioural sciences describe innovation from a behavioural perspective. Sociologists have described the degree of willingness to adopt innovations that can be linked to behavioural traits. Furthermore, they argue that technology does not determine human action, but rather, that human action shapes technology. Economists have described innovation in terms of creative destruction, which ousts incumbent structures. During this process existing supply-and-demand equilibriums are disturbed. A new branch named evolutionary economics focuses on providing explanations for economic change required to overcome limitations of neoclassical economic theory based on equilibriums. The term path dependence is used by economic historians to describe how a course of events explains a certain outcome. Connected to this is the term lock-in that is used to explain how, at a certain point, self-reinforcing mechanisms prevent alternative development routes from losing their viability.

For the history of technology perspective, the term technological evolution is used to explain the process that leads to the diversity and complexity found in man made things.
A perspective referred to as Science Policy and Innovation Studies, or just Innovation Studies, focuses most explicitly on innovation processes and describes the industry dynamics associated with it. This perspective also provides us with the nomenclature to designate characteristic elements of innovation processes. In particular the terms dominant designs, technological discontinuity and technology cycles appear to be core concepts that support the understanding of the nature of innovation processes. In Innovation Studies, the evolutionary metaphor is often used to explain the process of innovation in terms of variation, selection and retention.

P1: *Technological innovation can be described as an evolutionary process.*
This proposition is confirmed by literature discussed in Chapter 3, in particular Nelson & Winter (1982), David (1985), Basalla (1988), Geels (2002), Anderson & Tushman (1990), Tushman & Murmann (1998) and Murmann & Frenken (2006).

The meme has been proposed as unit of cultural information analogue to the gene for biological information. However, the evidence for the meme has not been irrefutable and so far did not provide explanatory leverage for innovation processes. Consequently it has been parked in this thesis as a philosophical concept that currently does not have any practical application here.

In the field of architecture and design engineering studies, the biological world has long served as a source of inspiration for designs. The recent attention for biomimicry is testimony to continuing attention for nature-inspired design. However, nature-inspired design appears to be a very broad topic. Moreover, the evolutionary metaphor as used in the propositions P1 and P2 is not necessarily connected to what is referred to as biomimicry. Therefore, the next chapter will investigate, for several cases, how we can investigate *'technological innovation as an evolutionary process'*. Chapter 5 will then explore the concept of 'lineage' and reflect on the extent to which it can be applied to human culture. Subsequently these lines of thought will be used in Chapter 6 to propose an analytical conceptual framework that can be used to investigate how new (types of) products come about.

4

Technological Innovation as an Evolutionary Process

4.0 Introduction

Stone tools are generally regarded as the oldest and most primitive tools ever made and, as such, are associated with the dawn of mankind. Evidence of direct stone tool manufacturing dates back to over 2.5 million years, (Semaw et al, 1997) and stone tool assisted consumption of animal tissues to even 0.8 million years earlier (McPherron, et al, 2010). It is possible that other tools of softer materials prone to decay, like wood, were made even before then. With the oldest discovered remains of our own species *Homo sapiens* being an estimated 0.2 million years old, it is clear that toolmaking goes back a long way, to our very distant ancestors. As the first stone tools date from 2.5 million years ago, the rate of development of these products was rather slow, at least by today’s standards. For over two million years the most prominent tools of which remains have been found were based on stone technology. The technological era in which these tools were produced is therefore referred to as the Stone Age.

The oldest stone tools were flakes chipped off from larger stones. Over time stone technology advanced and produced complex, meticulously-shaped products like the hand axe (Figure 4.1 left), which requires deliberate manufacturing planning and dexterous craftsmen. Stone technology continued to advance, for example by improving functionality with heat treatment to harden sharp edges (Schmidt et al, 2013), or adding wood or bone extensions to sharpened stones. This led to the creation of improved axes, as well as new tools like spears, daggers or arrows. People then started to write, live in cities and engage in various labour specialisations. People discovered how they could use metal to make tools such as axes (Figure 4.1 right) and arrow points. This marked the transition from the Stone Age to the Bronze Age.

Ever since our technological history has been characterized by the increasingly rapid development of new and more advanced types of tools. This thesis builds on the observation that tool manufacturing started with simple tools and that the complex types we use today were only recently produced.

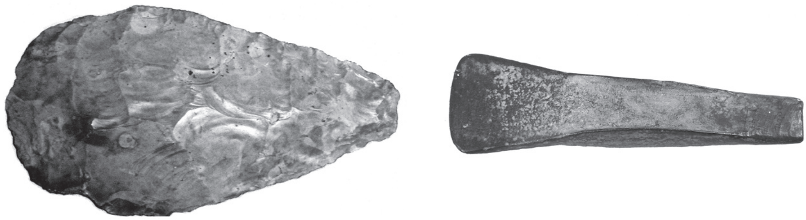


Figure 4.1. A stone hand axe (left) and a bronze axe (right). Note: not the same scale.

4.1 Knowledge Accumulation and Innovation

As described in Chapter 3, various authors have explained the process of innovation in evolutionary terms. Basalla (1985) described how a process of invention accumulation eventually led to the current diversity as well as complexity in tools. He writes that *"continuity implies that novel artefacts can only arise from antecedent artefacts – that new kinds of made things are never pure creations of theory, ingenuity, or fancy. If technology is to evolve, then novelty must appear in the midst of the continuous"* (p. vii-viii). In other words, Basalla postulates that inventions like the bicycle or smartphone build on previous inventions and he states that the evolution of technology implies a continuum in which one artefact can be invented by building on knowledge associated with previous artefacts. Consequently there is no 'inventive-leap' that explains the sudden appearance of inventions like the bicycle or smartphone. Instead the emergence of these products can be explained by a continuum, in which step-by-step product-technology combinations evolve.

This reasoning implies that next generation products evolve which, over time, lead to more advanced products whose existence was not intended by the initial developments, nor could initially have been conceived. The rocess of know-how and know-what accumulation over time therefore explains how new products emerge and give rise to new types that could not have been envisaged initially. The introduction of new products, let alone new types of products, is therefore not an example of *'Generatio spontanea'*[1]. Rather it is enabled by a long process of accumulation of know-how to make elements of the first elementary version of the product, which enables the exploration of the know-what with a view to providing new functionality.

The notion that our current knowledge builds on previous discoveries was first used in the 12th century by Bernard of Chartres (McGarry, 1955), who introduced the metaphor of *'dwarfs standing on the shoulders of giants'*. The metaphor compares our current generation with dwarfs who can look beyond previous generations not because of better vision, but because we are lifted up by the knowledge accumulated. The knowledge accumulation referred to in this metaphor also holds for know-how (to make products) and know-what (products to make), used in today's products or technologies.

Technological innovations accumulate over time and cannot skip a generation. Each step from one generation to the next, although technically challenging, has to be feasible based on new combinations of know-how and

1 This term was used by Aristotle to explain that new generation spontaneously arose as he observed eels and flies coming from cadavers.

know-what available at that time. After all, skipping a generation would require an inventive-leap or a knowledge fundament that is unavailable. The philosopher Dennett (1995) uses the metaphor of skyhooks (which use no fundament) and cranes (which rest on a fundament) to explain the difference between the emergence of a new design by a divine intervention (for which a skyhook suffices), and Darwinian evolution in which adaption and selection elucidates how accumulated changes (that build the fundament) over time explain how new designs in biology come about. This metaphor also supports the accumulation of know-how and know-what as a more plausible argument for the emergence of new types of products by technological evolution[2] rather than divine intervention (also referred to as intelligent design).

Consequently, any innovation is a next 'inventive-step', which builds on prior art. Before new types of products could be invented a fundament of know-what (functions to fulfil) and know-how (to make these products) had to be accumulated. It is this knowledge and skills accumulation process that can explain the appearance of highly complex tools, such as the recently introduced smartphone.

Today's smartphones would not exist without preceding mobile phones, which were, in turn, developed to overcome limitations of telephones using landlines. Every new type of telephone was not only introduced to improve upon earlier models but could not have been invented or developed if these prior models and a rich source of adjacent knowledge were not available. The next section illustrates how products (telephones) evolve, nested in a large technological system (telephone networks) that is inextricably linked to evolution in components (e.g. transistors).

4.2 System Evolution: the Case of the Telephone

This section will show that to understand how a nested product evolved, it does not suffice to regard it as a stand-alone product. Instead, one has to look at the evolution at different levels (system and component) to understand how they influence each other.

Telephones should be regarded as an element of a large technological system (Figure 4.2), using a network of landlines, telephone exchange facilities,

2 Dawkins (1986), who explains how accumulating small changes explains the diversity and complexity in organisms, also discussed a computer program (p.43-74) that shows how a succession of small changes can produce evolving fictitious two-dimensional organisms.

and telephones to allow users to talk to each other over a large distance. In other words, the product (telephone) is nested in a larger system (telephone networks). This large technological system can be analysed at different levels. Although the breakdown in levels is ambiguous, in the case shown in Figure 4.2 we assume four levels when analysing the telephone system. The reason is that it requires four levels here to show how changes in a network technology (system) affect design details in the telephone (subsystem/product). In addition, changes in, for example, electric circuits (components) explain the changes in network technology (systems).

The telephone was commercially introduced in 1876. It consisted of a speaker and a mouthpiece next to a wood panel body with various electrical parts. There is disagreement about who should be given credit for the invention of the telephone, although the Bell and Edison patents dominated early telephone technology and are regarded as commercially decisive (Wikipedia, 2015a). However, the invention of the telephone and its network technology was clearly not the work of a single inventor. Instead it was the accumulated inventive work of many individuals over several decades.

Over the years telephone usage grew and had an enormous impact on our society. The telephone allowed more efficient communication and was

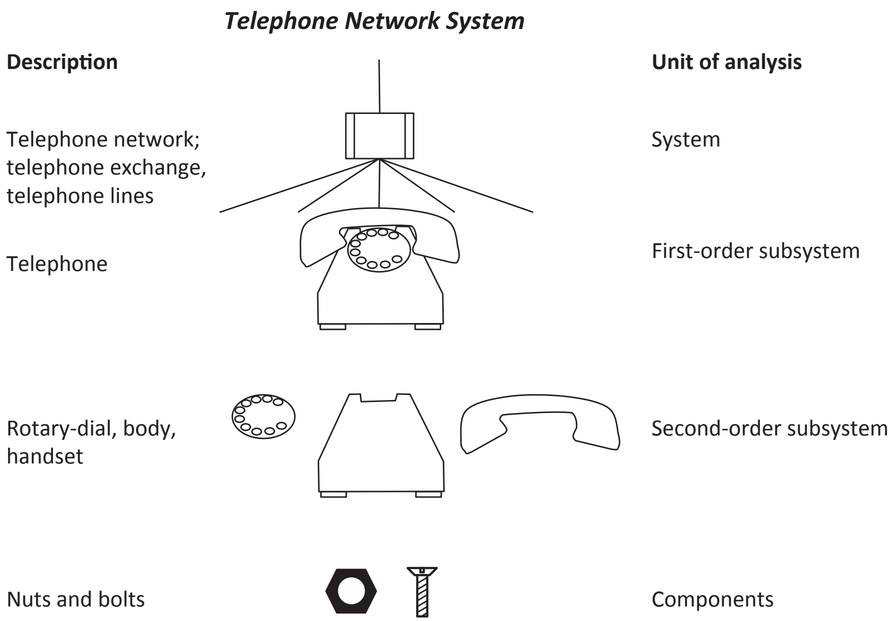


Figure 4.2. The telephone network system diagram showing four levels of analysis. In this perspective, the telephone is a first order subsystem.

instrumental in societal modernisation. For example, it enabled women to participate in jobs like switchboard operator, outside the confines of the house. Women turned out to be avid users of this new technology and were first discouraged from using the telephone for 'mere idle gossip' as the telephone was emphasized as a device for practical use in business. After a while, the industry wholeheartedly encouraged women to use telephones (Fischer, 1994). As is the case with many products, the way we use and perceive them evolves over time. The aversion of inventors and businessmen to unforeseen types of use of the telephone proved to be only temporary. In the end, increased use stimulated business.

The growth in the number of users also led to raised expectations of telephone systems. Initially, telephone exchange facilities were filled with operators using switchboards to manually establish connections. Operator-established connections turned out to be expensive and not always available, as operators did not work 24/7. To overcome limitations associated with human operators, the pulse network technology was developed, that automated the process of establishing connections.

In order to allow the system to work with pulse network technology, the first-order subsystem (telephone) needed a second-order subsystem to generate pulses. For this purpose a second order subsystem (the rotary dial) was developed. In the case of the first pulse network telephones, the rotary dial was simply added as a 'Fremdkörper' to the body of telephone model that existed at that moment (Jacobs e.a., 1987) in the 1920s. Then, over time, a more advanced telephone model was introduced, integrating the second-order subsystems rotary dial and base. The second-order subsystems speaker and mouthpiece became integrated into an assembly named the handset. With the adoption of pulse network technology, the operator-switchboard networks slowly disappeared. The dial pulse network technology is also referred to as Plain Ordinary Telephone Service (POTS) and was the standard until about 1960.

Increased use placed higher demands on the networks, the volume of calls increased, not only for local calls, but also for long distance. The dial pulse network technology had a technical limitation as regards the physical distance over which it could automatically make connections using dial pulses. To overcome this problem operators were still used to connect long-distance calls, using special equipment based on multi-frequency signalling and a 16-digit keypad. Operators used this equipment at system level to contact next down-stream operators to establish connections. This semi-automated signalling and switching equipment proved to be successful from the point of view of both speed and cost effectiveness. Based on this success, new equipment using dual-tone multi-frequency (DTMF) signalling was developed, that could be operated without intermediate operators. The DTMF system uses 16 signals established by combining two frequencies from a matrix of four by four (Figure 4.4).

Engineers who developed the system, envisioned phones being used to access computers. To facilitate this they used two symbols (asterisk or * and hash or #) and four letters in addition to the 10 digits. The letter keys were used for menu selection and were dropped from most phones (Wikipedia, 2015b). The keypad required a new telephone design (Figure 4.5) using a second-order subsystem with push buttons replacing the rotary-dial. Again, the new design of the product telephone, a first-order subsystem, was due to changes in the network technology at system level.

Figure 4.3. Evolution in early telephones: at system level operator networks were replaced by pulse network, the second-order subsystem rotary-dial was introduced and then the designs of second-order subsystems like dial and handset were further integrated.

	1209 Hz	1336 Hz	1477 Hz	1633 Hz
697 Hz	1	2	3	A
770 Hz	4	5	6	B
852 Hz	7	8	9	C
941 Hz	*	0	#	D

Figure 4.4. The Dual-Tone Multi-Frequency matrix and the push-button keypad.

Figure 4.5. Evolution in telephones, from pulse- towards tone networks.

According to Jacobs e.a. (1987) the product telephone design evolved towards an archetype with an integrated handset similar to the one pictured in the middle of Figure 4.5 in the 1930s. The beginning of the telephone archetype referred to by Jacobs is a Siemens & Halske telephone produced in the early 1920 (not pictured here). It is described as a cube with dial on a chamfered front side, a handset with integrated speaker and mouthpiece placed transversely to the body. Initially, plenty of both small and large firms brought a wide variety of telephone models to the market. Once the generally applied design solution for speaker and mouthpiece had converged towards an integrated handset, a new design standard appeared (i.e. dominant design). Smaller firms purchased this subsystem from the larger manufacturers and assembled it on a variety of body-subsystems, targeting different types of use. Then, over time, the number of manufacturers decreased and with that the diversity in models. The (wired) handset appears to have become the core element in the design of telephones. The importance of this subsystem for the product telephone became evident in the manner in which Jacobs summarizes the results of the research with the following thesis: the device is a telephone once it contains a handset[3].

The telephone evolved in a wider context that influenced its development. New ways to match supply and demand were introduced by using the telephone. This increased market transparency, which had economic effects as markets changed for both producers and consumers[4]. Increased participation of women on the labour market was another effect. In general, widespread use of telephone technologies had an enormous impact on society. Reciprocally, how people used telephones and what telephone types they preferred affected selection from available variants and therefore had an effect on telephone evolution. This illustrates that social and economic forces are an example of context affecting evolution in a product.
Another example of influences on the evolution of the telephone comes from the technological domain. Innovations in electronics delivered new components like the transistor. Researchers at Bell Labs, a research laboratory of a large telephone company, produced a first working transistor in 1947. Ironically, this resulted from wartime efforts to improve radar technology, not telephony. The transistor heralded a new era of technological opportunities, enabling a dramatic reduction in the size of electrical components which, in turn, led to microelectronics and microprocessors which became key components of the computer technology that developed in the following half century. This new technology, by no

3 In Dutch. Een apparaat is een telefoon als er een hoorn aan zit.

4 Recently, the introduction of Internet pages like eBay caused similar change in matching supply and demand.

means specifically developed for telephony, contributed as an enabling technology to further innovation in telephone network systems. The transistor was key to the development of computer and associated digital technology, which allowed voice to be converted into digital data which, in turn, could be carried over networks more efficiently than analogue voice signals. At system level the increased capacity of networks contributed to a further reduction of cost, which again increased use. With the advance of computing technology and the introduction of the Internet, the networks that initially carried only voice now changed into data networks. Currently telephone conversations are carried over networks using a so-called voice over Internet protocol (VOIP), often using glass fibre instead of copper lines. Each time a new telephone network technology was introduced that allowed more technical functionality and capacity, this translated into lower cost and led to the ousting of incumbent telephone network technologies. Over time the appearance of telephones evolved together with network technologies. The first-order subsystem telephone evolved in conjunction with the network technology applied at system level. The evolution of the product telephone therefore appears to be nested in the evolution of a larger order telephone network system and the evolution of system, subsystems and components appears to be influenced by a context of diverse factors ranging from enabling technologies and business interests to social factors. Figure 4.6 shows successive telephone network technologies.

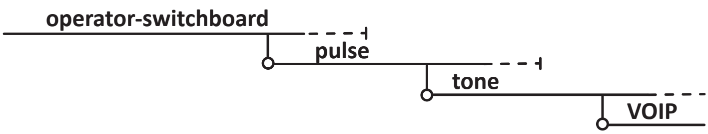


Figure 4.6. Evolution in telephone network technologies.

4.3 When the Time is Ripe, New Types of Products Emerge from a Fundament of Know-how and Know-what

The above text shows how a succession of network technologies and associated telephone models led to today’s models. The example of the telephone shows how technology is a means to an end, in this case allowing people to speak to each other over a long distance. The telephone network system was developed to make this basic function possible. The product telephone is an element nested in the larger system and has no function without it. The technology used in modern telephones is by no means the exclusive result of developments targeting this product. Instead it builds on the wider know-how and know-what developed in many adjacent fields. The technological knowledge accumulates over time, enabling a first version of the system. Over time change occurred in many elements of the system and changes in the dominant design on system level led to changes in first and second-order subsystems. In addition, changes in components (e.g. transistor, glass fibre cables, VOIP) led to change at system level. Evolution in elements of the system affect each other both upwards and downwards in the hierarchy of systems and the evolution of the product cannot be explained without interaction with its context.

As observed by other authors (e.g. Eger, 2007a), the first products of a new type perform their function in a simple way, at rather high costs, and are developed using knowledge available at that point in time. These products first appear in a niche (Geels, 2002) catering to a small group of users. The first users to adopt such new, expensive products which do not yet function that well are referred to as 'innovators' (Rogers, 1962). It should be noted that not only professional inventors, engineers or designer (the 'producer-side) contribute to new products. A share of the renewal comes from what is referred to as 'lead users' (Von Hippel, 1986) who are known to experiment with products and tweak their designs to fit their needs more effectively. Known examples of users modifying products for their own use range from professional software to extreme sporting equipment (Von Hippel, 2005). Ideas for improving the product and/or the technology used to perform the functionality resulting in new designs are therefore generated by a wide community from both the producer and user sides. Over time newer, more advanced versions appear on the market that could not have been made if the first product of this family had not been developed because the required know-how and know-what would simply not have been available. When the first telephone was introduced, there was no intention for it to pave the way for the smartphone. Nevertheless, it is very unlikely that smartphones would exist today unless these primitive telephones had first existed[5].

Today's products, such as smartphones, are intentionally designed. This determination probably holds for most products. However, when one considers long-term accumulation of innovations, for example from early telephone to smartphone, one has to conclude that, although it can be argued that the small steps result from intentional actions, the long-term outcome (i.e. the direction of evolution in products over many decades) is not the result of a deliberate, continuously aligned set of actions designed to achieve

5 Although this is exactly the point to be made here, other possible historical development paths that could have led to the smartphone will not be further explored. This would simply take too much time. Besides, it is debatable if we should consider the smartphone to be an advanced telephone, or a successor of what was once referred to as a personal digital assistant (PDA), including a telephone function. Recent publications on the use of smartphones indicate that making calls is now the fifth most used function on smartphones (O2, 2012). Apparently making phone calls has lost its position as the basic function. It is a mere case of "one damn thing follows another" (David, 1985; p. 332).

a defined goal. Rather, technologies and products evolve autonomously by building on prior art in-and-under influence of a context, without a pre-set goal many decades ahead. And the telephone is by no means an unique example as will be shown in case studies of compact fluorescent lamps and child seats later in this thesis. New types of products do not appear out of the blue. Instead of standalone, serendipitous inventions or intelligent design, they can better be described as the result of accumulated, inventive work of many individuals fuelled by many knowledge domains and shaped by selective pressure from various contextual forces. Evolving products are therefore the result of a long selection process in which many designs are ousted and discontinued. Competing manufacturers and their development teams provide *variation* by developing many competing designs. After that *selection* and industry dynamics produce dominant designs. Further accumulation is then clarified by *retention* of know-what (specification) and know-how (manufacturing technology).

Several sources mention cases of similar inventions having been described and patents filed prior to the invention that is regarded as the start of a new type of product. As regards the incandescent lamp patented in 1879 by Swan in the UK, and in parallel Edison in the USA, 19 prior inventors of incandescent lamps are described, (Friedel & Israel, 1985, p.91). In the case of the telephone, four inventors preceding Gray, Bell and Edison are mentioned as being associated with the invention of the telephone (Wikipedia, 2015a). According to David (1985), Christopher Latham Sholes, known for the QWERTY keyboard, was preceded by 51 inventors of typewriters. Apparently, at a certain moment, time is ripe for a particular type of invention. No skyhooks are required. Once the fundament is laid we can wait for new (types of) product to emerge on it. The know-how and know-what required for the invention (the fundament) is available, and creative individuals, whether cooperating or not, envision new functionality and find novel combinations of available technology that produce the invention. People experiment with functionality and therefore cause further know-what development. Know-how developed for one domain influences other domains. Product evolution is a complex process shaped knowledge that evolves in a context. Prior art or the fundament explains the emergence of new and ever more complex and advanced inventions.

4.4 Subsystem Evolution: the Case of the Electric Bicycle

Bicycles evolved over time from a first primitive type into designs that dramatically improved in functionality and price (Eger, 2007a). The first man-driven vehicles with wheels appeared at the end of the 18th century and were used as a sort of running machine. Many different configurations

for cycling without feet on the ground using two, three or four wheels were proposed in second half of the 19th century. In 1870 James Starley and William Hillman patented a bicycle named 'Ariel' that would become very successful under the name 'high bi', also nicknamed the 'penny-farthing'. This bicycle consisted of a huge front wheel with solid rubber tires and paddles attached to it. This bicycle required substantial skill, daring and a fit constitution to ride. Consequently, only well-off young men that wanted to show-off used it in bicycle races. This bicycle was neither practical nor safe to ride and was not intended for use by ladies. The historical development of the bicycle is strongly influenced by the way in which different social groups perceived and used it. Human action literally shaped its evolution (Bijker, 1997).
The second half of the 19th century provided an environment where production became industrialised as exemplified by the many machining factories available at that time that produced sewing machines, typewriters, guns and other metal products. These provided enabling technologies like steel tubes that allowed for the improvement of existing product concepts, or the conceptualisation of new types of products. Various subsystems like the tube frame, air tire, spokes, chain driven rear wheel, and steering mechanism were developed independently. By 1884 John Kemp Starley (a nephew of James Starley) and William Stutton presented their new design for the 'Rover safety bicycle'. It comprised a same size front and rear wheel, a chain drive to the rear wheel and a diamond-shaped frame. By 1890 Dunlop introduced the air tyre that would drastically improve comfort on bicycles as well as their speed. This ousted the earlier bicycle designs and their restricted types of use. The bicycle became more user-friendly, allowing many different types of use, and the dominant design for the modern bike was born.

The evolution of bicycles and the introduction of dominant designs for different subsystems are pictured in Figure 8.4. It shows how, according to Bakker (2013), different design configurations for a bicycle evolved over time and led to the Rover Safety Bicycle as the first type using the configuration still used by contemporary variants. Based on this design contemporary variants evolved, such as the city, racing and folding bicycle. All variants are designed for specific types of use, also referred to as niches.

Although patents for electric bicycles like Figure 4.7 date back to the end of the 19th century, these variants did not thrive. In the 1990s enabling technologies became available with torque sensors, power controls and improved batteries (nickel-cadmium (NiCad), nickel-metal hydride (NiMH) and more recently lithium-ion polymer (Li-ion)). This led to a new design variant for the electric bicycle. Compared to the conventional bicycle it features two new subsystems, namely an electric motor to support

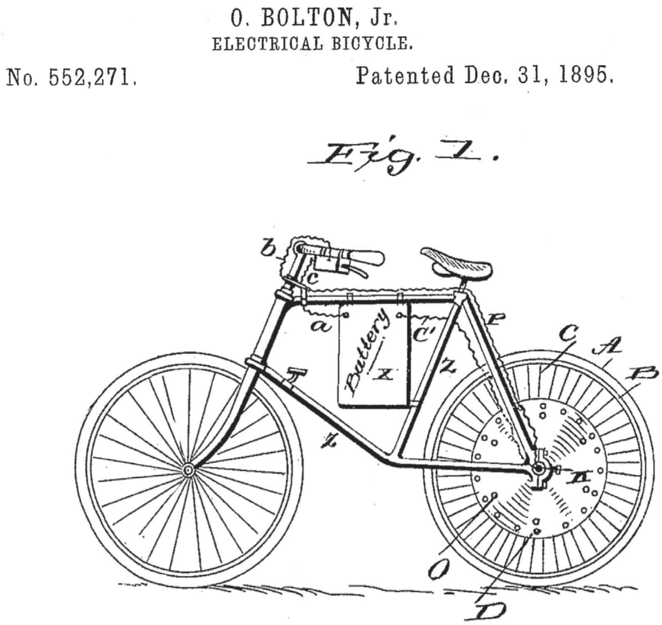


Figure 4.7. An early example of an electric bicycle patented in 1895. Figure reconstructed from patent document (Google patents).

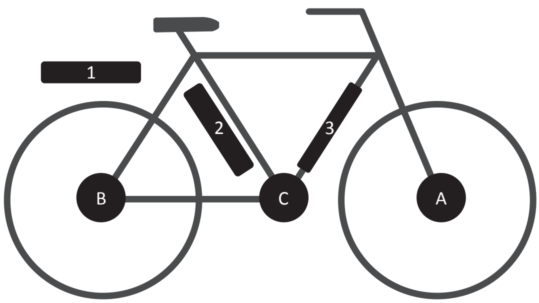


Figure 4.8. The electric bicycle for which designs compete for dominance in subsystems motor (A, B, C) and battery (1, 2, 3).

propulsion and a battery to provide energy. Initially, the new electric bicycle was met with scepticism and frowned upon as a product for the elderly. However, this changed over time with improving technology, more design variants and decreasing cost. The electric propulsion is used as a booster and enabled the range comfortably covered by bicycle to be increased and led to its frequent use for commuting. This resulted in competition across a transportation product class (mopeds, cars etc.). The sales of electric bicycles increased rapidly, making up 21% of new bicycles sold in the Netherlands in 2014, up from 10% in 2008 (CBS, 2015).

At the time of writing the electric bicycle is a typical example of a product design in the ferment phase with different competing subsystem designs. The technology cycle had not yet reached closure in terms of selection of a dominant design for its motor and battery subsystems (Figure 4.8).
The electric motor is currently offered in three positions; A-front wheel, B-rear wheel, and C-crank axle. All solutions have their pros and cons. Having the motor in the front wheel (A) is technically the simplest and cheapest solution. However, this position has a negative effect on the controllability of steering as the e-motor kick is a bit abrupt and pulls the front wheel through corners. It is known that this causes an increased level of fall incidents, especially amongst elderly people who sometimes have a reduced level of responsiveness. Placing the motor in the rear wheel (B) is more expensive as the construction of the rear wheel is more complicated. This position does not have the same drawbacks of the motor positioned in the front wheel. However, it requires a sophisticated mechanism to control the tension on the chain which, in turn, controls the e-motor. A third, more recently offered solution is to place the motor in the crank axle (C). This solution is the most radical in technology and design terms, as it requires the construction of the frame around the crank axle to be changed. This implies the use of a non-standard and therefore more expensive frame. However, the advantages of this solution are a more direct drive, robustness, positioning close to the centre of gravity and the use of normal rear wheels.

As far as the battery is concerned, three design solutions are offered; 1-beneath the rear carrier, 2-between seat tube and rear wheel and 3-in the down tube. Position 1 beneath the rear carrier is often used. It has the advantages that the battery can easily be exchanged and enables a simple construction. However, it is the highest position used for batteries and significantly increases the centre of gravity, which makes the bicycle less stable. The advantage of position 2 between seat tube and rear wheel is that it lowers the centre point of gravity, which increases stability. The battery can also be exchanged, although not as easily as in position 1. Besides that the frame needs to be adjusted in order to position a battery in position 2, as normally there is insufficient space available to place a battery here. Position 3 in the down tube also has the advantage that it lowers the centre point of gravity and thus enhances stability. A disadvantage is that the down tube needs to be designed to house the battery, which implies a frame that is not standard and therefore more expensive.

The different design solutions for subsystems of electric bicycles compete in an evolutionary race. Time will tell whether dominant designs for the electric bicycles will emerge. This example makes clear that subsystem evolution allows for major changes in a product family and that this evolutionary race is not confined to technological changes. How people use technologies and products shapes evolution in these technologies and products. Types of use for bicycles stretch and or change, made possible, for example, by the increased range of electric bicycles. Consequently, the influence might extend beyond the product family and affect the use of other types of products. It is also illustrative that many countries still struggle with the legal status of electric bicycles. Some variants with strong motors easily exceed 40 km/h which often means they are classified in the same legal class as mopeds.

4.5 Product Evolution

As described in Chapter 3, evolutionary metaphors have been used before to describe the process of innovation in domains such as economics, sociology, science policy, innovation studies, and industrial design engineering. The variety of schools of thought listed indicates the number of angles from which one can view the process of innovation. It cannot rightfully be described from a single perspective. However, the many perspectives on technological innovation that have been described form a fragmented landscape when it comes to exploring origins of products that contribute to the ever-increasing diversity of man-made goods. So far they have been explored from technology-centric and behavioural perspectives. A product-centric perspective appears to be barely used. What is more, a *'Theory of Product Evolution'* that explains how new (types of) products emerge appears to be absent. It may therefore come as no surprise that there is a yawning gap between journal-based academic literature on the topic of innovation targeting scholars, and practical tools and methods for those involved in the development of new products.

This thesis aims to bridge that gap and combine perspectives by proposing a *'Theory of Product Evolution'* that employs the Product Evolution Diagram (PED) in Chapter 6 as an analytical framework to study how new types of products come about and develop over time into a family of more advanced versions. The PED provides a graphical template for capturing the development history of products, revealing relationships in complex technological developments and their context, that would be otherwise difficult to see. By doing so, the PED contributes to a comprehensive view on the question of how new products emerge, develop through time and relate to the context in which they develop. As such it provides a tool to both those who study innovation and those who develop new products. Where most studies of innovation are technology-centric, this thesis takes a product-centric perspective. Instead of describing innovation as a technological process, it investigates how new (types of) products come about and develop into families of more advanced versions. To that end, the focus is on consumer products instead of technologies.

The usefulness of a product-centric perspective is exemplified by the way we describe these artefacts. In our daily language, the noun used to designate a specific product also assigns meaning and function to the construct. This is well illustrated by the case of the 'bicycle' product. We do not ride a system consisting of subsystems and components like tubes, spokes, chain, metal parts and rubber profile. Instead we ride a bicycle because this product has a meaning to us and fulfils a well-recognized function. It should be noted that this thesis does not explore the concept of 'meaning' in relation to 'products'. Scholars who do explore this topic include Desmet & Hekkert (2007) [6] and Verbeek (2000) [7].

4.6 Conclusion

Authors from many schools of thought have already illustrated that technological innovation can be described as an evolutionary process. However, a product-centric perspective is not commonly used. This makes it hard to comprehend how new types of products emerge. Given the aim of describing this process, a product is defined as a construct designed to realise a specific function.

Various authors have explained technological innovation as an evolutionary process. It has been argued that accumulation of know-how and know-what can explain continuity, diversity and complexity in man-made goods.

In literature the definition dominant design is used to designate a specific design that becomes a common denominator and is also associated with change in the nature of competition in an industry. Dominant designs can be designated at different levels: system, subsystem and component. It has been shown that products can be regarded as (parts of) systems. Change at top system level can cause changes in subsystems. Similarly, change at component level can invoke change at system level. This appears to be a consequence of the fact that technological evolution happens across different levels, and across different technological domains. Besides that,

6 Desmet & Hekkert (2007) have provided a 'framework of product experience' that recognizes three distinct components or levels of product experience (aesthetic experience, experience of meaning and emotional experience). According to this framework the meaning level allows an assessment of the personal or symbolic significance of products.

7 Verbeek (2000) proposes a theory of technological mediation that systematically analyses four different human-technology-world relations (embodiment relations, hermeneutic relations, background relations and alterity relations).

technological innovation is influenced by many factors that make up a context. This context appears to be part and parcel of the evolution of products. Describing evolution in products from a single perspective does not, therefore, reflect the complexity of the process.

Availability of *enabling technologies* (know-how) provided by one domain is a known cause for technological change in other domains. Technologies developed for one technology or product family are transferred to others and invoke further product evolution there.
New types of products first start to offer a basic function in a simple way, at rather high cost. The availability of a *basic function* (know-what) provides a point of departure to continue exploring and refining that functionality. Experimentation with new ways of using products leads to further evolution of the basic function (know-what) of products.
Different ways of providing a basic function compete within a product class. Evolution in one product family might influence another. All together, evolution in products can be described as a function of developing know-how, know-what and context.

Evolution in products is a complex process that takes place at different levels and has, up to now, been commonly described from different perspectives. It is assumed that describing technological innovation in general, and evolution in products specifically from isolated perspectives, does not promote a comprehensive understanding of these phenomena. Therefore a new analytical framework is needed that continues to build on existing schools of thought and integrates various perspectives developed. To that end, a *'Theory of Product Evolution'* is proposed that employs the product evolution diagram proposed in Chapter 6 as a tool to integrate perspectives and supports an understanding of the way new (types of) products emerge.

Lineage

5

5.0 Introduction

This thesis investigates how new (types of) products come about and develop through time into a family of advanced versions. This implies that we investigate how products *relate* to each other. To that end, the concept of *lineage* is explored.

The concept of lineage is derived from the world of life, where it is used to describe how a sequence of species evolved from a predecessor. This chapter provides an overview of methods used to map lineage, describes how they originated and then became used to explain how the world of life evolved. Lineage is also applied to elements of human culture as will be shown here. However, due to its different nature, depicting lineage for the world of made requires different rules to be applied than those used to map lineage for the world of life.

5.1 Theoretical Background and Embedding

A first attempt to view technical change as an evolutionary process can be attributed to the archaeologist Pitt-Rivers who, at the end of the 19th century, believed that the form of artefacts was based on small modifications of pre-existing versions. He collected primitive artefacts and organized them in a sequence of closely related shapes. As an example he organized Australian aboriginal weapons in a picture (Figure 5.1) in a way that makes them appear as evolutionary sequences radiating from a most simple version in the middle (Basalla, 1988, p. 19). Pitt-Rivers argued that every made thing could be placed within a sequence that could ultimately be traced back to the earliest human artefacts. Since the 1980s, evolutionary theories have been applied more prominently to technological change.

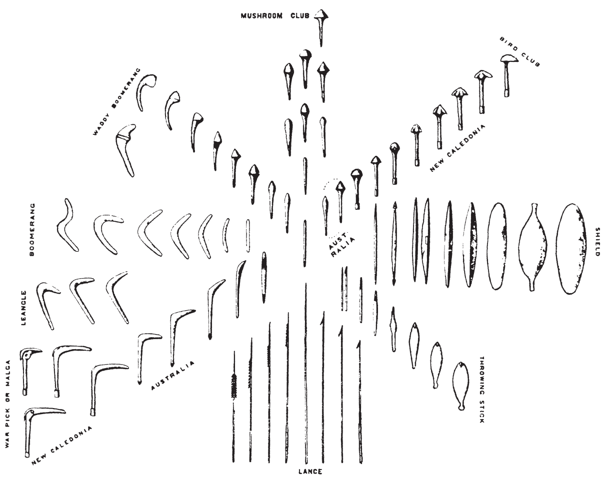


Figure 5.1. The evolution of Australian aboriginal weapons according to Pitt-Rivers (Basalla, 1988, p.19).

Basalla (1988) is particularly interesting for his extensive exposition of *'the evolution of technology'* as an explanation of how the process of technological innovation produces novel artefacts, and how society applies selective pressure to available artefacts. Basalla argues that technological novelty and diversity can only be explained if there is continuity in artefacts, just as there is continuity amongst species through lines of descent. As an historian of technology, Basalla speaks of artefacts rather than products or technologies.

Besides Pitt-Rivers and Basalla, there is a wide body of literature on innovation that is interesting to review in this context. Most of these authors analyse one particular element, such as the innovation adoption rate (Rogers, 1962), the locus of innovation (Abernathy & Utterback, 1975), periodical change in the speed of innovation (Anderson & Tushman, 1990), or the limiting effects of a development path (David, 1985). Evolution is often described as a process of variation, selection and retention. Evolutionary economics (Nelson & Winter, 1982) build on this view to describe how economies continuously change or innovate instead of being frozen in stasis and equilibriums. Another perspective regards evolution as a process of unfolding and creating new combinations which destroy the old ones (Schumpeter, 1942) resulting in paths and trajectories (Dosi, 1982). Geels (2002) notes that technological evolution starts with novel configurations in niches, which become influenced by a patchwork of socio-technical regimes which aggregate finally as technological transitions.

This thesis does not pretend to provide a complete new perspective on the process of innovation. Rather, it assumes that the process of innovation cannot rightfully be described from a single perspective and therefore builds on many previously published theories. Abstracts of those theories which are considered most relevant have been listed in Chapter 8 of *'On the Origin of Products'* (Eger & Ehlhardt, 2017). Prudently, the writers of this book do not claim that this collection of theories is exhaustive. This thesis presents the Product Evolution Diagram (PED) as a graphical narrative rather than prose to picture the developmental history of products. The objective of the PED is to map how new types of products emerge and develop over time into more advanced versions. The PED makes it easier to comprehend the interdependencies between technological developments, their predecessors and their context, which are indispensible for understanding how products evolve.

As an introduction to the use of the concept of lineage, as well as a visual means to represent it, this chapter explores its use in both biology and human culture and also discusses its limitations.

5.2 Mapping Lineage in Biology

In the 18th century, the Swedish biologist Linnaeus (1707-1778) started to systematically organise different types of plants based on their taxonomy, i.e. based on their shared physical characteristics. Subsequent naturalists further organised natural life according to the methodology that has since become known as the Linnaean taxonomy. Linnaeus proposed a formal system of naming referred to as binomial nomenclature, giving all species a name consisting of two parts, using Latin grammatical forms. The first part of the name identifies the genus to which a species belongs. The second part identifies the species within the genus. This naming convention is still in use today and is used to classify biological life in eight major taxonomic ranks[1].

Linnaeus based his work on similarities he observed in species (Figure 5.2, left side) and did not question the origin of species. According to the prevailing beliefs of the time, divine design explained the diversity of life found on earth. Lamarck (1744-1829) was a French naturalist and the first proponent of the idea that evolution occurred and then shaped life forms. His idea of *transmutation of species,* altering one type into another, received a lot of opposition from the scientific community of that day. However, it became an important step in the development of evolutionary thought. Today Lamarck is widely remembered for his theory of *inheritance of acquired characteristics*.

In the 19th century scientific knowledge continued to accumulate and fuelled the debate of the process that is responsible for the diversity of life. Charles Darwin (1809-1882) travelled around the world on HMS Beagle from 1831 to 1836. Darwin was puzzled by the geographical distribution of wildlife and fossils which he collected on his trip. He developed ideas to explain, by an evolutionary process, the origin of species and their diversity, which he had observed, as well as their relationship with fossils of extinct types (Figure 5.2, right side). Aware of the controversy his ideas would cause, Darwin waited decades before publishing his ideas until he was forced into action. To his dismay, Darwin was approached by his contemporary Wallace (1823-1913) who had independently conceived a theory of evolution through natural selection as well. Apparently the new theory on evolution was crystallizing in like minds. In order not to lose his claim to a theory of evolution by natural selection Darwin opted to co-author a paper with Wallace entitled *'On the Tendency of Varieties to Depart Indefinitely From the Original Type'*, published in 1858. Swiftly Darwin proceeded to publish his book *'On the Origin of Species'* in 1859, which describes how all

1 These taxonomic ranks from small to large are; Species, Genus, Family, Order, Class, Phylum, Kingdom, and Domain.

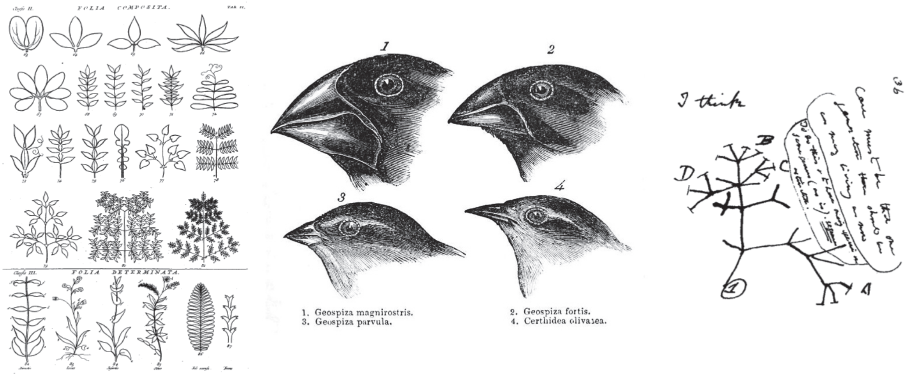


Figure 5.2. On the left a picture from a book by Linnaeus (1738) in which plant leaves are organized according to their physical characteristics. In the middle, the finches as Darwin encountered them in the Galapagos archipelago (1831-1836). On the right, a note by Darwin (1837) on his idea for the evolutionary tree structure.

species of life have descended over time from common ancestors (Bryson, 2003). Darwin's observation of finches that adapted beaks to types of food available on the different islands in the Galapagos archipelago became the archetypical example of adaptation by natural selection.

The ideas that accumulated in the *'Origin of Species'* remained controversial until the ideas from several fields of biology came together a century later in what is referred to as the modern evolutionary synthesis (Huxley, 1942). Koltsov proposed in 1927 that traits were inherited via a giant molecule made up of two mirror strands that replicate, using each strand as a template. Finally the shape of this molecule, with a double-helix known as deoxyribonucleic acid commonly abbreviated as DNA, was first claimed in 1953 by Watson and Crick[2]. The discovery of DNA marks the beginning of modern biology. The technique of analysing DNA coding allowed the genetic characteristics of species to be read and organised according to their degree of genetic kinship or genetic distance. This in turn allowed the construction of a so-called phylogenetic tree with a single root, which represents the first life on earth. This technique was pioneered by Woese (1928-2012) and led to the discovery that the Linnaean classification was incorrect. Woese and Fox discovered a new type of microbial life, which they

2 Although James Watson and Francis Crick receive almost all the credit for discovering DNA, they did not independently achieve this scientific landmark. First of all they built on work of many predecessors. Secondly they did not work in splendid isolation. Two other scientists, Rosalind Franklin and Maurice Wilkins were also active in UK academia looking for the structure of DNA (besides others in the USA). Franklin produced the first crystallographic images of DNA making their double helix structure visible. Unfortunately Franklin died early of cancer caused by excessive x-ray exposure during her work. After her death Watson, Crick and Wilkins were awarded the Nobel Prize for their discovery of DNA (Bryson, 2003).

called the archaebacteria or Archaea. Archaea did not fit in the traditional tree of life and Woese redrew the taxonomic tree to create a three-domain system. The new phylogenetic tree of life shows an overwhelming diversity of microbial life. It became evident that the vast majority of diversity is not found in large complex organisms, but rather in single-celled organisms. Many scientists have contributed to modern biology, our current view on the origin of species and the diversity found in biological life. Several individuals have been rewarded with eternal fame for their landmark scientific discoveries. However, it is clear that they could never have achieved these landmark discoveries if they had been unable to continue building on the work of others.

The way in which scientific insights regarding 'the evolution of organisms and the role played by genes' have developed over the last three centuries, is an excellent example of the way in which knowledge accumulates. Each new generation builds on the knowledge fundaments laid by previous generations, and from time to time overthrows knowledge structures that block the view to new horizons[3]. It is this accumulated knowledge that allows us to look beyond what was possible for previous generations.

5.3 Lineage in Human Culture

Our current view of lineage in biology does not hold for the world of artefacts. Whereas in biology a common code defining heredity has been identified, there is no such thing for artefacts. Although the meme has been postulated (Dawkins, 1976), memetics has not led to scientific breakthroughs as known in genetics. According to Edmonds (2005) memetics has not been very successful in providing *"explanatory leverage upon observed phenomena"*. Nevertheless, family tree structures have been successfully proposed to describe how human culture evolves. A prime example of human culture is found in languages. Linguistics, that is the study of human languages, has been using family tree diagrams for decades to show the historical relations between languages (see also Figure 5.4) in a single picture (Southworth, 1964). Such language trees show, for example, how German and English descent from common Germanic protolanguages.

Stemmatics is a branch of study concerned with analysing the relationship of surviving variant versions of a text to each other. Based on the analysis of transcription errors it traces back original versions, for example in religious texts. It uses cladograms (i.e. family trees) to depict lineage in text documents. Family trees have also been used in relation to man-made

3 This is what Kuhn (1962) describes as paradigm shifts, a watershed moment in the evolution of scientific knowledge.

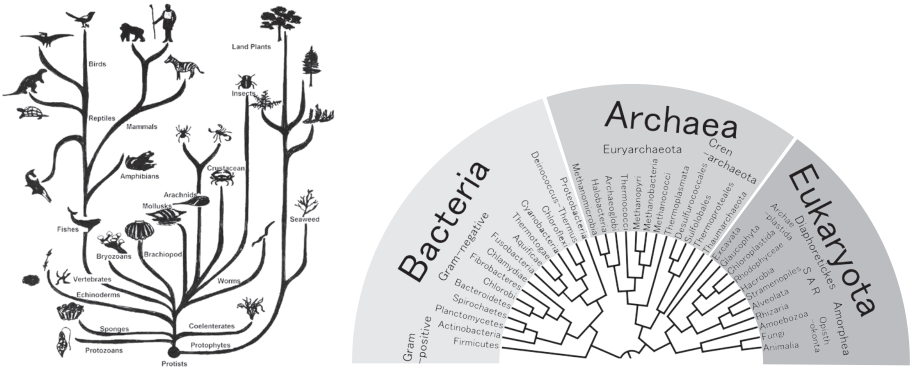


Figure 5.3. Two versions of the tree of life. Left: Linnaean classification (1738), right: Phylogenetic tree of life by Woese (1977) (Free after source: Wikipedia (2016a)).

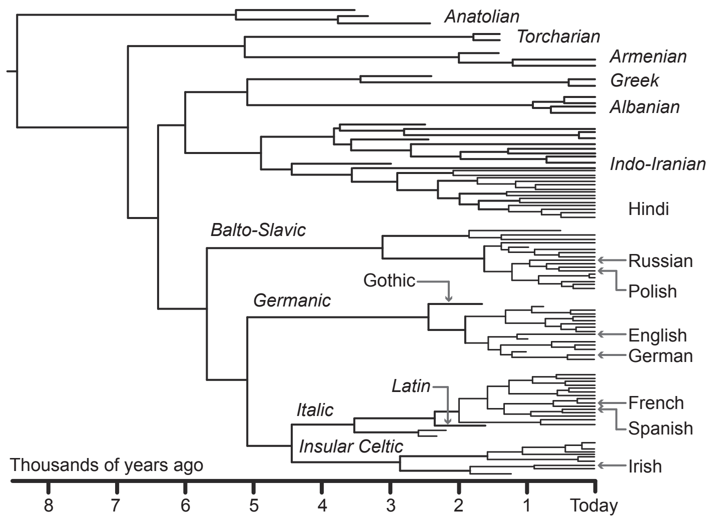


Figure 5.4. Language tree of Indo-European languages. Free after Gray & Atkinson (2003) and Bouckaert et al (2012).

things. Butler (1863; 1872) explored the idea that machines developed in a way similar to the evolution of living creatures by constructing an evolutionary tree that classified mechanical life. Kroeber (1948) used a tree of cultural artefacts with branches that not only split from, but also grow through, each other, symbolizing the contrast with biological descent (Figure 5.5). Steadman (1979; p. 158) shows a branching diagram that depicts the process of evolution of *standard types*[4] of artefacts (in this case knives) that was originally published by the architect Frederick Kiesler. The diagram departs from a 'present standard type' of the artefact via *variations* that

4 Note that the use of 'standard types' by Kiesler is equivalent tot that of 'dominant designs' as introduced by Abernathy & Utterback (1975), see also Section 3.3.1.

evolve to meet the needs for different purposes. Over time a 'new standard type' artefact evolves to meet new needs. A large category of discontinued branches are formed by what Kiesler calls *simulated* artefacts that are characterised by functional inefficiency and designated as insignificant deviations from the standard. Carlson (2000) described the stages in the invention of a telephone by Edison in a tree diagram (Ziman, 2000). A figure attributed to Sanderson has been used to map structural patterns in technological change (Ehrnberg, 1995). Valverde and Solé (2015) analysed evolution in programming languages and devised a method to map their relationship, claiming their study to be a first full systematic characterisation of phylogenetic patterns in a cultural evolving system beyond the human language case. Nevertheless, their paper does not reveal phylogenetic tree-like diagrams, similar to those known in biology, but rather dense webs. The analysis of Valverde and Solé takes account of a high level of horizontal transfer of information (i.e. between different programming languages existing at the same time) and reveals non-uniform rates of change in the evolution of programming languages.

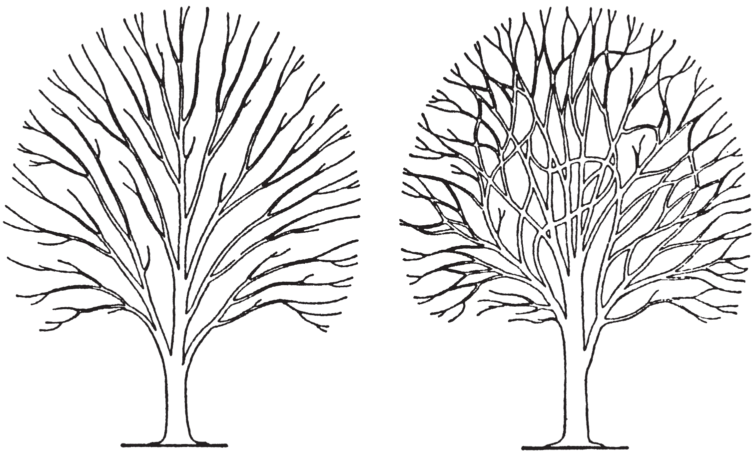


Figure 5.5. Kroeber (1948) proposed a tree of cultural artefacts (right), which has branches also growing through each other, in contrast with the tree of life in which branches once split do not intersect (left).

5.4 Conclusion

In biology, life was first classified based on appearance. In the mid 19th century, ideas on how different species might have evolved from a common ancestor were introduced and gradually became accepted. This led to a graphical depiction of biological lineage called the 'tree of life'. Only after the discovery of genes did it become possible to map evolutionary relations in terms of genetic distance in a so-called ‘phylogenetic tree’, which has no visual resemblance to the previous graphical depiction.

In human culture, lineage diagrams have become commonly used to depict how languages relate to each other, and descend from common protolanguages.
For human culture, the meme has been postulated as a unit of heredity analogue to the gene. However the meme and its study (memetics) have until now remained a philosophical concept.

It can therefore be stated that the use of tree diagrams is a commonly accepted method for portraying lineage relationships. Graphical depictions of relations have been used to portray human culture, in particular languages (both common human languages, and computer programming languages). However, given the lack of an irrefutable unit of cultural heredity, tree diagrams for human culture are not as unambiguous as the phylogenetic tree in biology.

Product Evolution Diagram

6.0 Introduction

Products are defined in this thesis (see definitions in Section 2.2) as constructs designed to realise a specific basic function. This is a narrower description than assigned to artefacts, a term commonly used by archaeologists for objects made by human beings. Products in this thesis are therefore a specific type of artefacts designed to realise a specific function and are a distinctive element of human culture. This thesis proposes a *'Theory of Product Evolution'* that holds that new (types of) products emerge as a nested hierarchy of system, subsystems and components on the fundaments laid by previous developments though a process of variation, selection and retention. This theory employs the Product Evolution Diagram to study how new (types of) products emerge. The Product Evolution Diagram makes use of the groundwork described in previous chapters and of the fact that evolutionary patterns are now commonly used to describe innovation processes (Nelson & Winter, 1982; Basalla, 1988; Anderson & Tushman, 1990; Tushman & Murmann, 1998; Murmann & Frenken, 2006; Dosi & Nelson, 2013), as well as the fact that evolutionary relationships in human culture and those between products are now near-universally accepted.

The Product Evolution Diagram (PED) is introduced below as an analytical framework for investigating how new (types of) products come about and develop over time into families of more advanced versions. The PED (Figure 6.1) uses a graphical template to relate different versions of a product as they appeared sequentially through time within the context in which its development is interwoven. The PED was introduced in previous publications[1] (Ehlhardt, 2012, 2013) and has since been extended and refined. The PED is used in Evolutionary Product Development (EPD) which is a design approach based on the observation that products typically go through a series of phases after their initial market introduction. EPD is a low-risk new product development (NPD) strategy. The PED comprises two key elements, namely the Product Family Tree and the ecosystem.

6.1 The Product Family Tree

The first element, called the Product Family Tree (PFT), is a tree-like diagram, similar to the family tree based on the Linnaean taxonomy known from biology. However, the PFT has some distinct differences compared to the biological family tree. The biological family tree draws heredity

1 A first publication analysing the evolution of Child Restraint Systems (Ehlhardt, 2012) introduced the Product Family Tree and the Ecosystem (see also Section 7.1). Subsequently, the name Product Evolution Diagram was devised with the aim of connecting both elements in a single analytical framework. This name was formally introduced at the 15th International Conference on Engineering and Product Design Education (Ehlhardt, 2013).

relations from current species towards the first form of life according to the Linnaean classification. The more modern phylogenetic tree allows for unambiguous definition of lineage relationships (which the Linnaean family tree could not). This unambiguous lineage description is made possible by genetic analysis of the genome. In the world of made, such unambiguous lineage analysis is, to current understanding, not possible. Memes have not provided an explanatory leverage in the world of made equivalent to that which genes provided for the world of life. Product Family Trees depict a family of products, starting with a first-of-a-kind, a product that can be regarded as the beginning of a new family of products. Product Family Trees show how over time product variants have been introduced. Typically, when a product family is in the segmentation phase, the PFT has different parallel branches that each cater to different segments.

The Product Family Tree is intended to be an analytical tool, which can be used to reconstruct how new (types of) products are created. To that end it includes drawing conventions or symbols that designate markers in the evolution of a product, and so helps to read the Product Family Tree, similarly to symbols on a technical drawing or road map (Phaal, Farrukh & Probert, 2004). Examples of markers these symbols designate are a dominant design, the end of a branch and forking in a product family. The Product Family Tree as part of the product evolution diagram is intended to support a better understanding of innovation processes in terms of how new types of products emerge and develop into families of more advanced types. For practical reasons, the PFT depicted in Figure 6.1 is oriented horizontally from left to right while biological family trees are traditionally oriented vertically from bottom to top.

The PFT maps the main relations between products through time, connecting a new type of product with later ones as lines of descent. The evolution of products is not bound by strict and unambiguously assignable lineage relationships, as are common in phylogenetic trees used in biology. It is based on progressing know-how and know-what. This accumulation does not restrict to a particular product lineage. Rather, it is a common pool of knowledge from which many product lineages draw[2]. A new type of

2 As noted before (Valverde & Solé, 2015) horizontal knowledge transfer explains for a large portion of evolutionary influences on a product. If it were impossible to measure a unit of cultural heredity, analogue to measuring genes (as some might envision with memes), it would surely also be impossible to provide information that would allow the constructing of a tree as clearly and unambiguously as the phylogenetic tree by Woese. Instead we should expect a dense web, where the amount of interlinking is a proxy for the level of relatedness. This means a particularly high number of links between products in the same family. A lower number of links can be expected between products in a same class. Again, a lower number of links between products using the same technology.

product constitutes a new 'construct fundament' on which a product family evolves. Dominant designs constitute successful incarnations in a lineage of constructs. New types of products that give rise to new product families are rooted in prior accumulated knowledge, although, as noted, lineage is not strict and unambiguously defined here as in biological heredity as we have no equivalent of the gene for products. Consequently, PFTs cannot unambiguously be combined into a single continuous branching tree, starting at the earliest products (stone stools) through to present-day products. Instead, a PFT is intended to be an analytical instrument to map how products evolve from a new type of product into a product family. It is therefore a simplified representation, limited in scope to a single product family and intended to explain the process of establishment of new types of products and their further evolution into a family of products. Various PFTs connect to other earlier products or technologies via their roots.

6.1.1 Patterns Revealed by the Product Family Tree

The purpose of mapping a PFT is to provide a concise graphical overview of the historical development of products. The PFT reveals patterns in this historical development.

First, it identifies that any developed product builds on previously developed products or accumulated knowledge. At least a share of the elements (know-how and know-what) required to develop a new (type of) product is available at the time of conception. These elements are not all invented at the same time for this particular product. The technology used for the invention and or primitive versions of a new type of product are called antecedents or *'roots'*. The new type of product emerges, as it were, on top of the fundaments of pre-existing knowledge.

Second, a new type of product commences with a first design somewhere in time that marks the beginning or first node of what is here called the *'base'*. Over time new variants appear, with their success being defined in commercial terms by the volume produced, the market share achieved and/or the profit generated. Successful designs that become widely adopted and change the nature of competition in the corresponding industry are referred to as dominant designs (not necessarily the technically superior ones) and, for a period of time, determine dominant branches in the PFT. Dominant designs are marked in the Product Family Tree with a square node (■) to differentiate them from other designs that cannot be regarded as dominant designs. Any other product marked in a PFT that is not defined as a dominant design, is designated as an open round node (○).

Third, not all products are continued. The competing and/or incumbent designs that are ousted are marked with *'dead ends'* in the tree diagram. For example, rooted in earlier professional formats, Betamax and VHS videotape formats were developed and marketed in 1975 for the consumer market. Competition led to the dominance of VHS, although the video quality was known to be inferior to Betamax. Over two decades VHS was the standard for video recording to be ousted by DVD in 2000. The recorders and tapes became obsolete. Tape recording became a dead end in their PFT of video recording.

Fourth, product families often develop into various dominant designs that cater to various segments of the market. In the PFT this leads to *'branches'* or variants that together form a family of related products that exist at a certain moment in time, addressing different needs or segments. This branching pattern, revealed by the PFT, is associated with the segmentation phase. The products, catering to different segments in the market, have a level of sophistication in terms of know-what or specification that was not conceivable when the first-of-a-kind of new type of products was designed. An example is provided in Chapter 7, describing the evolution of child restraint systems (Ehlhardt, 2012), which over time developed into a family of products addressing different segments, which are distinguished as age, weight or length groups.

Fifth, last but not least, the combination of PFT and ecosystem reveals how, over time, the context and the evolving product influence each other. The ecosystem is part and parcel of the evolution of products. The case of the evolving child restraint system showed how related legislation developed over the course of the historical development of the product and played a prominent role in the evolution of the product family. This legislation was refined after better performing products appeared, leading to cycles of refinement in both product and legislation. The availability of both product and context was instrumental to the learning cycles and led to knowledge accumulation materialized in advancing products.

6.2 The Ecosystem

The second element in the PED is called the Ecosystem and is used to map contextual influences that affect the evolving product. In the biological realm, an ecosystem is defined as 'a community of living organisms in conjunction with the non-living components of their environment (things like air, water and mineral soil), interacting as a system' (Wikipedia, 2016b). Speciation, the process evolutionary process by which new biological species arise, is driven by isolation or differences in interaction with the environment in which species interact as part of a system. It appears that the environment in which products interact as part of a system also influences the evolution of products. Basalla (1988) frequently refers to environmental, social, economic and political conditions that influence the evolution of technologies. However, he does not provide a method to systematically map influences on the development of products. For this purpose, use of the PEST method (Chapman, 2006) is proposed here. PEST, an acronym for Political, Economic, Social and Technical, describes a framework used in strategic management studies to scan for factors in the macro-environment that *exante* will influence further development of the topic of study.

- Political covers, for example, product safety laws (such as for CRSs) or legislation used to ban the incandescent lamp.
- Economic covers, for example, rising oil prices, high prices for copper, falling purchasing power in times of economic crisis or increasing purchasing power in rising economies.
- Social covers, for example, demographic shifts such as retiring baby boomers or increasing urbanization.
- Technical, the most obvious perspective in this context covers inventions such as the transistor and standardization such as USB3.0 or WiFi. Commonly they influence many other PFTs than the one they were originally developed for. They are referred to in this thesis as *enabling technologies*.

The author has already used the PEST method successfully in a strategic study that explored the future of 'End-of-Life Vehicles' supply to scrap yards for Auto Recycling Nederland (PA Consulting Group, 2009).

Including an ecosystem in a PED allows the juxtaposition of a context to a PFT and lists factors in time that shape the evolution of products and technologies. Chapter 7 elaborates on two case studies that, for example, show how legislation in completely different products is an important element that shapes the development path of products.

6.3 Timeline

The timeline in the PED relates the product evolution to the context in which developments took place. By doing so, the PED provides an inclusive overview of the development history of those products. The graphical narrative provided by the PED helps to visualize relationships between complex technological developments and contexts that shape product families. Without that it would be much harder to grasp those interdependencies that are essential for an understanding of historical

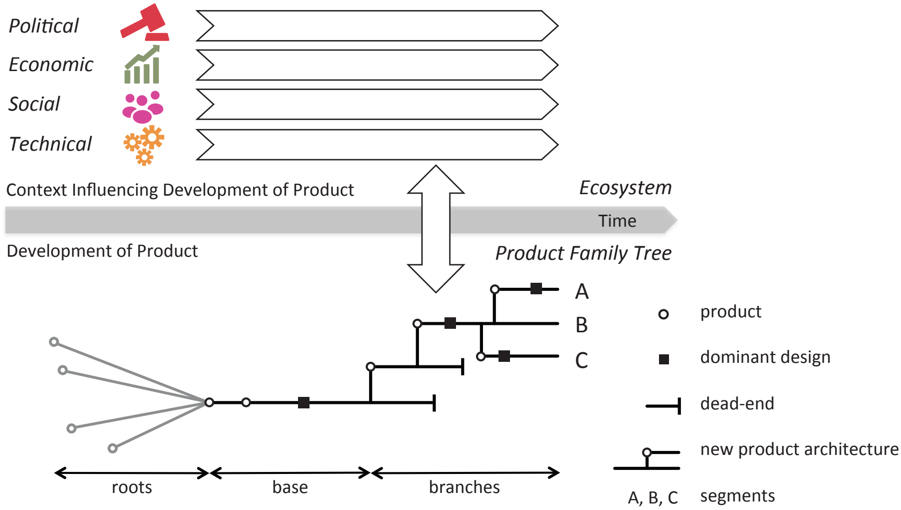


Figure 6.1. The Product Evolution Diagram.

developments: this is a clear case of *'one picture telling more than a thousand words'*. As such, the PED promotes a more comprehensive understanding of how products emerge and develop over time into a family of more advanced versions. The PED builds on insights from different schools of thought and aims to integrate them in an analytical framework as an *'appreciative theory'* (Nelson & Winter, 1982; Geels, 2002). The PED is offered to students Industrial Design Engineering as analytical framework providing graphical narratives in a product development course. From work of students, it can be concluded that the PED is easy to understand and apply (see Chapter 8).

6.4 Use of the Product Evolution Diagram

In new product development processes many tools and methods are used to provide structure and direction to designers as well as to reduce risk. Depending on 'newness' of the product, the type of product, the reason for developing a new product and the stage of the development process, different tools and methods are used. Roozenburg and Eekels (1995) provide an overview of product design fundamentals and methods. For example, the ideation stage commonly uses formalised creative processes like brainstorming or TRIZ[3]. In the case of an existing product that requires to be improved, Value Engineering can be used as method to improve the balance of function, performance, quality, safety, and cost (SAVE, 2015).

3 TRIZ or the 'Theory of Inventive Problem Solving' is a method for problem-solving, analysis and forecasting derived from a study of inventive patterns in patent literature, developed by Genrich Altshuller (Altshuller, Shulyak, & Rodman, 1999) and associates.

New product development (NPD) commonly starts with market research to investigate what features make it likely for a new product to be successful on the market. The findings of such research are embodied in voluminous reports full of text, numbers and graphs. Designers then have to get to work. According to Sleeswijk Visser (2009) conventional research reports do not meet designers' creative thinking needs. Therefore, a frequently-used method for making market research information easier to grasp for designers is the use of *'personas'* that enable the designer to achieve empathy with the user of the products or services being designed. These are fictional people created for the purpose of representing information on users to whom the design is targeted. The idea of using personas was introduced by Cooper (1999) and then further elaborated towards theory and practice (Pruitt & Grudin, 2003; Pruitt & Adlin, 2010; Miaskiewicz & Kozar, 2011). Currently the use of personas is embedded in the design processes of large and small companies alike (Sleeswijk Visser, 2009).

According to the author's observations during lectures, students following the course Evolutionary Product Development at the University of Twente were unfamiliar with concepts of Science and Technology Studies (STS) or other scientific schools of thought that explore the process of innovation. Furthermore, these design students found it difficult to understand the complex relationship between technological developments that lead to new products and the context in which they take place. However, it is known that designers in general are used to working with personas (Sleeswijk Visser, 2009). The Product Evolution Diagram is elaborated as a method that provides a means to represent the complexity of technological developments over time, as well as their interaction with a context, in a single graphical narrative. Similarly to how personas are used to translate the results of market research into concise design briefings, the Product Evolution Diagram can be used as a concise visually-oriented means to describe how new types of products come about and develop through time. The Product Evolution Diagram can function as a synopsis of the historical background designers work on and can also offer designers an overview of the present market and developments in the ecosystem that helps them to explore opportunities or new niches for future products.

6.5 Constructing a Product Evolution Diagram

A thorough understanding of the historical development is required to draw a PFT. Sources like patents provide a detailed description of the innovative art of the invention concerned. Patents also contain a clear time stamp and often references to prior art, which means earlier, related inventions. Patents are becoming easily accessible via the Internet and reviewing them

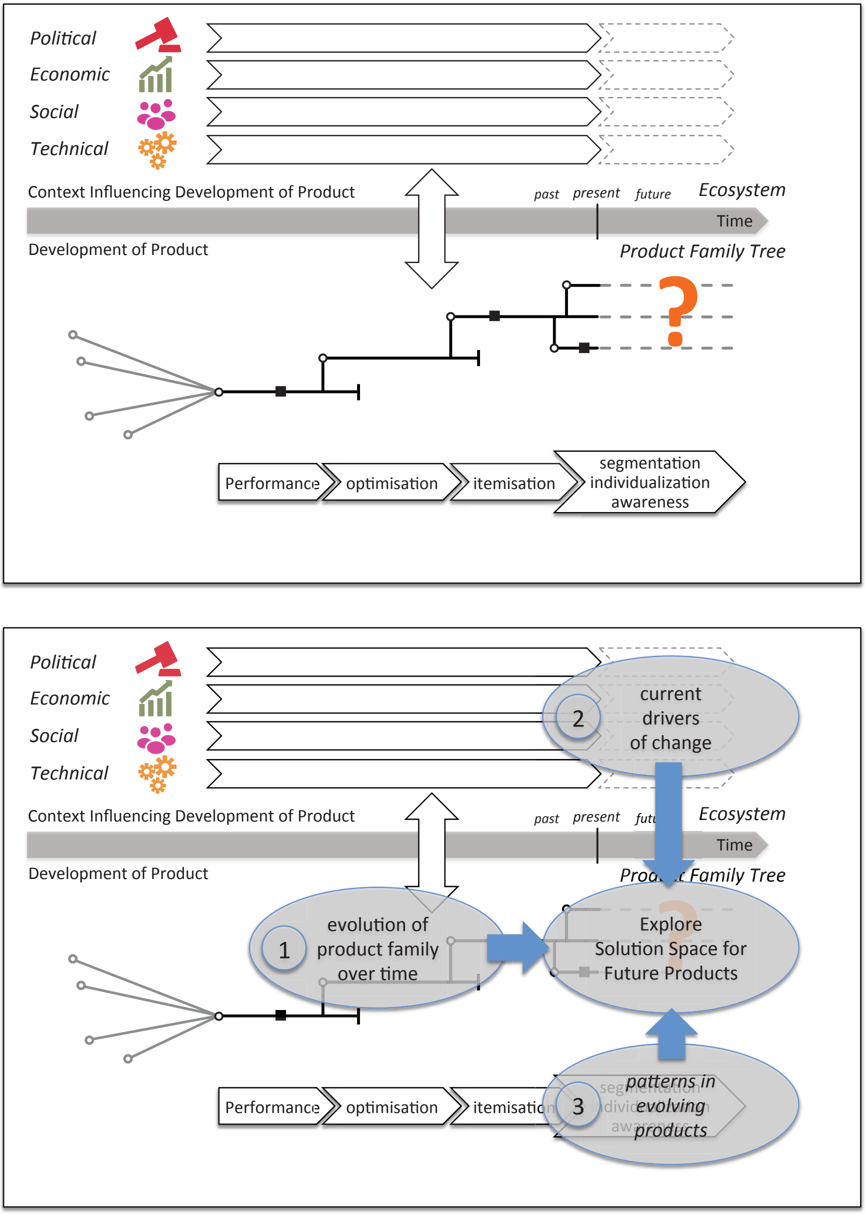


Figure 6.2. Using the PED to explore the solution space for future products.

is part of the standard homework of any new product development team. A lot of products are subject to legislation via which the development can be traced and – importantly – upcoming changes identified. Depending on the type of product, books, encyclopaedia like Wikipedia, catalogues or consumer guides provide further historical (or more up-to-date) information. The collected information can be used to construct a PFT. The points at which branches split are markers for changes in addressed user segments, technology, product architecture and/or dominant designs that have to be identified in the upfront analysis. The level of familiarity cannot be calculated as in phylogenetic trees that are constructed on the basis of genetic distance. Constructing a PFT is a trial-and-error process (like any design), in which various types of diagrams can be used. While collecting information that is used to construct the tree-like diagram, one will come across information about the ecosystem or environment that influenced the development of the product. There are tools and methods that can be used to make sure different relevant perspectives are included such as PEST (see also section 6.2).

All these elements can be used to explain past developments, as well as list factors that are current drivers for change in a product class. The information of the product evolution and ecosystem is combined into one picture separated by a timeline.

6.6 Extrapolating Developments

Any development in products builds on previous developments. For that reason, understanding how a product came about, what influenced the development in the past, and what will influence its future are instrumental when developing a successful next-generation product. Figure 6.2 shows how the PED can be used to explore the solution space for future products. First one maps the Product Family Tree of a product or technology in focus. Secondly, one needs to investigate which current context factors drive change. Research into historical drivers of change for the product in focus helps us assess the extent to which current drivers of change are likely to affect future versions of the product. As a third step we examine typical innovation patters.

A warning should be given here since we must be very careful about predicting the future. Many cases are known of respectable academics who reflect on the future potential of a certain product or technology only to find themselves faced with predictions that turn out to be false.

A first example of a prediction that turned out to be false was made by Basalla (1988, p.185) who remarked the following about the home computer. *"Of course it is much easier to identify fads of the past than to recognise those we have so recently foolishly embraced. By the mid-1980s the home computer boom appeared to be nothing more than a short-lived, and for some computer manufacturers, expansive fad. Consumers who were expected to use these machines*

to maintain their financial records, educate their children, and plan for their family's future ended up playing electronic games on them, an activity that soon lost its novelty, pleasure, and excitement. As a result a device that was originally heralded as the forerunner of a new technological era was a spectacular failure that threatened to bankrupt the firms that had invested billions of dollars in its development".
The line between 'home' and 'business' computers disappeared once the IBM Personal Computer compatibles were introduced. These Personal Computers now commonly referred to as PCs have become ubiquitous in home environments and (put euphemistically) have drastically changed business environments. Obviously, Basalla would have made a better case if his predictions had been attenuated.

A second example is the prediction made by Van den Hoed (2004, p.145) who remarked the following on the development of Fuel Cell Vehicles (FCVs). *"…, concerning technological preferences, the case shows how in a period of 10 years the expectations concerning FC technology have shifted from 'not considered' to 'preferred technological solution' to achieve sustainable mobility. The focus on FCV was at the expense of BEVs (Battery Electric Vehicles)".* At time of writing this thesis FCVs seem to be further away than predicted by Van den Hoed. HEVs (Hybrid Electric Vehicles) like the Prius manufactured and marketed by Toyota and BEVs like those by Tesla have taken at least a significant lead over FCVs.

These examples of predictions-not-come-true should serve as an illustration of the caution that needs to be taken when predicting the future. This especially applies to predictions made with regard to developments further into the future. After all the future is obstinately difficult to predict. Therefore, it is noted here that the purpose of the PED is to provide a canvas on which the historical development of products can be painted and related to the context in which it evolved. Its first purpose is to support a comprehensive understanding of how particular products came about and only secondly to perhaps provide clues for directions in which evolutionary next versions of products might develop.

6.7 Conclusion

Building on the groundwork of many scholars who make use of evolutionary patterns to describe innovation processes, a *'Theory of Product Evolution'* is proposed that holds that new (types of) products emerge as a nested hierarchy of system, subsystems and components on the fundaments laid by previous developments though a process of variation, selection and retention. This Theory of Product Evolution uses the PED as an analytical framework for investigating how new (types of) products come about and develop over time into families of more advanced versions.

The PFT has been proposed as a method to map the historical development of a product family over time. The PFT reveals a number of patterns that are characteristic for the way new (types of) products come about and evolve into a family of advanced versions.

The ecosystem has been proposed as a means to map the elements from a context that influence the evolution of a product. The ecosystem is part and parcel of the evolution of products. The PFT and ecosystem are linked by a timeline in a PED. The PED is particularly useful to grasp the interdependencies between an evolving product and the context.

Now the PED has been proposed, it will be used in Chapter 7 to analyse the development history of two products in retrospective case studies. Then Chapter 8 will reflect on the use of the PED in an educational setting.

Retrospective Case Studies

7

7.0 Introduction to Case Studies

Availability of information is a prerequisite for case study research. At the start of this PhD a complete archive was created of all the volumes of *Consumentengids*, the Dutch consumer guide. An index of all product test published since 1959 was also built. The following sub-criteria were used to identify cases which would be suitable for study if sufficient information were to be available: 1) the tests published need to cover at least two decades, 2) at least ten tests need to have been published. Filtering the index produced a shortlist of products that met these information availability sub-criteria. It is noted here that the products selected here emerged after the industrial revolution. Chapter 9 further elaborates on the use of consumer guides for this type of research including limitations experienced.

Differences in nature of cases studied make for interesting research. Therefore, two very different products have been examined here. The first product selected as case study was a Child Restraint System[1] (CRS), a product that evolved to meet growing in-car safety needs. It appeared to be not possible to express the development of price-performance over time in the case of a CRS. A reason for this is the absence of a single unit of performance for CRSs.
This led to a search for another product in the shortlist for which a known unit of performance was available which allowed the mapping of the price-performance development over time. The Compact Fluorescent Lamp (CFL) appeared to be an excellent candidate for a case study including price-performance development because it was introduced to meet energy efficiency and therefore needed to express its economic performance. The performance of lamps producing electric light is expressed in lumen per Watt. Both performance and price records are available for over two decades, therefore making it possible to map the price-performance development over time.
At the time of introduction it was argued that a superior price-performance ratio would soon allure consumers to adopt the CFL and so oust the incandescent lamp. Interestingly, the case study shows this assumption (Bouwknegt, 1982) to have been incorrect. The Product Evolution Diagram is used as an analytical framework to show the value of integrating very different perspectives into a single picture with the objective to explore how this product came about and further developed.

1 The case study on CRS was published before in the Journal of Design Research (Ehlhardt, 2012). The version published here in Section 7.1 is supplemented with additional insights gratefully building on the work of Reigersman (2014a) as well as new insights from the author of this thesis (e.g. Figure 7.1, Figure 7.15 and the signs and symbols used to mark elements in the Product Family Tree).

Both cases are told in a mosaic of elements: developing technologies and products, standardisation, societal change, legislation and many more. This was required to place the emergence of the products in a broader perspective. The Product Evolution Diagram is used as a canvas on which the mosaic elements are fitted together to form a graphical narrative. Both story lines are completed with data quantifying the development.

7.1 Child Restraint Systems

7.1.1 Introduction

This section analyses the development history of Child Restraint Systems (CRSs), also known as child car seats, as a retrospective case study. The CRS is a product that is used while nested in another type of product: the car. It evolved from a product intended to restrain movement towards one intended to enhance child safety. The evolution of CRSs is inextricably linked to the evolution of cars and, in particular, car safety systems and safety perception and expectations. The changing perception of safety in cars is reflected in the changing function of CRSs, as will become clear in this chapter. The story of the evolution of CRSs from a first child restraint seat into a family of advanced safety seats tailored to different segments and distinguished by age, weight or length groups, as well as a variety of factors from the ecosystem that influenced its evolution, is summarized in a Product Evolution Diagram.

7.1.2 Availability of Cars and a Niche allowing CRSs to Emerge

The presence of cars was a prerequisite for CRSs to emerge as a new type of product. The first cars with an internal combustion engine appeared in 1807. For about a century cars still looked like horse carriages, but just with an engine instead of a horse[2]. These predecessors of today's cars were highly exclusive products. The average young family could not afford them. There was little traffic, the average speed was low and in-car safety was not a major concern. Consequently, there was no need for a product that provided safety to children travelling in cars. It took 100 years before large-scale production of cars started. Henry Ford began mass-producing cars with the Model T that came onto the market in 1908. Figure 7.1 shows the development of car ownership in the USA and Western Europe[3]. The USA was the first market

2 This is also referred to as the horseless carriage syndrome, an expression used to describe how new types of products that, at first, strongly resemble their predecessors. Time is needed for own designs to evolve.

3 The graph of car ownership development in Western Europe is based on averages of figures of car ownership development in Germany, France, Italy, UK and the Netherlands. The West European countries show different car ownership development rates through time. However, compared to developments in the USA, all West European countries show car ownership development rates that are quite similar.

on which large-scale car ownership developed, following the introduction of the Model T. In the 1930s the level of car ownership in the USA rose to over 200 vehicles per 1000 people.
The mass production of cars meant that they became more affordable, and the number of cars on the road therefore increased, along with the problems we associate with cars today, such as congestion and accidents. Increasing car ownership dramatically increased our mobility and, with that, the way we organize urban and rural areas changed. Cars slowly became a standard feature of everyday life and this created a niche[4] for CRSs to emerge.
In Western Europe it took four more decades to reach a similar level of car ownership as seen in the USA of the 1930s (Staal, 2003). This explains why the CRS models first appeared in the USA and not in Europe.

7.1.3 How CRSs Came About

7.1.3.1 The Root Period of CRSs

Today, parents are legally required to use Child Restraint Systems (CRSs) if they carry small children in their car. This has not always been the case. The first known example of a product used for restraining small children in cars dates back to 1898 (Smith, 2008). According to Smith, 'the device was little more than a drawstring bag that would attach to the actual car seat'. The device did not look like the products that we know today. It was not intended to prevent injuries during accidents, but to restrain children and so keep them from falling or getting up from their seats when the car was moving. The first CRS products resembled existing child seats and rockers, commonly used to comfort babies.

In the 1920s car ownership rose to over 100 vehicles per 1,000 people in the USA and sources (Smith, 2008) refer to the production of CRSs. Patent files show that various inventors came up with ideas for CRSs. In 1928 a child seat was invented by B. Coleman Silver (Figure 7.2) that looked similar to the free-hanging CRSs that were still common in the second half of the 1960s and early 1970s. These products were intended to keep the child from moving around. Child safety was not the main concern. Nevertheless the product was brought onto the market by suppliers like the Bunny Bear Company, which started to manufacture CRSs in 1933. In the 1930s car safety belts became more prevalent. Slowly but surely, safety in cars started to become an issue, but not yet as far as child passengers were concerned.

4 Geels (2002) also uses the term 'niche' as designation for the micro level on which radical innovations occur that eventually may lead to technological transitions that ultimately manifest on a macro level.

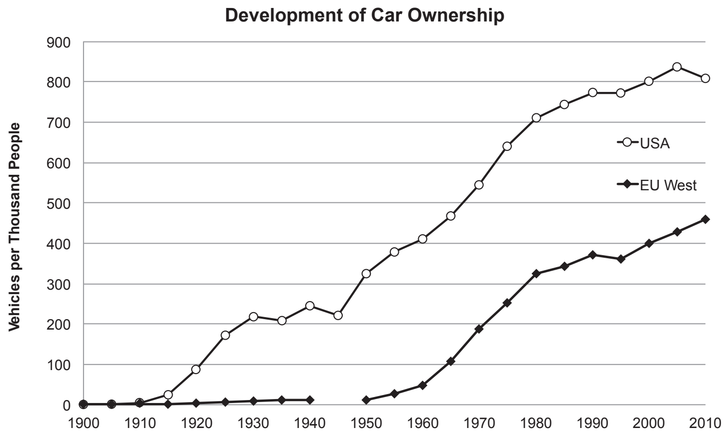


Figure 7.1. Development of Car Ownership in the USA and Western Europe (Staal, 2003; Davis, Diegel, & Boundy, 2003).

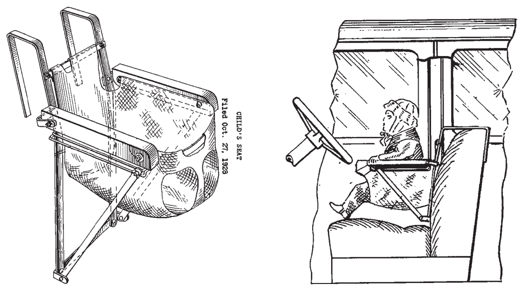


Figure 7.2. Child's seat invented by B. Coleman Silver in 1928 (Google Patents).

7.1.3.2 Introduction of Car Safety Features Influenced Child-Passenger Safety Expectations

The first safety belt patents date back to the nineteenth century. It was the Swedish inventor, Nils Bohlin who, in 1959, came up with the modern three-point seat belt that is now a standard safety device in most cars. Volvo introduced the lap-and-shoulder belt in 1959. As Volvo wanted to encourage the saving of lives, it decided not to patent this belt (Kelley & Littman, 2005) but the company did support the idea of it becoming standard safety equipment for adults in the 1960s. Crash tests proved that these belts saved lives. However, they were met with resistance. Passive safety features such as three-point belts, self-applying belts, front and side-impact air bags, plus active safety such as Anti-lock Braking System (ABS) and Electronic Stability Control (ESC) increased the level of protection for adults. These types of safety equipment became available from 1966 to 1995 (see also Figure 7.15). The crash safety performance of new cars was tested by the European New Car Assessment Programme (Euro NCAP) and was made transparent to consumers via a star rating system. Although the above-mentioned developments cannot clearly be categorised as enabling technologies, these measures increased the safety consciousness and expectations of consumers and so paved the way for safety expectations for CRSs.

7.1.3.3 The First Safety-Focused Child Restraint Systems Appeared in the 1960s

The first CRSs which were truly focused on safety were developed in the early 1960s. In 1962 an English couple named Jean Helen and Frederick John Ames invented a padded seat that was strapped against the rear passenger seat (Figure 7.3). The child was restrained by a five-point-belt harness that slipped over its head and shoulders and fastened between the legs. The CRS itself was anchored to the car seat with belts. According to the description in the patent, the object of the invention was "to provide a child's safety seat for vehicles which affords protection for the child comparable to that provided for adults by safety belts and harnesses[5]" (Ames and Ames, 1964). The first safety-focused CRS was not a legislation-driven product. At that time, relevant legislation was simply not available. The inventors saw an opportunity to improve the safety of children in cars, which was not provided by the belts designed for adults or the CRSs available thus far.

In the same decade Bertil Aldman, a Swedish professor in biomechanics, was also working on child safety and became inspired by seats used in the Gemini space programme that were shaped to distribute G forces evenly across astronauts backs. Aldman first tested a prototype of a rear facing CRS in 1964 (Figure 7.4). In 1972 the first rearward facing CRS was launched in Sweden (Volvo, 2014).

In the USA, the Ford Motor Company introduced the Tot Guard in 1968 (Figure 7.5). Consumer Reports reviews this product in 1972 as ACCEPTABLE-fair-to-good and the General Motors Infant Carrier (of which no pictures are available) as ACCEPTABLE-good.

7.1.3.4 Unsafe CRSs remain on the market

In 1963, the German manufacturer Storchenmühle launched their first 'Niki' CRS (Figure 7.6) onto the market. The product architecture was still the same as that of Coleman Silver's CRS from more than three decades earlier. The CRS was attached to the car seat by means of a hook. Obviously, this CRS would not remain in place in the event of a collision and consequently the child passenger would be seriously hurt in the event of a crash. This CRS type was tested and found to be very unsafe during collisions in the 1970 issues of the Dutch consumer guide (Consumentengids, 1970). All nine CRSs 'hook over bench backrest' types were rated as 'serious injury foreseeable' in the event of a slight collision. For that reason the 1974 issue did not include this type in the test (Consumentengids, 1974). Nevertheless,

5 Note that the basic function is redefined to 'providing safety', whereas before the basic function of the first CRS was 'restraining child'.

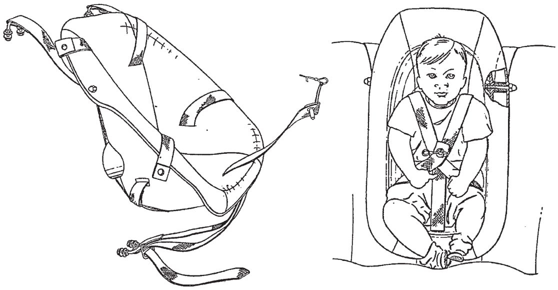


Figure 7.3. The Ames 'children's safety seat', patent application date: 22 November 1961 (Google Patents).

Figure 7.4. Prototype of a first rearward facing CRS tested in 1964 (Volvo, 2014).

Figure 7.5. The Tot Guard introduced by the Ford Motor Company 1968 (Mentalfloss.com, 2013).

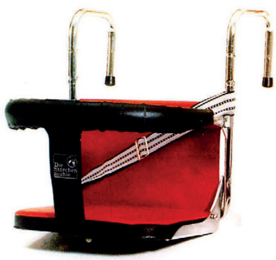


Figure 7.6. Storchenmühle CRS type 'Niki' introduced in 1963 (Dorel, 2005).

Figure 7.7. The Storchenmühle CRS 'Jet SM 12', 1967, clamped between the backrest and seat (Dorel, 2005; Consumentengids, 1970).

it was still available on the market at the time. A second model marketed by Storchenmühle was a child restraint that was clamped between the backrest and the (rear passenger) seat (Figure 7.7). Similarly to the other Storchenmühle child seat, the child was not safely attached to the seat, nor was the seat securely attached to the car. Obviously it would not remain in place during a serious collision. Five CRSs 'clamped between backrest and

Figure 7.8. Rimo belted harness with inflatable support (Consumentengids, 1970).

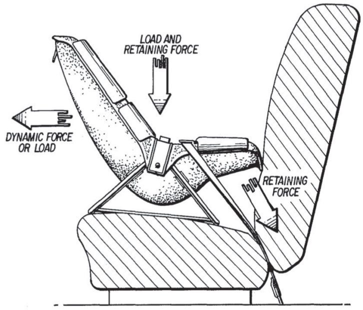


Figure 7.9. Baby carrier and car seat, patent 4,231,612 filed in September 1978 by Paul K. Meeker (Google Patents). An earlier version was filed in 1977.

seat' types were rated as 'injury foreseeable' in the event of a slight collision. Consumentengids featured this seat in tests in 1970 and again in 1974, where it was described as not providing sufficient protection. Finally, the guide advised against the use of this CRS type, describing it as unsafe due to the lack of anchoring to the car in the 1977 issue (Consumentengids, 1977). The perception of the product (and its basic function) began to change and the guide started to advise against unsafe types. In the USA, the test review by Consumer Reports rated 12 out of 15 CRS tested as not acceptable. Typically for the changing perception the article opened with the following line *"A restraint system for a child riding in an auto should not merely confine him so he cannot distract the driver; it should also protect the child in a crash, much as seat belts protect adults"* (Consumer Reports, 1972; p.485). Clearly the know-what (to make) regarding CRS changes as a result of a changing ecosystem.

Consumer associations recognized early in the 1970s that, to be safe, a CRS needs to be anchored to the car. Such anchoring ensures that the CRS, and with it the child, remains in position during a collision and, furthermore, it benefits from the energy absorption system of the car. An interesting concept with anchoring was the CRS type of the Rimo brand (Figure 7.8). It consists of a belt harness connected to the car supported by an inflatable seat. In the 1970 issue of Consumentengids this is the only CRS type for children aged up to 2 years (out of 17 tested …) for which the test report mentioned that, if a child was belted into its seat, no injury would be expected during a collision (Consumentengids, 1970). Curiously, the product disappeared from the test a few years later and, as is assumed here, from the market as well. The 1970 test of CRS in Consumentengids describes 17 different CRS types for children aged up to two years and five CRS types for children between two and six years by a total of 17 brands. In 1977 this increased to 18 brands and 29 different types. The number of CRS available on the Dutch market increased.

7.1.3.5 Consumer Guides Start Influencing Legislation

The increasing use of cars, the related increase in accidents, and the presence of CRSs that actually provided some safety created a climate in which legislation started to develop from the early 1970s onwards. In the USA articles in consumer guides also influenced CRS development. A 1972 issue of Consumer Reports, the American consumer guide published by the Consumers Union, states that most car CRSs that passed the FMVSS 213 legislation (which was the Federal Standard for CRS enforced in the USA at that time) could not withstand crash tests (Consumer Reports, 1972). In 1975 this led to a proposal to revise the regulation issued in 1971. With the USA having a history of being a single constitutional entity dating back to the end of the eighteenth century and Europe still struggling to form one, it will come as no surprise that child safety legislation was also harmonized in the USA earlier than in Europe. It would take until 1981 for ECE-44-01, the first European CRS legislation, to be introduced. Since then legislation, both from the European Union (EU) and the USA, has played a major role in requirements imposed on the design and use of CRSs.

The development of CRS legislation and CRS products is closely intertwined. CRS legislation did not result in the invention of the first safety-focused CRS, but was developed after the products had appeared on the market. However, the continuous development of CRS legislation in both the USA and the EU set the scene for increasing legal requirements imposed on CRSs. Along with the development of CRSs as a product family, an increasing body of knowledge on (mis)use developed. Child passenger safety advocacy groups, consumer associations and standardisation programmes have encouraged governments to continue renewing safety legislation. Four decades later the resulting level sets a threshold for minimal safety functionality for CRSs well above what was achieved by the best performing CRS in the early 1970s. CRS legislation co-evolved with the CRS products.

7.1.3.6 Legislation Starts to Influence CRS Design

The legislative changes in the USA in 1975 led to heavy, and therefore difficult to handle, CRSs, and this prompted designer Paul K. Meeker to develop an easier to handle CRS (Figure 7.9). The resulting CRS was sold by Questor Corporation as the Infanseat 440 or the Dyn-O-Mite. The reclining seat could be used for different activities like sleeping, feeding, playing and as a car seat. It was a rearwards facing CRS using the belt to secure it to the car seat. In 1977 Sjef van der Linden, a Dutch entrepreneur in baby articles, saw the Dyn-O-Mite in Macy's store in Manhattan while on a business trip to the USA (Dorel, 2005). Recognizing the potential of this product to fill the void in the European market, he started importing the CRS and selling the product in Europe. The first version was supplied by an Italian concession holder, Babymex Italiana. However, this product failed in crash tests at the Dutch contract research institute TNO. It turned out to be made from a different and more brittle type of plastic, which was permissible in Italy, where it was not used as a car seat. The plastic type was changed and the design improved with the help of a Swedish test institute and a Dutch designer. From 1985 onwards, the product was sold in Europe under the name Maxi-Cosi (Figure 7.10). This signalled the start of the currently dominant design for CRSs in the Netherlands, targeting the baby segment, the youngest age group.

Figure 7.10. The Dyn-O-Mite was imported into Europe and sold as the first Maxi-Cosi (Dorel, 2005).

In a 1983 issue the Dutch consumer guide observed that there was still no proper CRS for the smallest and youngest children (Consumentengids, 1983). The carrycot used for babies was described as a product that did not properly fulfil its safety function. In the event of collisions the belt might cut through the thin sides of the carrycot. Besides this, any child that was not belted inside the carrycot would be slung so hard through the device that he or she would sustain injuries. In 1987 Consumentenbond (Consumentengids, 1987) published a first review that included the Maxi-Cosi and mentioned that CRSs were finally starting to become available that would really qualify as safety seats for babies. This took a quarter century from the invention of the first safety-focused CRS (…).

7.1.3.7 Types Come and Go

In the 1980s, Consumentengids continued to question the functionality of various CRSs types. One issue (Consumentengids, 1983) described the belt harness as an outdated restraint type. In the event of collisions, children aged six years and older would slide into the lap part of the harness and might slip under it ('submarine'). This could cause severe damage to the liver, kidneys and spleen of the child passenger. The arrival of a new, safer CRS type for children, the booster cushion, was welcomed as an improvement in child safety. This booster cushion is a seat type without a backrest that elevates the child in such a way that it can use the three-point belt. It is aimed at children in the 3 to 10 age group. The belt harness with its apparent unfavourable position in the competitive landscape disappeared from subsequent reviews in the Consumentengids. Reports like these helped increase consumer awareness of what makes a safe CRS and what not. Consequently they influenced sales and resulted in the ousting of this belt harness CRS type.

7.1.3.8 Perception of CRS Changes and Dominant Designs Emerge

Historic sources, such as advertising by manufacturers and articles in consumer guides, reflect changes over time of the perception of CRSs and how they should be used. Increasing safety requirements and the changing categorization are examples of this. The introduction of CRS categories marks the introduction of new dominant designs[6] on product or system level for which safety is important. As each category caters to a different segment in the market, it is a clear marker that this product enters the segmentation phase. In the 1970s, Consumentengids only distinguished between Child Seats and Child Belts. The seats were for children aged up to three years old. Children aged between three and six were supposed to wear belt-type restraints. In the 1980s, the Consumentengids tests started to provide an overview of the different products, categorized into age groups. Following changes in legislation, the 1983 article on CRSs distinguished between the following age and product groups: up to nine months (cradles), about nine months to five years (seats), about three to ten years (booster cushions) and finally about four to twelve years (the harness belts). The 1984 article on CRSs adds weight classes to these age groups (Consumentengids, 1984b). The article on CRSs published in the 1990 issue of Consumentengids mentions, for the first time, an age group system that is aligned with the ECE legislation (Consumentengids, 1990b). It uses four groups (0/0+, 1, 2, 3) with progressive weight groups and corresponding age classes (see

6 Dominant design is a technology management concept introduced by Abernathy and Utterback (1975) to describe a product architecture and or key technological features that de facto become standard. See also sections on Definitions (2.3) and Innovation Studies (3.3.1).

also Figure 7.11). This weight and age classification system has been used for four decades. The same review states that the manufacturers of CRSs were trying to develop seats that can be used for longer and cover various continuous age groups. This approach did not initially prove to be very successful. Within a few years the situation improved. Three years later, the guide (Consumentengids, 1993b) was more positive and stated that several manufacturers sold CRSs covering age groups 2 to 3 that functioned fairly well, although those targeted at covering age groups 1 to 3 still performed rather poorly.

As reflected above, over time, more names were used for the family of CRS products, reflecting a changed perception of the basic function of the product (child car seat, child safety seat) as well as names becoming connected to segmentation, aimed at different age groups (cradle, infant safety seat, booster seat). Nevertheless, 'child restraint systems' remains the designation for this family of products in the English language. This is a remnant of the fact that the origin of the product family is inextricably connected to the fact that car ownership first rose substantially in the USA where initial use of the product was limited to restrain movement of children in cars. In other languages such as German (Kinderautositze, Autokindersitze) or Dutch (kinderzitje), car ownership rose four decades later at a time when car safety technology had also become available. Consequently, these languages do not use a direct translation of the default English language designation for this product family (child restraint system). Instead they use versions closer to the newer names that had also been introduced in the English language.

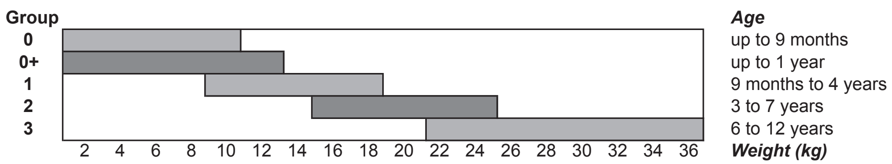


Figure 7.11. Overlapping age and weight groups (Consumentengids, 1993).

7.1.3.9 Coincidence Influences CRS Legislation

In 1994 the three-year-old Dana Hutchinson from the USA was killed after being struck by an airbag deployed while in a rearwards facing CRS in the passenger seat (Colella, 2010). During the investigation into why the CRS had not prevented fatal injuries her relatives found out that the vehicle seating position and the CRS that was secured in it were incompatible. The case received huge attention in the USA, and resulted in the formation of a child-passenger safety advocacy group called the Drivers Appeal for National Awareness (DANA) Foundation by Joseph Colella (an uncle of Dana) and relatives. The goal of this non-profit organisation is to raise public awareness of incompatibilities and misuse, and to collaborate with manufacturers and regulators on simplifying the correct use of child restraints. DANA successfully advocated legislation changes, which made warning labels on CRSs and airbag cut-off switches for cars obligatory.

7.1.3.10 Focus Shifts to Details

In general, CRSs still provide less protection than was possible and desired in the early 1990s. One of the reasons is that they do not go together well with modern cars and standard seat belts. Cars sold from 1990 onwards need to have safety belts available for the back seats. Once three-point belts had become common for rear seats, CRSs needed to adapt to this situation. Unfortunately, Dutch legislation of the early 1990s still allowed 'unsafe transportation' of children. The use of a CRS was only obligatory if available. Children aged three to twelve could use belts if present, no matter whether those were lap belts or three-point belts and, if no belts were available at all, they were still allowed to travel on the back seat (Consumentengids, 1993). In 1993 the Safe Fit belt adapter was sold as a CRS, which competed with booster seats (Figure 7.12). According to Consumentenbond (Consumentengids, 1993), this belt adapter should never have received the ECE-44 approval as it is unsafe. Consumentenbond requested clarification from the Minister of Traffic and Road Safety with regard to the assessment of approval for this particular belt adapter, and it subsequently disappeared from the market.

Once the dominant designs for CRSs started appearing in the 1980s, and car safety features improved, the focus of articles in Consumentengids shifted in the 1990s from descriptions of new and improved CRS types (basic function; providing safety) to an emphasis on comfort and proper use

Figure 7.12. The safe fit belt adapter designated unsafe by Consumentenbond (Consumentengids, 2012).

Figure 7.13. The Maxi-Cosi Pebble above a Maxi-Cosi FamilyFix base with light and sound controls for correct installation and semi-universal Isofix (Dorel, 2012).

(supportive functions; providing comfort and ease of use). Features such as removable lining were added to make CRS easier to clean. As studies show that more than half the CRSs are not installed correctly, the Dutch consumer guide underlines the need for proper manuals (Consumentengids, 1993). Apparently, the designs are still not sufficiently self-explanatory, and written instructions are still required. Additional CRS safety and comfort features were introduced after 2000. One example is Isofix, which makes it easier to install the CRS (see also the section on standardisation). Maxi-Cosi started to market a product called the FamilyFix (the base in Figure 7.15), which is connected to the car via Isofix connectors (Figure 7.13). Parents can simply snap in a Maxi-Cosi on top of the FamilyFix. The product uses electronics to indicate with a visual and auditory signal whether the CRS is connected correctly to the base. This ensures properly installed seats and therefore increases safety.

More and more manufacturers started adding so-called 'side wings' (the side protection in Figure 7.15) to CRSs that helped protect the child more effectively against injuries caused by the impact of a side collision. Legislation did not (yet) require these provisions, but consumer guides did assign a better score to products that had them. Helleke Hendriks, one of the researchers at Consumentenbond, claims that this was down to their reviews. "Our demanding tests are thus market guiding, as legislation does not require these side wings" (Consumentengids, 2010a). Several brands stopped producing booster cushions without backrests, as these do not protect children sufficiently from injuries caused by side impacts. The extent to which this change can be attributed to the success of the consumer association(s) remains unclear.

7.1.3.11 Standardisation and Safety Programme Organisations

Euro NCAP[7] has carried out child occupant safety assessments since its inception to ensure that manufacturers take responsibility for children travelling in vehicles produced by them. In November 2003, Euro NCAP introduced a child occupant protection rating to make it easier for consumers to understand the outcome of these tests. In these assessments, Euro NCAP used dummies sized as 18 months and three-year-old children in the frontal and side-impact tests. Apart from studying the results of the impact tests, Euro NCAP assessed the clarity of instructions for seat installation in the vehicle. In 1990 the International Organisation for

7 The European New Car Assessment Programme (Euro NCAP) is a European car safety performance assessment program. Euro NCAP has created the five-star safety rating system to help consumers compare vehicles more easily on safety performance. Vehicle tests are designed and carried out by Euro NCAP, providing independent safety comparison of new vehicles.

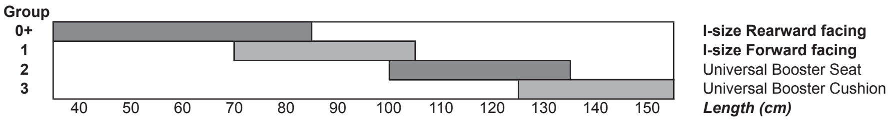


Figure 7.14. I-size classification based on length.

Standardisation (ISO) launched the Isofix standard in an attempt to provide a standard interface for fixing car seats into different makes of car. The system consists of a connector on the CRS and an anchor in the car seat (see also Figure 7.15). The US equivalent of this system is called Lower Anchors and Tethers for Children (LATCH). Obviously, to be of any use, this system needs to be adapted by manufacturers of cars and of CRSs. Consequently, the proliferation of this feature in CRSs (the fitness in evolutionary language) is dependent on the extent to which car manufacturers implement these connectors throughout their fleet. It took about a decade of discussions with the automotive industry before all involved agreed to the technical specifications. The current version of the standard was published in 1999. Some CRS manufacturers started selling Isofix-compliant baby car seats in the EU from around 2000. EU regulations required cars built from 2009 onwards to be fitted with Isofix anchorage points. As cars in EU countries were, until the 2004 expansion, on average, 8.5 years old (ACEA, 2009) this meant, with the average age remaining constant, that it would take slightly less than a decade, or until 2018, before half the cars on the road were compulsorily equipped with Isofix. This set the scene for the market adoption rate of Isofix in CRSs sold to consumers in the EU and shows that diffusion of new interface standards depend on changes in two types of products, each with very different life cycles.

The phasing in of LATCH in the USA was completed in 2002. Assuming that the average age and life expectancy of cars in the USA are similar to those in the EU, this means that 8.5 years later (at the beginning of 2011) LATCH would be compulsorily installed in the majority of cars on US roads. It could therefore be expected that LATCH would become the default installation method about seven years before Isofix reaches the same level as in the EU. The European Association for the Co-ordination of Consumer Representation in Standardisation (ANEC), a European organisation involved in the standardisation of consumer products, influenced the legislation and standardisation of CRS. Since 2006, the organisation (ANEC, 2006) has advocated an increase in the age up to which children are seated backwards from the current 9 to 15 months or 16.5 kg, as this increases safety during frontal collisions. Furthermore, the ANEC promotes a stature-based system referred to as I-size to replace the incumbent weight- based system (ANEC, 2011). I-size classifies CRSs by the child length rather than weight

(Figure 7.14). Further it requires rearward-facing transport until the child is 15 months of age and provide side impact protection. The I-size regulation came into force in 2013 (ANEC, 2014) and will, over time, oust all old style CRS from the market (ANEC, 2012).

7.1.3.12 Consumer Associations

Consumer associations played a pivotal role in the advancement of CRSs by publishing comparative tests. Between 1970 and 2010 Consumentengids published a total of 18 comparative tests on CRS. These articles reveal that, particularly in the 1970s and early 1980s, these products did not often perform very well as regards their primary functionality, namely to ensure safety during collisions for children travelling in cars. Consumer guides provide an independent and detailed overview of the quality and price of the products available in the market in the comparative tests. Pictures of articles tested, and relevant references to legislation, importers, and manufacturers are included. Products that perform best are designated 'best choice'. Producers often use these qualifications in their marketing, and retailers display copies of such articles at point of sale. Consumer associations therefore directly influence the purchasing behaviour of consumers and, in that way, exert evolutionary pressure (selection of the fittest). Consumer associations also directly address legislators and manufacturers as described in an article by Consumentenbond, which mentions the use of video recordings of crash tests with CRSs. These videos have been shown to both legislators and manufacturers in order to convince them that there was a need to improve the standards with which the CRSs should comply (Consumentengids, 1993). An example of the arguments used was that CRSs should not be tested with a lap belt, but with the retractable three-point belt instead. Those new requirements have subsequently been described in the ECE-44-03 legislation.

Consumer associations in various countries are united in different bodies such as ANEC, Consumers International (a federation of consumer groups) and International Consumer Research and Testing (ICRT) that focus on joint research and comparative testing. Consumer associations cooperate on product tests and share information used to compile the reviews published. Employees of various consumer associations participate in bodies like ANEC, for which they publish research into CRSs' safety with the objective of influencing legislation and standardisation (ANEC, 2003). Along these routes the different international consumer associations cooperate and influence both legislation such as ECE-44 and standardisation issues such as Isofix and I-size. Consumentenbond claims that this cooperation between various consumer associations in Europe has led to increasingly safe CRSs (Consumentengids, 1994).

7.1.3.13 Increasing Scale at Manufacturers Reduces Regional Design Differences

Similarly to cars and other consumer goods, regional differences can be found in people's preference for a specific technology, product architecture or design language. In the USA the larger car models like SUVs and trucks are widely sold. In Europe, where fuel has traditionally been taxed more heavily, the average car is smaller and more fuel efficient than in the USA. Similar differences can be observed for CRS. In Scandinavia, rearwards facing CRSs are promoted for up to four years. Other parts in Europe will adapt to a new length-based standard (I-size) that increases current rearwards facing from 9 to 15 months or 16.5 kg.

Over the decades a large number of companies have been involved in the development and production of CRSs. Historically they served different geographical markets. In recent years mergers and acquisitions caused a consolidation on the CRS market. Currently, only a few large players remain. In Europe the market is served by several large companies, plus a few smaller ones, and white label products from Asia. Dorel is a Canadian firm that acquired Maxi-Cosi, which primarily sells in Central and Western Europe, and Bebé-Comfort, which is traditionally strong around the Mediterranean. Britax Römer is an Anglo-German firm that, besides its own brand, also supplies CRSs to various automotive manufacturers that sell them under their own brand. Storchenmühle was originally a German manufacturer and is now owned by the globally operating Keiper Recaro Group that specializes in mobile seating. HTS (Hans Torgersen & Sønn AS), traditionally strong in Scandinavia, targets the European and Asian markets. These larger CRS manufacturers all have their own in-house development centres where they consolidate resources and know-how to develop new products. The scale increase in the CRS market, the international trade with ever more global companies, and the advent of the Information Age mean that know-what and know-how concerning CRS will disseminate faster than it did in the early 1970s. These changes in the CRS ecosystem can be expected to drive design differences gradually to become smaller.

7.1.4 Perspectives on the Development of CRSs

The CRS discussed in previous sections thus evolved into a product family that schematically can be pictured as shown in Figure 7.15. Variants of CRS designs through time consist of different executions of the subsystems that are configured according to prevailing views regarding the needs of the particular age, weight or length group. Thus, over time different design solutions evolved for different subsystems, each of which over time became more refined.

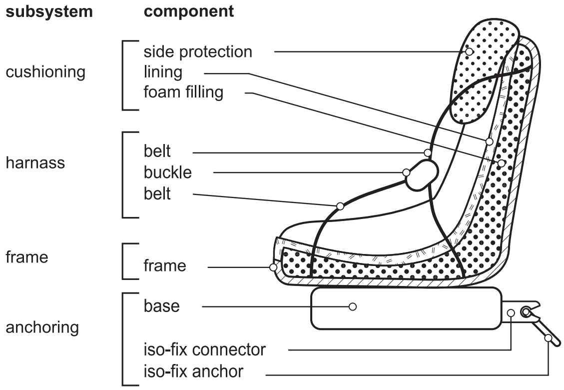


Figure 7.15. The system diagram of CRSs.

7.1.4.1 Mapping the Development of CRSs in a Product Evolution Diagram

The Product Evolution Diagram as introduced in Chapter 6 is used in Figure 7.16 to map the development of CRS over time juxtaposed with the ecosystem that influenced the evolution. As shown above, the CRSs did not originate at once, but evolved over a century from numerous designs at the hands of a 'collective body of inventors', a varied group of people such as designers, salesmen and test laboratory employees. As similarly remarked by Badke-Schaub (2007) on the subject of scientific discovery, CRSs have been shown to develop in incremental steps, based on past experience. The juxtaposed depiction of ecosystem above the Product Family Tree in the Product Evolution Diagram shows the influence over time of external events, such as the development of cars, safety belts, legislation and the death of Dana Hutchinson, on the development of CRSs. Clearly these factors had a major impact on the evolution of CRSs.

Figure 7.16 shows a Product Family Tree of CRSs that is rooted in earlier forms of baby cots and child seats. With the advent of the modern car, marked by the introduction of the Ford Model T, car ownership in the USA started to rise and provided a market for CRSs. In the early 1970s the level of car ownership also started to rise in Europe to over 100 vehicles per thousand people, a similar level as existed in the USA in the 1930s. Together with the diffusion of car safety technologies this fed the awareness and need for in-car safety for children. This set the scene for a rapidly increasing diversity in CRSs. Several designs proved to be unsafe and, although they subsequently became extinct, they influenced legislation for later generations of CRSs. The designs that provided better protection evolved into the dominant designs we know today.

The evolution of CRSs led to three different dominant designs which cater to different market segments (based on age, weight or length). The first is the

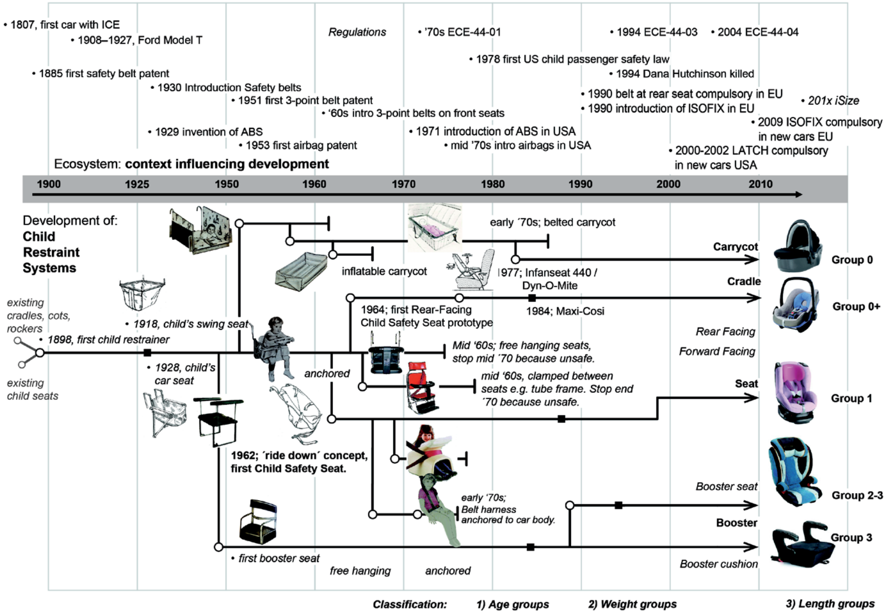


Figure 7.16. The Product Evolution Diagram of CRSs. The approximate appearance of dominant designs is marked with square nodes (■) on branches. Instead of designating dominant designs based on market shared, it is here assigned based on reviewing the types tested in consumer guides.

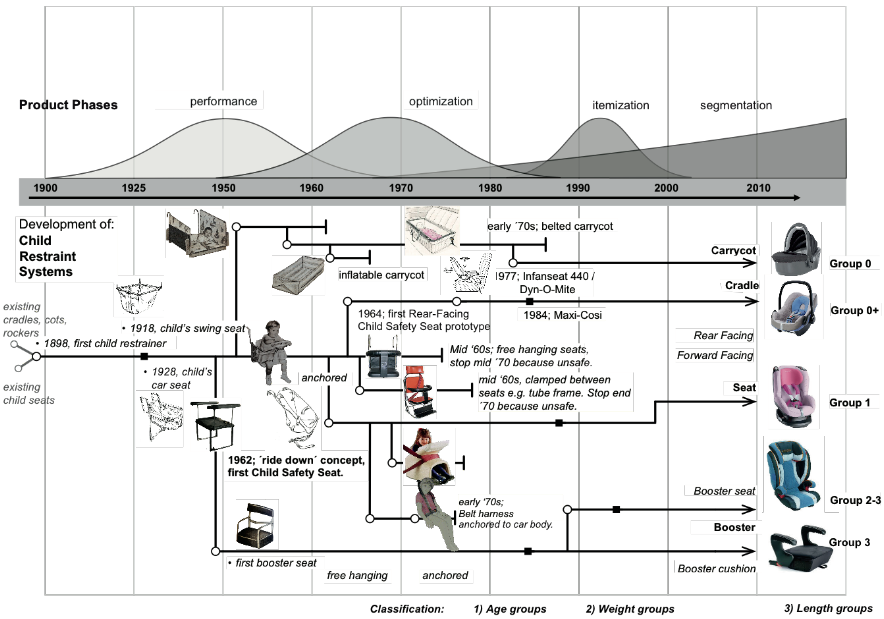


Figure 7.17. The product phases and the Product Family Tree of CRSs.

cradle type, in which babies and toddlers aged up to 1.5 years or weighing up to 12 kg lie rearwards facing in a reclined position. The second is the seat type for small children aged up to seven or weighing up to 24 kg. Both these types have their own belt harnesses for children whose bone structure, muscles and length are not yet mature enough to use the three-point-belt for adults provided in the car. The third, the booster type for children aged up to 12 years or weighing up to 36 kg, does not have a belt system of its own and uses the three-point-belt provided in the car. The evolution of the CRS product family into three types of dominant designs marks the segmentation phase as described in Chapter 1 of this thesis. The products literally evolved to meet the needs of three different market segments and, as can be concluded from this case study, the different product architectures evolved over time with certain designs surviving while others disappeared as they were designated as unsafe in consumer tests and/or banned by legislation that became stricter over time.

7.1.4.2 CRSs Developing Through the Product Phases

When a first CRS was introduced at the end of the 19th century the product was new to the market. As noted before, the product was aimed at 'restraining' the freedom of movement of children in cars. It did not yet provide safety because the concept of car safety did not yet exist. Various variants of CRSs appear on the market in the first six decades after introduction. As observed for other products (Eger, 2007a), the performance of CRS was poor. In terms of product phases the CRS is in the performance phase. Figure 7.17 depicts the Product Family Tree of CRSs juxtaposed with product phases.

In 1962 the Ames couple introduced a first CRS aimed at providing safety (Figure 7.3). Two years later professor Aldman experimented with a first rear facing CRS (Figure 7.4). These events marked the beginning of the optimization phase, characterized by new product development which was intended to improve the performance of products in terms of reliability, ergonomics and safety. In the 1990s the focus of CRS development and standards shifted to details. This characterizes the itemisation phase. Reviews in consumer guides started focusing on aspects like ease of installation and cleaning. Isofix and Latch were introduced to promote better installation of CRS in cars. Since the end of the 1990s almost all members of the target group (i.e. young parents using a car) became familiar with CRS. Legislation also enforced its use. After 2000 wide product ranges were being offered with increasingly complex features like Snap-On bases (Figure 7.13) and CRSs that combine with strollers. Expressive styling became more common and CRS (and strollers) started following fashion trends. It transpired that the product phases for CRS were not sharply demarcated in time. Instead, a certain development marked the beginning of a phase while elements characterizing the previous phase were still available on the market. This is why the phases are mapped with a peak marking wherever, in terms of time, this phase best describes the evolution in the product family in time while the start and end of the phase overlap with other phases.

As far as CRSs are concerned it transpired that not all product phases appeared simply in succession. The Product Family Tree shows that the branching that eventually shapes the CRS product segments actually started with the introduction of the first booster seat around 1950 and what led to the carrycot few years later. Then safety– focused CRS were introduced in 1962. For that reason, Figure 7.17 shows how initial segmentation coincided with the start of the optimization phase. For the product family of CRS, segmentation literally evolved over time, starting with the recognition of age groups, then weight groups and currently length groups. Although the optimization and itemization phase were not yet finished, the elements that characterize the segmentation phase were already visible. Apparently, the segmentation phase overlaps with earlier phases.

7.1.4.3 Relationship between Development of Product Family and Ecosystem

As noted in Chapter 4, the interaction between the development of product and ecosystem shapes the development of both. Other authors noticed similar systems and discussed the development of products in niches, which are influenced by developments in the wider ecosystem or socio-technical regimes and industrial landscapes (Geels, 2002; Joore, 2010). The role of legislation as an important element of these socio-technical regimes is discussed in connection with the development of forms of sustainable transport (Hoogema et al., 2002; Van den Hoed, 2004). Figure 7.18 depicts this mutual relation. The lower half shows a simplified CRS Product Family Tree. The upper half summarizes the ecosystem that interacted with the CRS product family as it developed over time. The case of CRSs shows a strong and mutual influence (hence two-way arrows) between the evolving product family and consumers (including consumer associations and advocacy groups), standardisation and related legislative bodies. This has been described as a direct or primary influence in Figure 7.18. An indirect or secondary influence on the development of this product family can be observed from the wider environment of general (car safety) legislation, (car safety) technology development and general development and diffusion of the environment in which the products are used (cars).

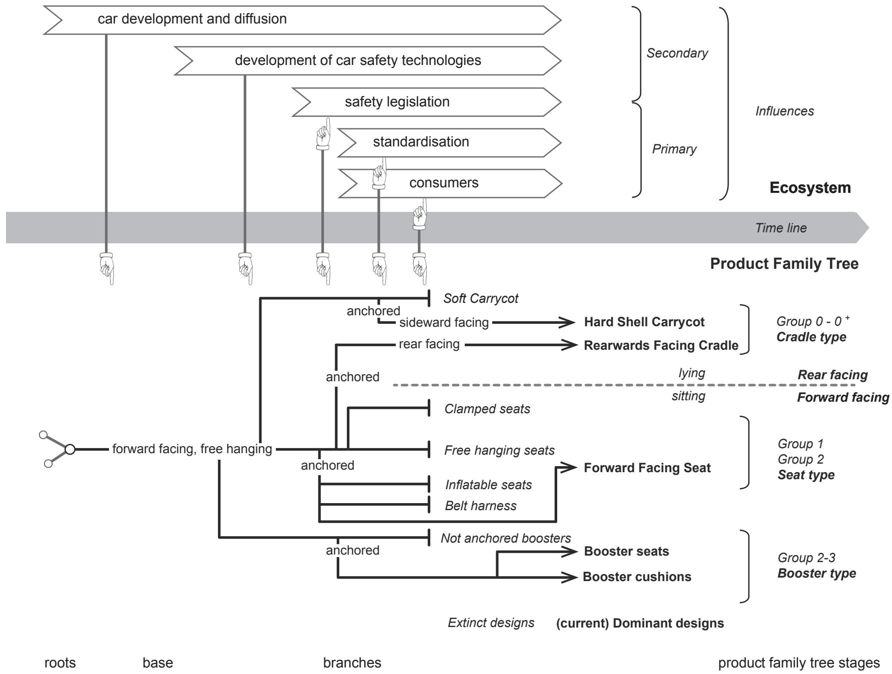


Figure 7.18. The relation between the Product Family Tree and the ecosystem.

7.1.5 Conclusion

The CRS case study shows an example of a new type of product that comes about and evolves into a product family catering to different segments. CRS segmentation evolved over time from age groups to weight groups and currently length groups and is related to the improving functionality.
The first documented use of a child restraint system (CRS) in a car dates back to 1898. This first device was little more than a drawstring bag that would attach to the actual car seat intended as a system used to restrain children from moving through the car. The mass production of cars started with the Ford model-T in 1908. In the 1920s the production of various CRSs started and patents for CRSs were filed. At that moment the level of car ownership increased to more than 100 vehicles per 1,000 inhabitants in the USA, which formed a CRS market, and with it the diversity of CRS designs increased. Once car safety technology had diffused from the 1960s onwards, the perception of required safety to be provided in cars changed. As a consequence, the then still latent needs for child passenger safety evolved into an awareness that child passengers did not receive the protection they needed. This created an environment in which CRS designs were developed which focused on providing safety to children travelling in cars. Slowly the perception of what functionality a CRS should provide changed amongst

manufacturers, designers, salesmen, consumer organisations, legislator and consumers. Then, in the 1960, the level of car ownership increased in Western Europe as well to more than 100 vehicles per 1,000 inhabitants. This condition allowed the market for CRS to grow in Europe as well.
The case study revealed that many different actors contributed in various ways to evolving CRS perception and designs. It was certainly not a process driven by designers alone. Besides that, international trade, consolidation amongst manufacturers, as well as coincidence, have been shown to influence CRS evolution. It has become apparent that the whole of influences from the context here defined as the ecosystem is part and parcel of the evolution of CRS products.
The development history of CRS that covers more than a century has been mapped in a Product Evolution Diagram using a Product Family Tree, and an ecosystem.

This supports the following propositions;
P2: *The emergence of new types of products, and their subsequent development into families of advanced types can be described as an evolutionary process.*
P3: *Evolution in products can be visualised as a Product Family Tree.*
P4: *The influences of a context on the evolution of a product can be mapped as an ecosystem.*
P5: *To understand how products evolve, one needs to analyse the interaction between a product family and ecosystem over time.*

The architectures of CRSs sold in the Netherlands have been stable over the last two decades. That does not mean that evolution has halted. It was noted (Consumentengids, 2010a) that the room for improvement in side-impact protection, the relatively high levels of incorrectly installed CRSs and the lack of support for booster-only cushions, mean that further improvement of CRS designs is possible. A major review by the ANEC (2014) towards I-size, a stature-based system promoting rearwards facing until 15 months, further refines standardisation for CRS. These are examples of evolutionary forces that can be mapped in a Product Evolution Diagram to provide direction for design and development of new evolutionary versions of CRS[8].

Based on this case study, it can be stated that CRSs have come a long way in terms of the safety they provide, their ease of use and their comfort.

8 Design student Noor Reigersman used the case of CRS as a topic for research as well as design. In Chapter 8 an example of a possible next generation CRS design is shown as designed by Reigersman.

It can be asserted that the current CRSs perform well as regards their current basic function, namely to provide safety to child passengers in cars during driving in general, and in the event of a collision in particular. The performance of this basic function is expressed in qualitative terms like 'bad, moderate, reasonable, and good'. A single unit of performance allowing quantification of the performance or the price-performance is not available for CRS. Therefore a next case has been selected of a product for which the development of the price-performance ratio over time can be quantified.

7.2 General Lighting Solutions and the Compact Fluorescent Lamp

7.2.1 Introduction

This section explores the historical development of electric lighting technologies in general and, in particular, the evolution of the *general lighting solution* (GLS) product class, zooming in on the *compact fluorescent lamp* (CFL) in a retrospective case study. Electric lighting is one of the key applications that sparked the demand for electricity and, as such, is an important factor in electrification. Electric lighting developed into three technology families: incandescent, gas discharge and solid state. Each of these lighting technologies families is based on different physical functional principles leading to different technological solutions to generate light. Each family represents complex development paths producing a plethora of products. The incandescent family was the first to produce a highly successful product that became known as the general lighting solution (GLS). The GLS became the dominant design for electric lighting products and is based on a lamp using a screw base as standard interface and is roughly the shape and size of a pear. GLS developed into a product class when lamps based on other technologies started to provide the same interface and basic function. The case illustrates that superior economic and environmental performance is not always enough to oust an incumbent dominant design. It appears that the evolutionary path of products is influenced by many factors like consumer preferences, legislation and technology from other domains.

The case study starts by drawing a picture of electrification, the technology transition that was part and parcel of evolution of electric lighting. Next it explores the rise of three different lighting technologies. After that, the development of the CFL is explored in more detail.

7.2.2 Electrification and the Rise of Electric Lighting

Electric lighting played an important role in electrification, a technology transition that modernised our world from the mid-1880s through to around

1950. The roots of electric lighting go back to the start of the 19th century. The invention of the battery by Alessandro Volta in 1800 provided a first practical source of electricity. Soon that would lead to the discovery of incandescent light by Humphry Davy in 1802 who first observed a platinum strip illuminate light as it heated up by the electric current conducted through it. Around the same time, Davy also demonstrated that light could be produced from an electric arc. The gas lamp, powered by coal-gas, had been invented a decade before, leading to the first public street lighting in 1807, in London. The gas lamp proved to be a more practical illumination solution than candles and oil lamps. During the following decades gas illumination spread to other countries like France, the USA and Russia. However, open fire and toxic fumes associated with gas lamps imply an intrinsic hazard. The gas lamp made the world receptive for a safer and more practical form of artificial light provided by the incandescent lamp described in section 7.2.3.1. Electric lighting however required an infrastructure that provided electricity to the point of use, which was not yet available. Once a practical electric lamp was invented, the infrastructure developed over time, shaped by an intense battle of standards and technologies in which *"the details of the timing of small historical events could have important and lasting consequences"* (David and Bunn, 1988). In this era of ferment (Anderson and Tushman, 1990) the foundations were laid for today's electric network standards that roughly divide the world into 110 Volt and 220 Volt regions. Together with electric networks and electric lighting, many more products using electricity were developed and distributed throughout the world. Electric motors were soon being used in manufacturing, thereby ousting steam engines that once powered the industrial revolution. Electrification not only enabled electric light, it also changed the world.
The evolution of electric networks is a case example of path dependency in development that caused technological solutions to become locked-in. Once the (110 or 220 Volts) networks had been laid, it became nearly impossible to change them due to the costs involved in changing the networks and products based on these standards.

7.2.3 Electric Lighting Technology Families

Since its conception, wide ranges of competing lighting technologies have been developed (Figure 7.19). The CFL can be regarded as a precursor to energy-efficient lighting products that mark the current transition to energy efficient societies. CFL is part of a group of lighting technology families of which the development paths are complex and interconnected. It is therefore an interesting case to study how new types of products come about and develop into families of more advanced versions. The sections explore how three technology families evolved and all produced a product that became part of the General Lighting Solution class.

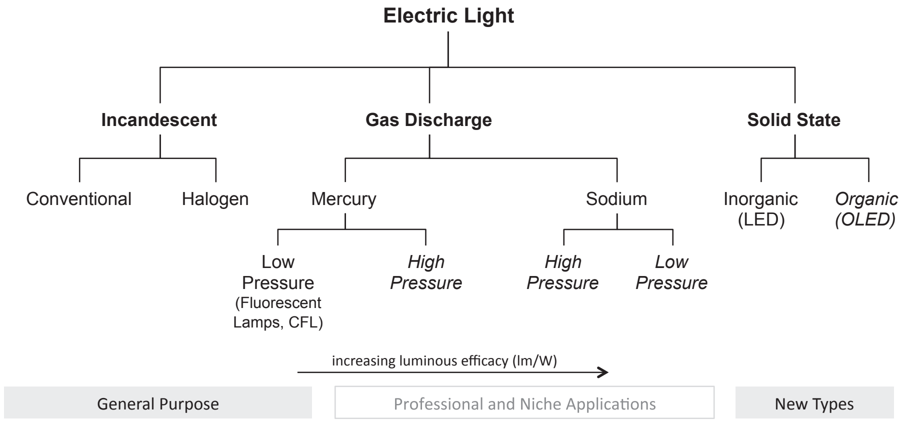


Figure 7.19. Electric lighting technology families (note: the lighting types mentioned between brackets is not exhaustive, and only those discussed in this section are included).

7.2.3.1 Incandescent

In 1879 both Joseph Wilson Swan in the UK and Thomas Alva Edison in the USA applied for a patent for a carbon filament incandescent lamp and started to produce them soon after. In the Product Evolution Diagram (Figure 7.20) this is marked as '[A]', the new branch of carbon filament lamps with Swan's lamp (Figure 7.21). However, Friedel and Israel (1985; p. 91) mention no fewer than 19 inventors of incandescent lamps prior to Swan and Edison[9]. All these inventors experimented between 1838 and 1879 with variants of filaments (carbon, platinum and platinum/iridium) and atmospheres in the enclosure (vacuum, air, nitrogen and hydrocarbon). Those inventors built on prior work of Humphry Davy who, in 1802, discovered the principle of electric light by incandescence when he used Volta's newly discovered batteries to drive a large electric current through a platinum strip. Nearly eight decades of development were required for the roots of incandescent lamps to accumulate into the first commercially available product.

Basalla (1988) described how Edison developed electric lighting as a system inspired by the existing gas lighting infrastructure, and as alternative to the carbon arc lamp that produced a too intense light for domestic use. Edison understood that, in order for electric lamps to become successful, electric

9 Edison, although undoubtedly technically a very gifted and resourceful person, did not act alone while developing "his" light bulb. In 1876 Edison set up a research laboratory in Menlo Park, New Jersey. Over the years, as many as 200 'assistants' worked with Edison. Half the 1,093 patents claimed by Edison are based on work in this laboratory. Edison claimed all credit for this work, cunningly played the media and created almost mythical status being referred to as 'the Wizard of Menlo Park' (Friedel & Israel, 1985).

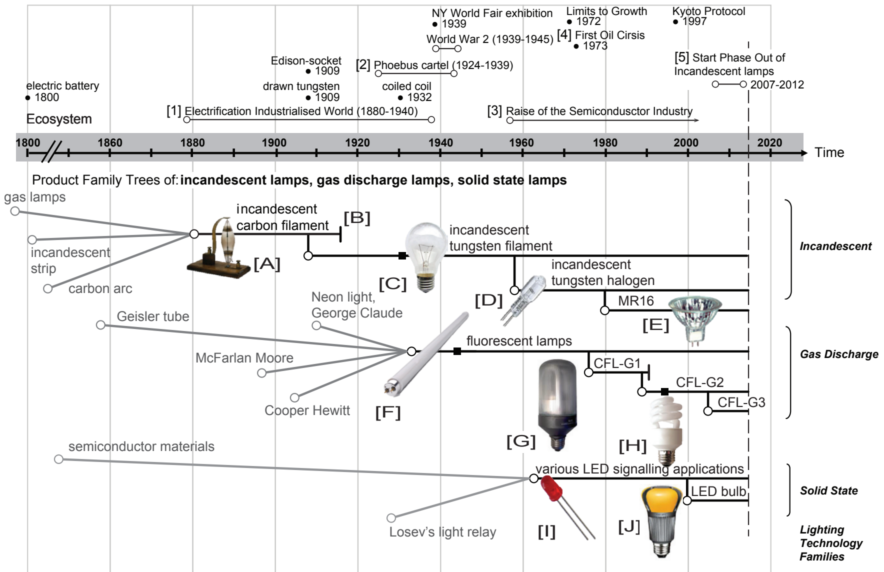


Figure 7.20. Product Evolution Diagram of the most common types of electric lighting technologies.

Figure 7.21. The first incandescent lamp by Joseph Wilson Swan (1879).

networks had to be developed to power them. Companies commonly referred to as the utilities started producing and distributing electricity. Others started to develop and manufacture products using electricity. The introduction of electric lighting gave the impetus for the development of a whole range of new industries targeted at generating and transporting electricity as well as products that used it. The process of electrification had started (marked '[1]' in Figure 7.20).

The incandescent bulb was the first source of electric lighting embraced by the consumer market. It has been the dominant lighting technology for domestic use for more than a century, although more efficient types of

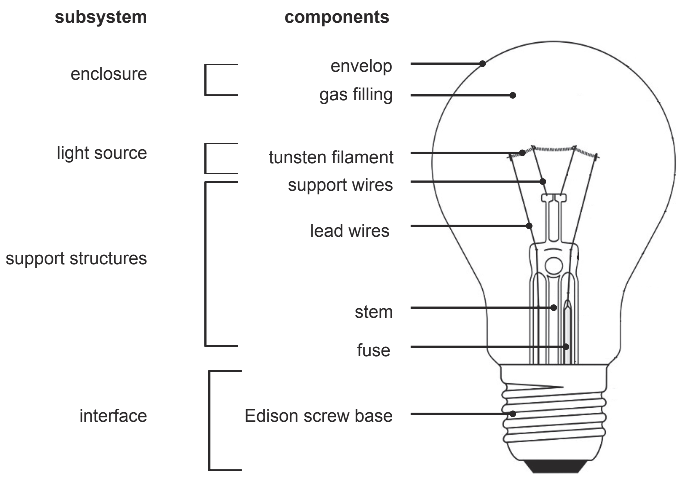


Figure 7.22. The incandescent lamp system diagram.

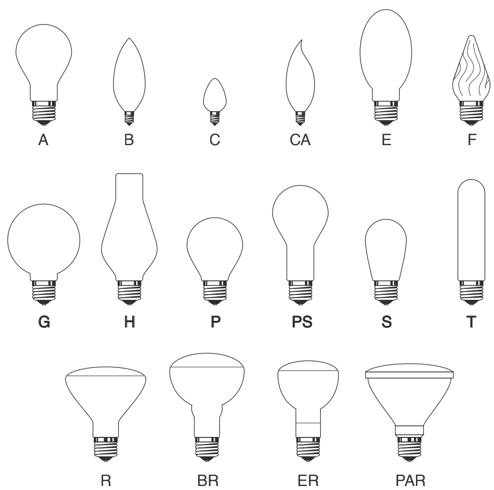


Figure 7.23. Range of shapes and sizes used for incandescent lamps (Wikipedia, 2015e).

lighting technology have been invented since it first appeared on the market (Menanteau & Lefebvre, 2000). It was also one of the first major applications to use electricity. Due to its relative safety it outcompeted gas illumination that constitutes an inherent fire hazard.

Initially, incandescent lamps used a carbon filament, which had a lifespan of about 40 hours, and produced a yellowish light due to the relatively 'low' operating temperature. They needed to be replaced very often. To make them easy to replace, a screw base socket (see also Figure 7.22 and '[C]' in Figure 7.20) developed by Edison in 1909 was used. This subsystem became the interface standard for mounting incandescent lamps in North

America and continental Europe (Wikipedia, 2011). In the UK, and many countries associated with the British Empire, the bayonet socket became the interface standard. In order to produce a more white light, the lamp needed a higher operating temperature, which reduced the lifespan. These conflicting demands resulted in a technology cycle in subsystems filament and enclosure. Experiments with all kinds of filament materials and different gas mixtures led to a wide range of different types of incandescent lamps. Finally, experiments using metals with high melting points led to the invention of drawn ductile tungsten filaments in 1909 by General Electric (GE) employee William David Coolidge (Brittain, 2004) that combined well with a nitrogen atmosphere. Soon afterwards this new and improved type replaced the carbon filament lamps[10] and they ceased to exist as a common form of lighting. In Figure 7.20 this is marked '[B]', as a dead end in the Product Family Tree (PFT) of incandescent lamps. The tungsten filament evolved from straight to coiled and then double coiled, further improving its luminous efficacy. Since then the basic design of the incandescent lamp has remained the same (Figure 7.22). The incandescent light bulb is a non-directional lamp that became the dominant design for electric lighting and has since been referred to as 'general lighting service' (GLS) or 'general service lamp'. The operational lifetime for GLS incandescent lamps increased to 1,000 hours. This lifetime was allegedly capped by the Phoebus cartel ('[2]' in Figure 7.20) that operated from 1924 to 1934. Over the years a series of incandescent lamp variants emerged, each designed for different types of use in a variety of fixtures or lampshades. The most common variant is marked with an A in Figure 7.23. The GLS has become associated with this specific variant also referred to as the type-A or the A-bulb.

In terms of product phases, the incandescent lamp entered the performance product phase in 1879, when Edison and Swan started producing the first incandescent lamps with carbon filaments. From the end of the 1880s until the turn of the century, the electric lamp was in the optimization product phase and many experiments led to variants being produced in order to improve their life span and efficiency and make them suitable for different types of use. Metals like platinum, tungsten, molybdenum and tantalum, and even ceramics, were used to make more robust filaments, thereby increasing the lamps' lifespan. In the 1890s the electric lamp entered the itemisation product phase. Many different types of lamps designed for different purposes became available on the market. These included very small lamps for use in microscopes and focus lamps for use in projectors.

10 It is noted, however, that the carbon incandescent lamp did not completely disappear. Carbon filament lamps are still available on a very small scale for nostalgic reasons. Similarly to steam engines, these carbon filament lamps do not die out or disappear but lose their socio-technical relevance.

After 1910 the electric lamp entered the segmentation phase. The drawn tungsten filament, the Edison screw base (1909) and the coiled coil filament invented by Philips in 1932, provided the incandescent lamp with its final architecture. Evolution in the various subsystems of the lamp finally led to the *general lighting solution* or *GLS* that remained stable for nearly a century as the dominant design of the product that provided electric lighting to consumers. The many variants of the incandescent lamp displayed in Figure 7.23 cater to different segments of use. In recent years a new variant referred to as the 'GLS halogen incandescent lamp' has been added as an energy efficient new member to this family.

7.2.3.2 Gas Discharge

The German glassblower Heinrich Geissler invented a proto gas discharge lamp in 1857 that became known as the Geissler tube, and that produced a strong green glow on the walls near the cathode end. This first version of a gas discharge lamp was very inefficient in terms of light production and had a short operating life. Various decades of experiments led to two to three metre-long tubular nitrogen-based gas discharge lamps, made by Daniel McFarlan Moore (USA) in 1895 that enjoyed some commercial success. Although the lamps were much more complex and expensive to install, they were considerably more efficient and produced a more natural light than their incandescent competitors at that time, that still used carbon filaments. Cooper Hewitt (USA) invented a first mercury vapour lamp that was marketed in 1901 and an improved version in 1903 that was widely used for industrial lighting (Encyclopædia Britannica, 2013). Inspired by Geissler and McFarlan, George Claude (France) produced a neon tube light in 1910, which became widely used in advertising applications.

Decades of experimenting with various forms of gas discharge lighting led to the modern fluorescent lamp that uses phosphorous coatings to convert UV into visible light. The key components for modern fluorescent lamps became available at the end of the 1920s. These are the ballast required to control the electric current, long-lasting cathodes (using ductile tungsten wire, here an *enabling technology* that earlier was invented to improve the incandescent lamp), reliable electric discharges, mercury vapour as a source of UV radiation, fluorescent phosphorous coatings and cheap glass tubing. In 1934 General Electric in the UK experimented in their laboratories with fluorescent lighting. Soon GE (from the USA) copied the experiments in their Nela Park laboratories. Bijker (1997) describes how the emergence of the fluorescent lamp technology is shaped by a power struggle between lamp manufacturers who competed with new products and electricity producers who feared their electricity sales would be damaged. Consumers allegedly did not play a significant role in this. Although fluorescent lamps were superior in terms of efficacy from the outset, this appeared not to be enough to oust the incumbent incandescent lamps.

Sales of fluorescence lamps ('[F]' in Figure 7.20) commenced in 1938 and the New York World Fair exhibition in 1939 used fluorescent lamps for illumination, thereby making them popular among the general public. Wartime manufacturing required large quantities of artificial lighting, boosting the further development and production of fluorescent lamps. Fluorescent lamps were developed in many types, of which the tubular lamp became the most commonly used. The shape and size of the fluorescent tube lamp or TL proved to be less practical than the compact bulb used for incandescent lamps, and incompatible with the compact screw base sockets that had become a widely available interface standard in lighting infrastructure. Furthermore, fluorescent lamps produce a type of light that is perceived as cold and unpleasant[11]. This made them less popular, particularly in markets that first adopted electric lighting and had grown accustomed to incandescent light that is perceived as more pleasant by the human eye. These disadvantages restricted application and therefore the growth of fluorescent lamp market. Incandescent GLS lamps remained the lamp of choice for consumers. In public and commercial spaces, fluorescent lamps had a stronger position as their higher efficiency and longer lifespan resulted in a lower total cost of ownership (TCO).

Decades after gas discharge lighting was introduced, a new era in lighting was triggered by societal developments that demanded energy-efficient technologies. In 1972 the Club of Rome, a global think tank that deals with a variety of political issues, drew considerable public attention with its publication 'The limits to growth' (Meadows, Meadows, Randers & Behrens, 1972). It stated that economic growth could not continue indefinitely because of the limited availability of natural resources, in particular oil. Shortly after, the first oil crisis (marked as '[4]' in Figure 7.20) was set off in 1973 by an embargo of the Organisation of Arab Petroleum Exporting Countries (OAPEC), leading to a spike in oil prices. These events encouraged major lighting manufacturers to start searching, with government backing, for more efficient forms of electric lighting (Roy, 1994). GE and Philips laboratories developed a more conveniently shaped version of the tubular

11 Incandescent lamps produce a light spectrum with a colour-rendering index (CRI) of 100. The CRI is a unit used to express the ability of a light source to reveal colours of illuminated objects. If the CRI is lower than 100, not all the colours are shown. Incandescent lamps operating at high power settings produce a CRI of 100 and thus reveal all the colours of illuminated objects. The development of phosphorous coatings enabled modern CFLs to produce CRI of typically between 80 and 85. Early gas discharge lamps produced much lower CRI values, which made illuminated objects look washed out. This low CRI value made gas discharge lamps unpopular among consumers who were used to the light from incandescent lamps.

fluorescent lamp using the widely adopted GLS interface standards (screw base or bayonet), that could be used as retrofit energy-efficient alternative to incandescent lamps. In 1981 the Compact Fluorescent Lamp (Figure 7.24 and marked as '[G]' in Figure 7.20) appeared on the market, marking the beginning of the awareness product phase for electric lighting. The introduction of the CFL created a product class for GLS lamps. Now products using different technologies to generate light could be used as substitutes for each other in the screw base sockets. CFLs have a significantly longer lifetime than incandescent lamps, according to the manufacturers ranging from 5,000 up to 15,000 hours, which means they need to be replaced less often. However, in practice, this promised lifespan is not achieved very often. Frequent on/off switching is a known cause of CFL failure. What is more, high temperatures building up in lamp enclosures are known causes for reducing the lifespan of electronic components used.

In the early 1990s CFLs had captured only about 2% of sales by volume in the domestic market and had achieved higher penetration only when they were specially promoted or subsidised (Roy, 1994). The utilities, that feared a drop in electricity sales after the introduction of fluorescent lamps in the 1930s, changed their position at the end of the 20th century. Some utilities in the USA initiated special programmes to distribute CFLs for free to customers because saving energy consumption was a more economic option to building new power stations (Roy, 1994), which were needed to meet the ever-growing consumption of electricity.

Figure 7.25 shows how, over time, demand for CFLs slowly increased in the beginning. During the first decade after market introduction only 'innovators' who constitute the first 2.5% of the market share (Rogers, 1962)

Figure 7.24. The Philips SL 18.

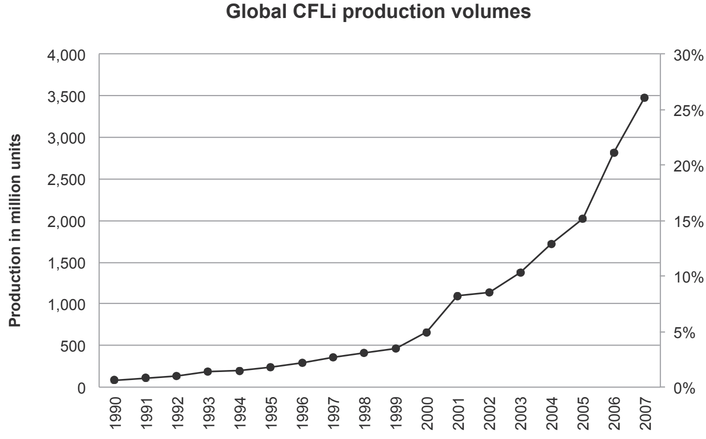


Figure 7.25. Development of global CFLi production volumes as share of GLS demand (Waide, 2010).

adopted the CFL. During the second half of the 1990s, the 'early adopters' and subsequently other customers followed.

7.2.3.3 Solid State Lighting

Light Emitting Diodes (Figure 7.26 and marked as '[J]' in Figure 7.20), commonly referred to as LEDs, were introduced by the semiconductor industry ('[3]' in Figure 7.20) that emerged at the end of the 1950s. LEDs are the first branch in the technology family known as Solid State Lighting (SSL). SSL technology is currently enabling a technology transition (Geels, 2002) to significantly more efficient and versatile electric lighting. The rooting period for this lighting technology started in the 19th century when experiments by scientist like Michael Faraday and Ferdinand Braun led to the discovery of certain material properties that we currently associate with semiconductors. Oleg Vladimirovich Losev is regarded as being the first to discover that diodes used in radio receivers emitted light when current was passed through them. He filed a patent in 1927 for a 'light relay' and published a first article on the matter (Losev, 1927) in a Russian journal and later in German and English journals as well.

A wide range of LED lighting types are currently entering the market, offering a combination of high efficiency, robustness and long lifetimes (according to manufacturers ranging from 20,000 up to 50,000 hours). Although the advertised lifetime of the LED bulb ('[J]' in Figure 7.20) means they need replacing 20 to 50 times less often than was common for incandescent GLS, it is still designed with a screw base so it can be used as a retrofit replacement in the same screw base sockets. The reason for this is convenience for the consumer and the large installed base of screw base sockets, and not technical necessity[12]. With the introduction of the LED bulb, a next competitor became available in the GLS product class.

Philips was the first to introduce a 60W incandescent GLS equivalent LED bulb in 2009 (DOE, 2011a) (Figure 7.27). A few years later Philips (2012) introduced a LED bulb named HUE (Figure 7.27) of which the light colour and intensity can be tuned via smartphone or tablet. Moreover, a range of software applications, controlled via smartphone or tablet, allows new functionality not available for the GLS product class or other consumer lamps before then. The development of LED lamps combined with other

12 In fact, it would be technically beneficial for the LED if it were to be designed into a fixture that acts as a heat sink. This could be used to achieve a lower operating temperature that would benefit the lifespan of the LED. GLS lamps are typically used for around 1,000 hours a year and thus need regular replacement. For LED lamps with lifespans of well over 20 years, replacement would become a rare event. Consequently an interface designed for regular replacement is not required. A screw base on a LED bulb can therefore be regarded as an evolutionary remnant of the days that lamps required regular replacement.

Figure 7.26. The light emitting diode or LED.

Figure 7.27. Left: the first 60W bulb by Philips awarded the L-Prize in 2009 by the U.S. Department of Energy. Right: the Philips Hue introduced in 2012.

new types of products opened up completely new opportunities in both functionality and perception, giving them a competitive edge over other GLS types, and changing the way lighting is used. As LED lamps had only just entered the market at the time of writing this thesis, further branching of the LED Product Family Tree should be expected.

The introduction of the LED bulb and other LED based lamps will disrupt lighting industry for two reasons. First, the 'conventional light'[13] products are replacement products requiring renewal every few thousand hours of operating time. Consequently the conventional lighting industry produced mainly for replacement, which is why it was called a replacement industry. The very long lifespan of LED lamps means 20 to 50 times fewer replacements, thereby removing most of the market in the event that the level of light use and the number of light points were to remain the same. Hence, a lighting industry producing LED lamps cannot be characterised as a replacement industry anymore. Secondly, the value chain for LED based lamps is completely different to the one for conventional light. The conventional light industry is used to produce more or less all components in house from raw material to finished product. Given the extremely high volumes produced, production mechanisation is key to achieving high quality for low prices. A LED (light emitting diode) is a semiconductor light source produced by semiconductor manufacturers. The diode is packaged with optical components used to shape the light radiation, and lead wires to connect to a printed circuit board. The lamp manufacturer acquires the LED as a component from another manufacturer (the supplier) and assembles it together with other sub systems (ballast, heat sink, optics etc.) in a lamp.

13 Incandescent lamp types and gas discharge lamp types are referred to as conventional light.

This process resembles consumer electronics manufacturing more than the process of producing incandescent lamps. Consequently, the industrial base used to mass manufacture conventional lamps does not suit the production of LED lamps. Change is therefore inevitable in this industry[14].

7.2.3.4 The Product Class of GLS Lamps

Section 7.2.3 has shown how three different lighting technologies evolved over time. The first of these technology families to evolve provided the incandescent lamp patented twice in 1879. After three decades, what became referred to as the GLS incandescent lamp, emerged as dominant design. This lamp remained the preferred type of electric light for consumers until the end of the 20th century.

Half a century after the commercial introduction of incandescent light technology, the gas discharge light technology family experienced a breakthrough with the introduction of the tubular fluorescent lamp in 1938. This tubular fluorescent lamp or TL was more efficient then GLS incandescent lamp from the onset. However, in markets where consumers first became used to light from the GLS incandescent lamp, these tubular fluorescent lamps were unable to oust the incumbent type. About six decades after the introduction of the GLS incandescent lamp, the Compact Flurescent Lamp or CFL was introduced as an energy-efficient alternative.

In the beginning of the 21th century, the second alternative to the GLS incandescent lamp was introduced, namely the LED bulb. As the GLS incandescent lamp, the CFL and the LED Bulb all target the same type of use, apply the same dimensions, interface and light distribution, they have together became referred to as GLS lamps. Being based on different lighting technologies but providing the same basic function, they are here defined as a *product class*.

7.2.4 Phase Out of GLS Incandescent Lamps

At the end of the 20th century, evidence built up that the production of greenhouse gasses induces climate change. In 1997 the Kyoto protocol was drafted that was intended to set binding obligations for industrialised countries to reduce emissions of greenhouse gasses. Burning fossil fuels is an important contributor to the build-up of greenhouse gasses. Therefore, targets are set to reduce emissions by increasingly stringent efficiency targets for all major energy using applications. With the CFL available as alternative for the infamously inefficient incandescent lamp, governments around the

14 The author of this thesis witnessed this change from the inside working close to the former mechanisation department of Philips Lighting.

world have deployed initiatives to phase out the GLS incandescent lamps ('[5]'in Figure 7.20) in recent years (Wikipedia, 2014). This policy has been a major support for the further rise of the CFL that, since its introduction three decades ago, has not been able to replace the incandescent lamps as general service lamp of choice by consumers, despite being much more economical in use.

Although actual phase-out[15] took more than a decade to start after the Kyoto protocol, Figure 7.25 shows a significant rise of CFL production volumes after 2000 and exceeded 25% of global GLS demand in 2007. The 21st century started as a new era for electric lighting in which halogen incandescent lamps, CFL and LED bulbs will compete with each other to fill the screw base sockets left empty by the phased-out GLS incandescent lamps.

7.2.5 The Emergence and Development of a New Type of Product: the Compact Fluorescent Lamp

In 1976 both Philips and GE developed a Compact Fluorescent Lamp, commonly known as CFL, based fluorescent tube lamp technology. The CFL was designed to compete with the GLS incandescent lamp, using similar dimensions and the same interface, allowing retrofit use in the same luminaires. In effect the introduction of the CFL opened the GLS product class, providing the same basic function (general lighting) and to be used as a substitute (using the screw base socket).

Shortly after introduction to the market, it was assumed that CFLs would soon compete with the ubiquitous GLS incandescent lamps. Firstly, because increasing energy consciousness resulting from the first oil crisis would lead to a growing interest in more efficient lighting sources. Secondly, because progress in lamp technology had opened the way for more extensive miniaturization of fluorescent lamps (Bouwknegt, 1982). This proved to be rather optimistic as revealed by Figure 7.25. Consumers did not appear to be eager to convert to this new and efficient type of lighting. The CFL innovation diffused very slowly and first targeted the service sector and not the residential market (Menanteau & Lefebvre, 2000). It would take another decade of technological development to overcome a series of disadvantages before the retrofit CFL presented some sort of competition to the GLS incandescent lamp.

15 Phasing-out of incandescent lamps started in Brazil per 2005, in the EU per 2009, in the USA per 2011 and China per 2012. Commonly, the phase-out is not enforced at once for all types of incandescent lamps, but starts with the most energy hungry ones. The halogen-incandescent lamp although belonging to the same technology family, is still in use. With the efficacy of halogen-incandescent lamps in-between that of incandescent lamps and CFL it remains to be seen if and when halogen-incandescent lamps will be banned at time of writing.

7.2.5.1 CFL Morphology

The CFL is essentially a folded up version of the straight tube fluorescent lamp with miniature ballast mounted into the base of the lamp. This required the development of a new ballast, sufficiently compact to fit inside. It required new phosphorous coatings that could be used with the smaller tubes because it needed to withstand the *'intense ultraviolet radiation occurring, for example, in lamps with a small diameter'* (Bouwknegt, 1982). It also required new tube geometries providing compactness and sufficient length, including the required production equipment. Three different tube styles evolved for CFL, as depicted in Figure 7.28. GE worked on a spiral shaped CFL (see also Figure 7.31) but abandoned the introduction because of the high investment needed to develop a production line. Philips used a simpler U-shaped tube design that was easier to produce and proceeded with production mechanization. The Philips SL18 (Self ballasted Luminescent, 18 Watts) was the first CFL to be marketed in 1981 (Figure 7.24 and also marked as '[G]' in Figure 7.20 and Figure 7.29).

CFLs come in variants with internal ballast, integrated between the discharge tube and screw base, often referred to as CFLi. CFLs are also sold with an external ballast (integrated into the luminaire), of which an example is shown in Figure 7.30 and Figure 7.29 marked with '[L]'. However, this section focuses on the CFLi that uses the same interface (Figure 7.31) as this version directly competed with the GLS incandescent lamp. From now on the abbreviation CFL used in this section refers to lamps with integrated ballast.

Over three decades many variants of the above three tube geometries have been developed to suit a variety of different market niches. Some

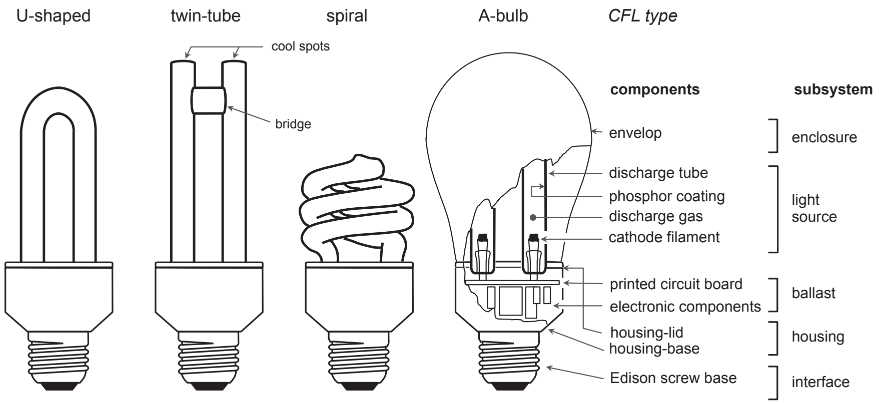


Figure 7.28. CFL system diagram. Three different CFL tube geometries evolved; if covered with a glass envelope they can be made to resemble the A-bulb incandescent GLS; the main subsystems and components are marked in this figure.

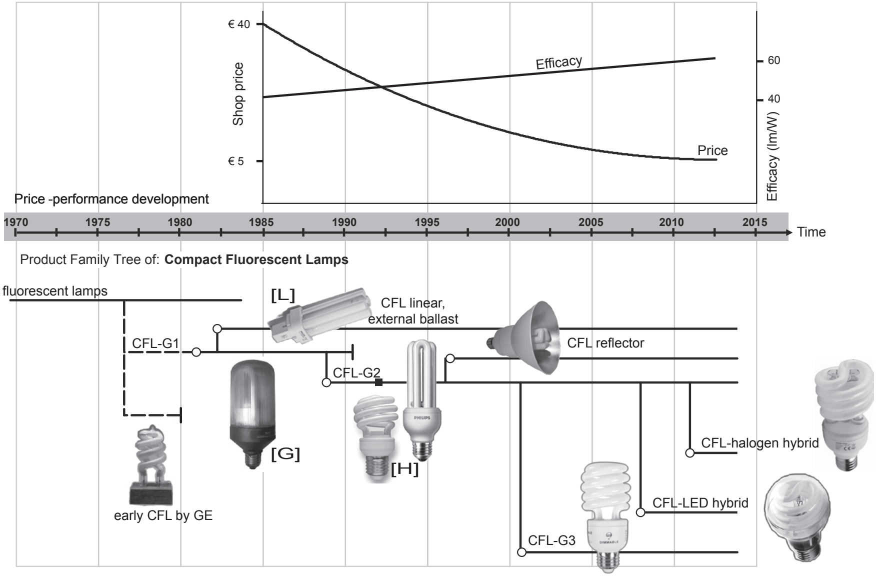


Figure 7.29. Product Evolution Diagram combining the CFL Product Family Tree, showing standard and exotic types, as well as price and performance development (based on standard types only).

Figure 7.30. The external ballast CFL.

Figure 7.31. A standard CFLi with spiral tube.

Figure 7.32. A CFL including reflector.

Figure 7.33. The CFL-halogen hybrid lamp.

Figure 7.34. The CFL-LED hybrid by OSRAM.

include an additional envelope, which makes their contour resemble an incandescent lamp (A-bulb in Figure 7.28). Similar to the GLS incandescent lamp, the standard CFL is a non-directional lamp as the tube emits light in all directions. For directional use there are CFLs types that include a reflector (Figure 7.32) on the base side that turns them into a spotlight or floodlight. There are CFLs with a daylight sensor, which switches them on automatically between dusk and dawn. GE (2011) introduced a hybrid CFL-Halogen lamp (Figure 7.33) that provides instant bright light. OSRAM (2008) introduced the DULED hybrid CFL-LED lamp (Figure 7.34) that has two modes: a first mode for normal use of the CFL source, and a second low-intensity light, using the LED source as an orientation aid in the dark (Consumentengids, 2012). Figure 7.29 contains a detailed Product Family Tree of CFLs that shows many of the above-mentioned CFL types.

7.2.5.2 Three Generations

The first generation CFLs (CFL-G1) weighed 520 grams, included a prismatic glass cover to refract the light, and was bulky compared to an incandescent lamp of less than 30 grams. This made the CFL-G1 incompatible with many situations in which conventional incandescent lamps were used. As a new type of product, the CFL-G1 started in the performance phase. The CFL-G1 used a magnetic ballast, did not produce a pleasant light colour, took three minutes to warm up, produced a 50 Hz flicker and could not be used with dimmers. Last but not least, the price of the CFL-G1 was factors higher than the price of the cheap incandescent lamps they competed with.

The ongoing miniaturisation of electronic components produced enabling technologies that fuelled a technology cycle in the subsystem ballast. At the end of the 1980s, the electronic ballast was introduced for CFLs which was much smaller than the previous magnetic version. The second generation CFLs (CFL-G2 marked as '[H]' in Figure 7.20 and Figure 7.29) marks the beginning of the optimization phase. The CFL-G2 became substantially more compact, lighter, had none of the 50 Hz flickering and was almost 10% more efficient. New mixes of components for phosphorous coating meant more and softer light colours could be offered. Consumers reacted positively to these technical improvements. Production volumes slowly increased from 1990 onwards (see also Figure 7.25). Increased competition in the manufacturing base and cheaper electronic designs drove the cost price steadily down, thereby making the CFL suitable for larger markets. The CFL-G1 disappeared from the market as it could not match the CFL-G2 in price, performance and compactness.

The evolving semiconductor industry provided cheap integrated circuits (ICs), an enabling technology that prompted a next technology cycle in the subsystem ballast. Using ICs meant the CFL could be operated more efficiently and it also worked with conventional dimmers commonly used for GLS incandescent lamps (NXP, 2009). This CFL is more efficient (up to more than 70 lm/W) and has a longer life (Waide, 2010). The third generation (CFL-G3), also referred to as the Super CFL, is currently gaining ground.

It can be argued that the CFL entered the itemization phase in the mid-1990s. Many different companies around the world manufactured CFLs. Cheap manufacturers in low wage countries like China and also in Eastern Europe and the availability of cheap electronic components caused prices to fall to below €10 (Figure 7.35). CFL prices steadily decreased and production capacity increased from 2000 onwards, thereby offering policymakers the opportunity to phase out the GLS incandescent light bulb, as an alternative was readily available in the guise of the CFL. The CFL is now in the segmentation phase. The CFL became available in similar variants as displayed in Figure 7.23 for the GLS incandescent lamp.

7.2.5.3 CFL Price and Performance Development

Many studies have investigated the development of the CFL market. Several studies also investigated CFL prices as an element of the barriers to adoption (Sandahl et al., 2006) or possible future price development (Iwafune, 2000). In this section one resource is used, namely the Consumentengids, a publication by the Dutch consumer organisation 'Consumentenbond', to analyse how price and efficacy have developed over nearly three decades. The comparative tests provide an independent and detailed overview of the technical performance of products and sales prices over time. This data was used to reconstruct the development of the average shop price and efficacy of CFLs over time. The prices analysed are referred to as 'shop prices' as they are common prices paid by consumers without the cost advantages of incentives from manufacturers (to gain market share), utilities or governments (to stimulate energy conservation). Only shop prices for standard CFL lamps with integrated ballast, which are also referred to as CFLi, have been used in this study (both magnetic and electronic). As only comparative tests from the Dutch consumer guide have been used, the products reviewed reflect CFL evolution in the Netherlands. However, given that the Netherlands has been a lead market in CFL sales per capita (Menanteau & Lefebvre, 2000), is the home market of Philips (a leading CFL manufacturer) and given that the same CFL technology is used throughout the world, with many lamps sold in the Netherlands being produced in different countries by many different manufacturers, the expectation is that the historical development analysed is valid for most geographies.

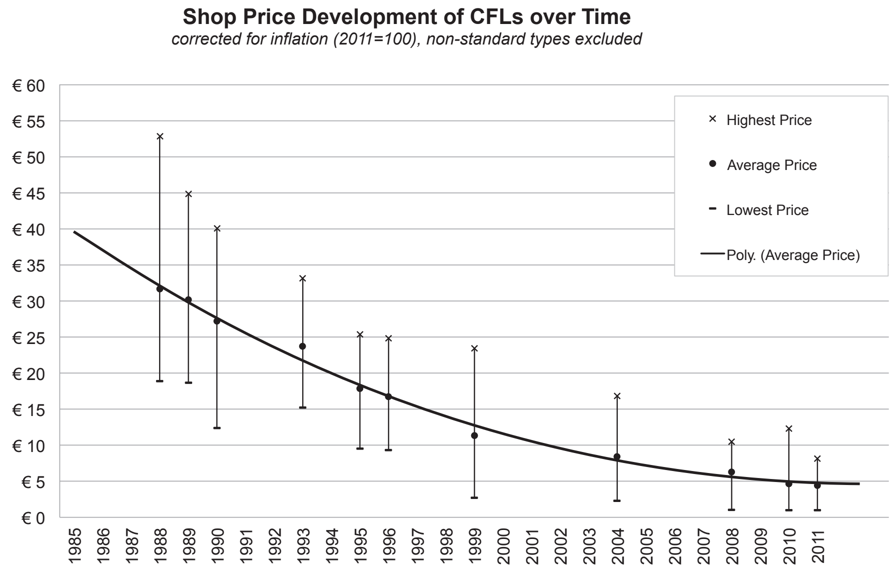


Figure 7.35. CFL shop price development over time in the Netherlands as published by Consumentenbond. Non-standard types have been excluded to make the comparison as uniform as possible (Consumentengids, 1988; 1989; 1990a; 1993a; 1995; 1996; 1999; 2004; 2008; 2010c; 2011). Prices have been corrected for inflation with 2011 as the reference year using Consumer Price Index figures published by Statistics Netherlands.

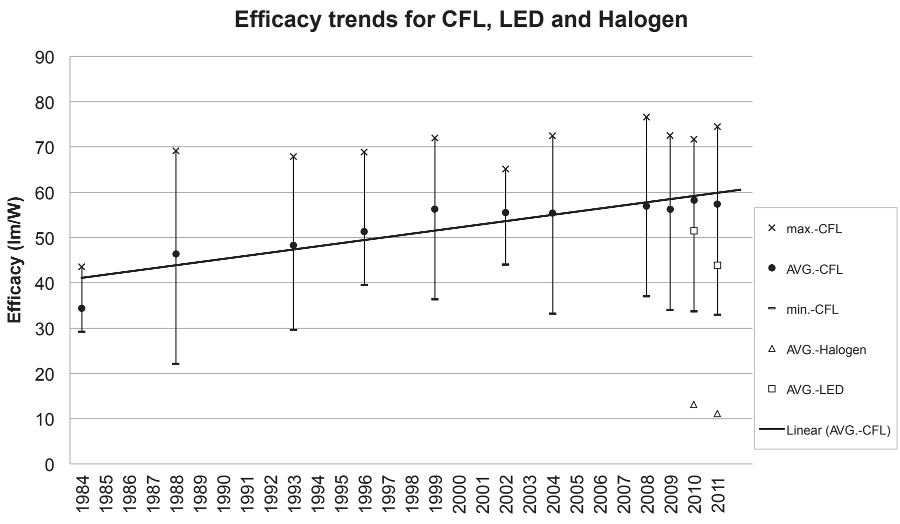


Figure 7.36. CFL efficacy development over time in which the last two year include the GLS halogen incandescent lamp and the GLS LED bulb (Consumentengids, 1984a; 1988; 1993; 1995; 1999; 2004; 2008; 2009; 2010b; 2011).

Figure 7.35 shows the development of shop prices from an average of just over €30 in 1988 to below €5 in 2011. The prices have been corrected for inflation, using 2011 as the reference year. According to the International Energy Agency, the overcapacity that remained after the incandescent GLS replacement peak is expected to erode prices even further (Waide, 2010). The luminous efficacy of lamps is expressed in lumen per Watt (lm/W) and used to define how much electric energy is converted into visible light. Figure 7.36 shows how the average CFL efficacy improved from below 40 to about 60 lm/W in 2010.

7.2.6 Competition amongst GLS Lamps

Christensen (1997) noted that technology platforms with initially inferior price-performance ratios can develop over time and overtake the market shares of previously dominant types. For GLS lamps, this picture proved to be more complex. CFLs have quickly outperformed GLS incandescent lamps from the point of view of economics (Lefèvre, et al., 2006). However, they have struggled to gain a market share. It appears that technological properties of the fluorescent lighting technology were the factor that constrained consumer perception and so withheld CFL from ousting the incandescent lamp on economic merits. Moreover, the final breakthrough may be attributed to legislation, rather than superior economic performance. Three decades after the introduction of the CFL, the LED bulb was introduced as a new contender in the GLS product class. Although LED already existed as a technology before the CFL was introduced, it had not yet been applied to general illumination. It took many technology cycles in the LED industry until white light could be provided, power became sufficiently high and prices low enough to allow useful application in the GLS product class. LED bulbs have developed since around the year 2000 with the first 100W incandescent equivalent introduced to the market in the USA in 2011 (Switch Lighting, 2011).

LED bulbs are still expensive compared to CFLs, but the technology is evolving rapidly. In just a few years Consumentengids (2010a; 2013a; 2013b) changed its reflections from ‘waiting’ to ‘encouraging’. Prices for LED bulbs are going down because LED elements are becoming cheaper, as dictated by Haitz’ law (Haitz et al., 1999). In addition, LED efficacy development is expected to continue for some time and eventually surpass that of CFL lamps by a factor of three (DOE, 2011b; Haitz & Tsao, 2011).
Economic performance is advertised as an important argument for the adoption of energy-efficient lighting technologies. Institutional buyers are known to use rational TCO comparisons. However, consumers behave less rationally. What is more, technical differences between available GLS lamp alternatives (halogen incandescent, CFL and LED bulb) mean that

consumers at large are unable to calculate the economic benefits of new efficient lighting technologies. Besides that, differences in the definition of lifetime and testing protocols for GLS lamps make it difficult, at the very least, to make meaningful economic comparisons, even for institutional buyers.

It is clear that LED lamps provide functionality not offered by both incandescent and gas discharge lamps. Therefore, it can be expected that competition between incumbent light sources and LED will go beyond traditional competitive properties such as purchase price, lifespan, efficacy and colour perception. The evolution of lighting technology has entered a new era. Taking account of the fact that LED for general lighting purpose is only a recent phenomenon, it is clear that the evolution of electric lighting will not stop at the developments spanning more than two centuries described in this section. Further development of LED lighting, software applications used to control light sources, and expected introduction of new types of light sources, for example based on so-called OLED[16] technology, will change the way we use electric lighting. Over time it might mean the end of the product class GLS, and most likely the introduction of new ones.

7.2.7 Conclusion and Discussion

Section 7.2 elaborated on how a new type of product – the general lighting solution commonly referred to as the GLS incandescent lamp – came about and developed through time into a family of more advanced versions. Subsequently, two more types of product evolved with the same basic function and addressing similar types of use. Together these three products constitute what is defined here as the GLS product class. Because each of these lamps uses a different physical principle to generate light, they belong to different technology families. The development history of three different GLS lamps has been mapped in a Product Evolution Diagram using three separate Product Family Trees, and one mutual ecosystem.

The case study of GLS lamps clearly shows that major inventions, like the incandescent lamp, the CFL and the LED bulb, do not just occur as stand-alone events, nor are they the work of a single genius. Major technological developments build on prior knowledge accumulation that provides a

16 OLED means Organic LED. OLEDs are not based on inorganic chemistry as LEDs that are based on silicon. OLEDs are made from organic molecules with semiconductor properties. Where LEDs are essentially point sources, OLED can better be described as illuminating surfaces. This means OLEDs are very suitable for the illumination of flat surfaces like screens of smartphones, televisions or roof tiles. These are the first niches in which OLEDs are applied. OLEDs were introduced decades after the LED and are therefore technically less mature and consequently much more expensive. At the time of writing there are not yet any significant applications that use OLED for general illumination and it remains to be seen how OLED as an illumination technology will develop.

foundation built by many individuals and collectives over the course of many decades. It is on this foundation that new types of products can emerge. The three examples reviewed in this section show that each required that same technological foundation, here referred to as the roots, before these new types of products could emerge. These root periods, that commonly require decades of experimenting with technologies, enable the 'breakthrough innovations' that are instrumental in the conception of new types of products. Once a new type of product emerges, technology cycles characterise further development of the product and can be described as an evolutionary process in terms of variation (technological discontinuity) selection (era of ferment) and retention (dominant design), both at system (or product) and subsystem level (Anderson & Tushman, 1990; Tushman & Murmann, 1998; Murmann & Frenken, 2006). Development into new types of products first focuses on the 'what', addressing functionality, and later on the 'how', addressing cost (Abernathy & Utterback, 1975; Eger, 2007a). For the case of the GLS incandescent lamp technology cycles in the subsystems of light source, enclosure and interface have been described here. The case of the CFL shows similar technology cycles in the subsystems of light source and ballast. The price and the performance development for the CFL have been visualized over time. Although it is tempting to view the battle between the different GLS products in price-performance ratios only, this case study shows that consumers greatly value other properties, like the extent to which lamps can reveal colours of illuminated objects, the start-up time and the ability to be dimmed. It also transpired that differences in lifetime and testing protocols make it difficulty to make meaningful economic comparisons, even for institutional buyers.

Furthermore, literature shows that in the cases of the incandescent lamp and CFL described here, the 'breakthrough innovations' that led to the first commercially available products occurred not once but at least twice, more or less simultaneously on different continents and in like minds.

This supports the following propositions;

P1: *Technological innovation can be described as an evolutionary process.*

P2: *The emergence of new types of products, and their subsequent development into families of advanced types, can be described as an evolutionary process.*

P3: *Evolution in products can be visualised as a Product Family Tree.*

The rise of the GLS incandescent lamp is inextricably linked to electrification, a large technological transition that has been described by Geels (2002) as an evolutionary reconfiguration process that unfolds on multiple levels.
As described by Bijker (1997) GLS incandescent lamps became a main consumer of electric energy use that needed to be generated by companies referred to as the utilities. It was their fear of a reduction in electricity consumption that made the utilities influence the development of intrinsically more efficient gas discharge lighting technology towards higher illumination levels instead of higher efficiency in the 1930s. Four decades later the perception of the availability of natural resources had changed drastically. With the need for energy efficient products now apparent, the CFL was developed as a retrofit alternative to the GLS incandescent lamp. Although it was first assumed that soon after introduction the CFL would compete with the GLS incandescent lamp, it transpired that consumers still preferred the incumbent two decades later. It was only after climate change mitigation efforts discussed in the Kyoto protocol that legislation was introduced that phased out the use of the GLS incandescent lamps.
The case of the CFL illustrates that the process of evolution in products cannot be understood if described in technology terms only. The ecosystem that constitutes contextual factors like societal change, economic development and legislation has been shown to be part and parcel of the evolution of the CFL.

> This supports the following propositions:
> P4: *The influences of a context on the evolution of a product can be mapped as an ecosystem.*
> P5: *To understand how products evolve, one needs to analyse the interaction between a product family and ecosystem over time.*

One can discuss to what extent the CFL is a successful product, or not. The fact that the CFL could not oust the GLS incandescent lamp based on consumer preference, could be used as an argument to advocate it is as a product which is at least partially unsuccessful or unpopular. However, the mere fact that billions of CFL lamps have been produced so far, and the role it has played in the transition towards energy-efficient lighting, are arguments for it being a successful product. Without having to answer the question, it can be remarked that investigating both successful and less successful cases probably contributes to the understanding of *how new types* *of products come about and develop through time into families of more advanced versions*. Although the CFL case was not chosen to explore an unsuccessful product, in retrospect it can be pointed out that it does make an interesting case to study because of its debatable level of success. This contrasts with cases that undoubtedly are regarded as successful (e.g. the GLS incandescent lamp) or those commonly regarded as failures (e.g. the unsuccessful development of a guided-transportation system in Paris as described by Latour (1993)).

8

Results from Education

8.0 Introduction

Evolutionary Product Development has been lectured at the University of Twente since 2005 and has been attended by a total of 294 students who investigated 170 different products (see also Eger & Ehlhardt (2017)). The research project described in this thesis started in 2010 and followed students that reported from 2011 onwards. In the period 2011 to 2015 a total of 143 students attended the course and investigated 82 different products. These students and the subjects studied are listed in Appendix A.

This chapter discusses work by students in the period 2011-2015. It particularly reviews the way these students pictured product development history. It also presents two examples of design work by students. Students who reported up to 2011 had not yet been lectured on the use of the Product Family Tree or the Product Evolution Diagram. From 2012 onwards the lecture series contained information on the Product Family Tree and ecosystem. The research project progressed and in 2013 a decision was taken to introduce the name *Product Evolution Diagram* for the analytical framework that integrates the two elements of *Product Family Tree* and *ecosystem*. The lectures 2014 and 2015 included this new name.

8.1 Examples of Work by Students

The purpose of reviewing work by students here is threefold. First of all the examples are used to reflect on the propositions posed for this research project. Second, the examples are used to examine whether students are able to use analytical framework provided. And third, the cases will be used to examine what particular issues students encountered in the cases analysed and what solutions they provided.

Below five examples are discussed of ways students solved different topics in their work.

Example 1: before and after lecture on Product Evolution Diagram
A total of five students analysed the development history of the electric toothbrush. Examples of work by two of them are included here. The first example (Figure 8.1) was produced in 2011, before a lecture on Product Evolution Diagram or its elements was provided. The figure shows a timeline with product phases. Connected to these phases are pictures of different electrical toothbrushes through time. The example contains no information on different brushing mechanisms, nor on the relationship between different models or any external influences. Other work by students

in 2011 contained similar representations of a timeline, a mapping of the product phases, and pictures of products related to the product phases. No interrelation between products, functional mechanisms or segments has been included in any of these reports.

The second example (Figure 8.2) shows a complete Product Evolution Diagram. The Product Family Tree shows how, over time, different segments evolve and distinguishes different brushing mechanisms. An Ecosystem is provided placing several events in time that influenced the evolution of electric toothbrushes. These events are organised according to the suggested PEST factors and here include, for example, (technological) the invention of nylon, the toothbrush engine, (political) recalls of toothbrushes with a potential shock hazard and an ISO standard for toothbrushes.

Example 2: enabling technologies

The influence enabling technologies have on an evolving product family was discussed during lectures given as part of courses on evolutionary product development. The proposed method for including references to enabling technologies has been to incorporate them into the ecosystem as shown in Figure 8.2. Several students presented an interesting alternative to this and included enabling technologies using visual references. An example picturing the evolution of backpacks (Figure 8.3) by Liesbeth Stam elaborates on the use of synthetic fabrics and polymer foams using an insert to the Product Family Tree. Robbert Bakker, who analysed the historical development of the bicycle, provides another example by mapping the introduction of technological solutions for subsystems below the Product Family Tree (Figure 8.4). Several of these technological solutions subsequently became dominant designs for these subsystems.

Figure 3.3 has been shown in the lectures from 2012 onwards and depicts how an era of ferment is closed by a dominant design, then followed by an era of incremental change, which is closed by a technological discontinuity. However, how this affects subsystems as discussed in section 3.3 was not shared with students in any of the years the lecture has been provided.

The fact that these students noted the introduction of new designs for subsystems, and the way they picture it, shows that they are familiar with the analytical notion that products (systems) consist of subsystems that have their own technological challenges and associated design cycles.

Example 3: visualizing additional parameters

The case of the Compact Fluorescent Lamp presented in Figure 7.28 shows how a Product Family Tree can be juxtaposed with a graph displaying development of parameters related to the evolving product. Marleen

Offringa, who analysed the evolution of ice skates, elaborated a Product Evolution Diagram (Figure 8.5) including the average winter temperature plotted over time in the ecosystem. Her report described how the ‘little ice age’ provided a context in which ice-skating became commonly practised as often pictured by 17th century Dutch painters. Offringa also shows how the speed achieved in ice-skating develops over time and relates to an evolving product family (Figure 8.6).

Example 4: functionality and standards
The development history of car radios was analysed by Kay Hoogsteder in 2015. Hoogsteder remarks in his report that, over time, a lot of functionality was added to the system that was originally only used to listen to the radio in the car. As time passed, new technologies and standards used to play music were introduced, which has had a major influence on the product initially referred to as ‘car radio’. Hoogsteder remarks that, at time of writing, the product has evolved into a ‘car entertainment system’, is used for much more than only the radio and commonly uses touch screens similar to those found on smartphones. Remarkably, although his report contains many pictures of car radio models though time, his Product Evolution Diagram (Figure 8.7) only contains text and maps out how radio technology, other relevant music standards and other related functionalities have been introduced over time.

Example 5: design work
The evolutionary product development course consisted of two parts: an analysis and a design. The first focused on analysing the development history of a product. The second part focused on designing an evolutionary next version of the product using the analytical pre-work, and suggestions provided by the product phases theory. Examples of work by two students who have provided excellent designs in the second course have been included here.

Noor Reigersman analysed the development of child restraint systems. Starting with a paper provided by the author of this thesis, Reigersman (2014a) found further elements of the development history of this product. The case included in Chapter 7 made thankful use of additional insights. The next section contains a Product Evolution Diagram with an elaborate ecosystem (Figure 8.8a) and a Product Family Tree (Figure 8.8b). In the second part of the course, Reigersman (2014b) developed a design for an evolutionary next version of the child restrain system (Figure 8.9).

Maarten Michel analysed the development history of basketball shoes and provided another interesting design case, which is included here. Analysing the context, Michel remarks that the Hip Hop culture became mainstream in the 1980s. An element of this culture is the use of sports shoes for casual use (also referred to as sneakers). At around this time companies started to provide so-called signature shoes that are associated with certain famous basketball players. These signature shoes have become a commercially significant development and a Product Family Tree of them is provided in Figure 8.10. Michel decided to focus on star player Anthony Davis who does not yet have a signature shoe. Davis is nicknamed ‘the Brow’ for his characteristic eyebrow and Michel uses this visual characteristic as a starting point for his design (Figure 8.10).

8.2 Conclusion

This research project aims to provide a better understanding of the way new (types of) products come about and develop into families of more advanced versions. To that end an analytical framework named the Product Evolution Diagram has been provided, which many students have successfully applied as shown in this chapter.

The research also aims to connect the study of industrial design engineering with other schools of thought as described in Chapter 3, that study the process of innovation. The aim is that this contributes to further academic forming of students of industrial design engineering.

Looking through the examples of work provided in section 8.1, it can be concluded that the students of industrial design engineering from the University of Twente are able to use the analytical framework provided and map the development history of an evolving product family to form a Product Evolution Diagram. Students already used visual mapping techniques before the Product Evolution Diagram or elements of it were introduced. This may come as no surprise as students industrial design engineering are trained to use visual elements in their work.

The Product Evolution Diagram provides them with a systematic analytical framework and a template for reporting their findings. It appears that students do not always apply the Product Evolution Diagram in exactly the same way as suggested in lectures. Nevertheless, it would seem to be the case that the variants used are easy to comprehend. Besides, inventive ideas to visualize particular aspects like ‘enabling technologies’ (Figure 8.3, Figure 8.4) and ‘parameters’ (Figure 8.5, Figure 8.6) can be regarded as interesting additions.

P2: *The emergence of new types of products, and their subsequent development into families of advanced types, can be described as an evolutionary process.*
P3: *Evolution in products can be visualised as a Product Family Tree.*
P4: *The influences of a context on the evolution of a product can be mapped as an ecosystem.*
Propositions P2, P3 and P4 are supported by the examples shown in section 8.1.

Besides the academic objectives of this research project, it should be noted that students who followed the course in Evolutionary Product Development have shown they are able to derive valuable design directions from their analytical work. Design work of two of them has been included in this chapter. The extent to which this particular course and the design approach provided lead to more successful product designs or professionals involved in new product development remains a subject for further research.

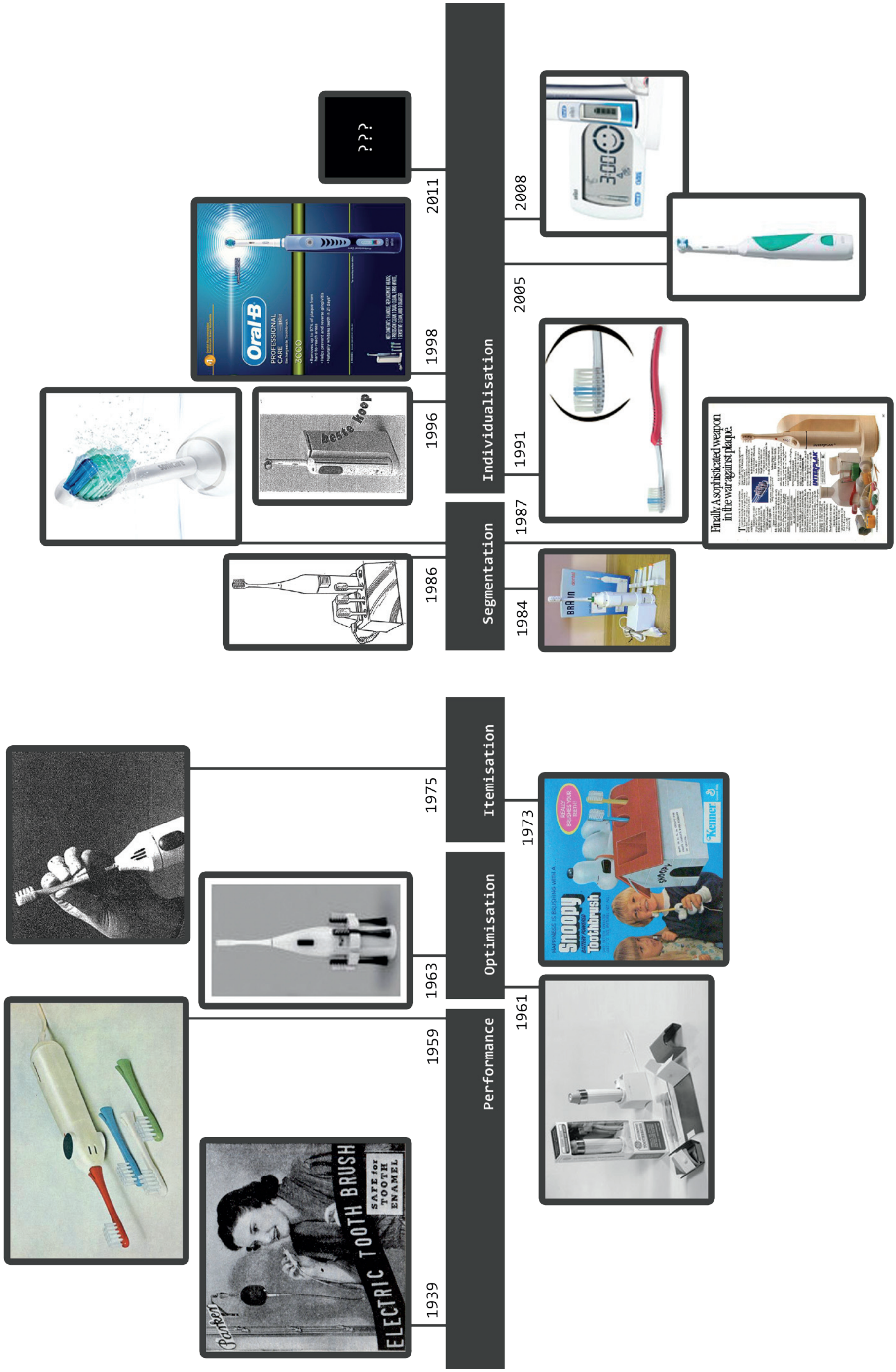


Figure 8.1. Timeline with product phases and associated electric toothbrushes (Bijkerk, 2011).

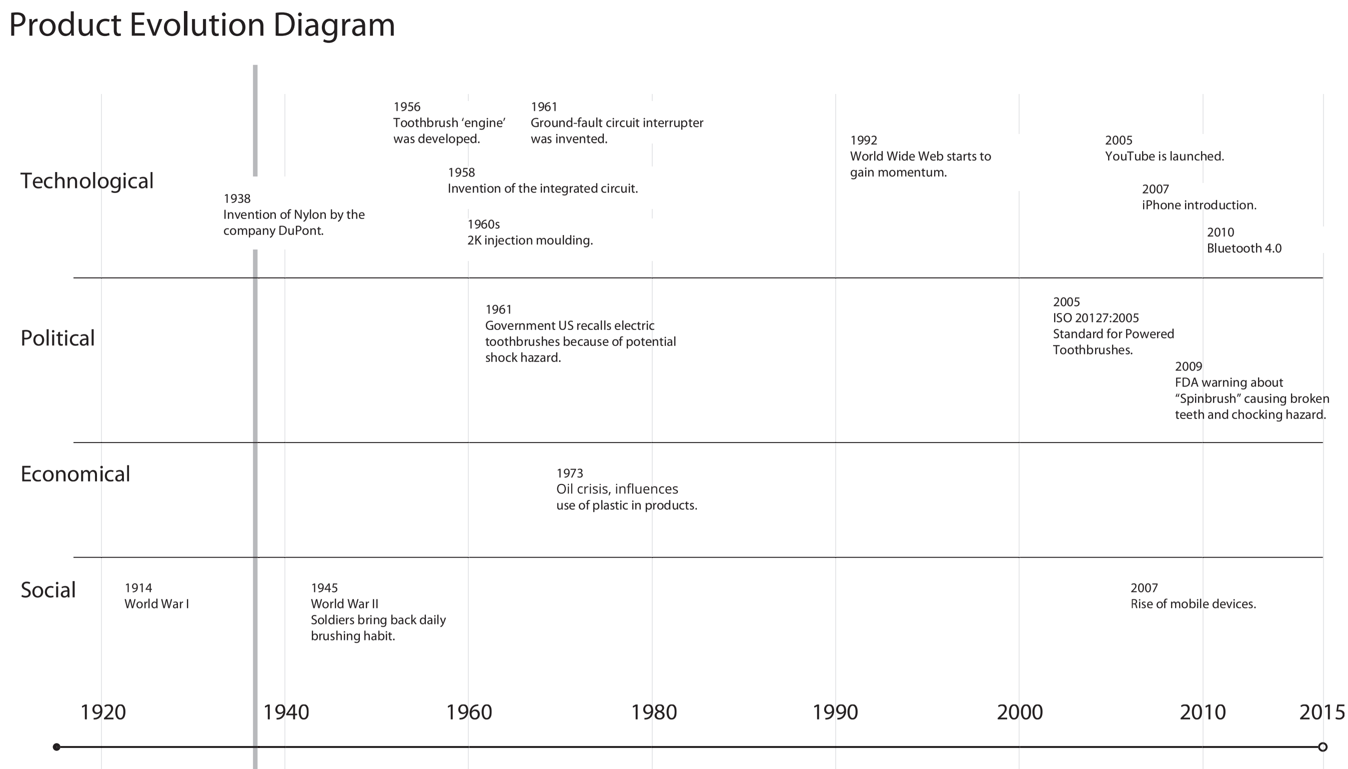
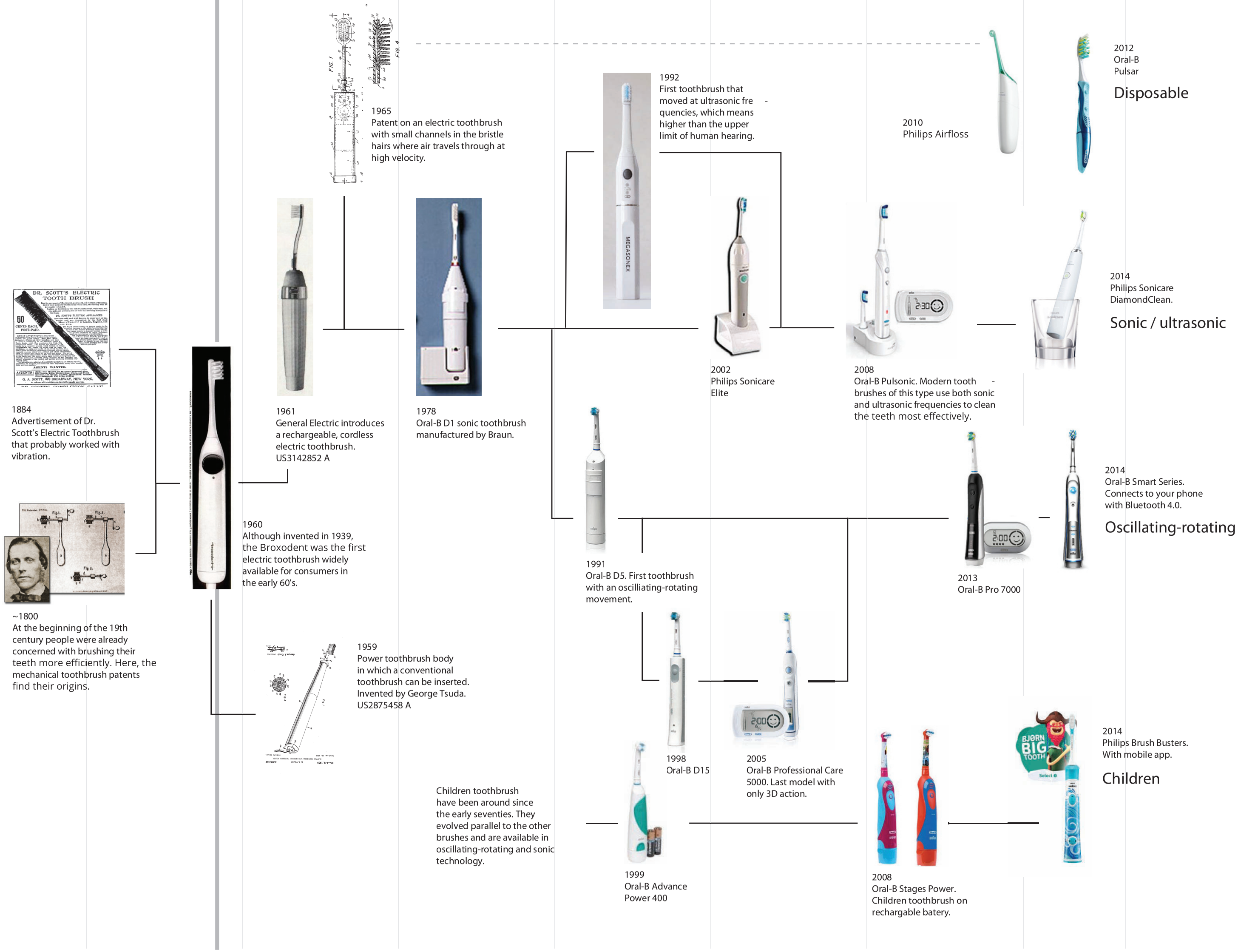


Figure 8.2. Product Evolution Diagram for an electric toothbrush (Hout van den, 2015).


~1800
At the beginning of the 19th century people were already concerned with brushing their teeth more efficiently. Here, the mechanical toothbrush patents find their origins.
1884
Advertisement of Dr. Scott's Electric Toothbrush that probably worked with vibration.
DR. SCOTT'S ELECTRIC TOOTH BRUSH
1960
Although invented in 1939, the Broxodent was the first electric toothbrush widely available for consumers in the early 60's.
1959
Power toothbrush body in which a conventional toothbrush can be inserted. Invented by George Tsuda. US2875458 A
1961
General Electric introduces a rechargeable, cordless electric toothbrush. US3142852 A
1965
Patent on an electric toothbrush with small channels in the bristle hairs where air travels through at high velocity.
1978
Oral-B D1 sonic toothbrush manufactured by Braun.
1992
First toothbrush that moved at ultrasonic fre - quencies, which means higher than the upper limit of human hearing.
MEGASONEX
2002
Philips Sonicare Elite
2008
Oral-B Pulsonic. Modern tooth - brushes of this type use both sonic and ultrasonic frequencies to clean the teeth most effectively.
2014
Philips Sonicare DiamondClean.
Sonic / ultrasonic
2010
Philips Airfloss
2012
Oral-B Pulsar
Disposable
1991
Oral-B D5. First toothbrush with an oscilliating-rotating movement.
1998
Oral-B D15
2005
Oral-B Professional Care 5000. Last model with only 3D action.
2013
Oral-B Pro 7000
2014
Oral-B Smart Series. Connects to your phone with Bluetooth 4.0.
Oscillating-rotating
Children toothbrush have been around since the early seventies. They evolved parallel to the other brushes and are available in oscillating-rotating and sonic technology.
1999
Oral-B Advance Power 400
2008
Oral-B Stages Power. Children toothbrush on rechargable batery.
2014
Philips Brush Busters. With mobile app.
BJØRN BIG TOOTH
Children

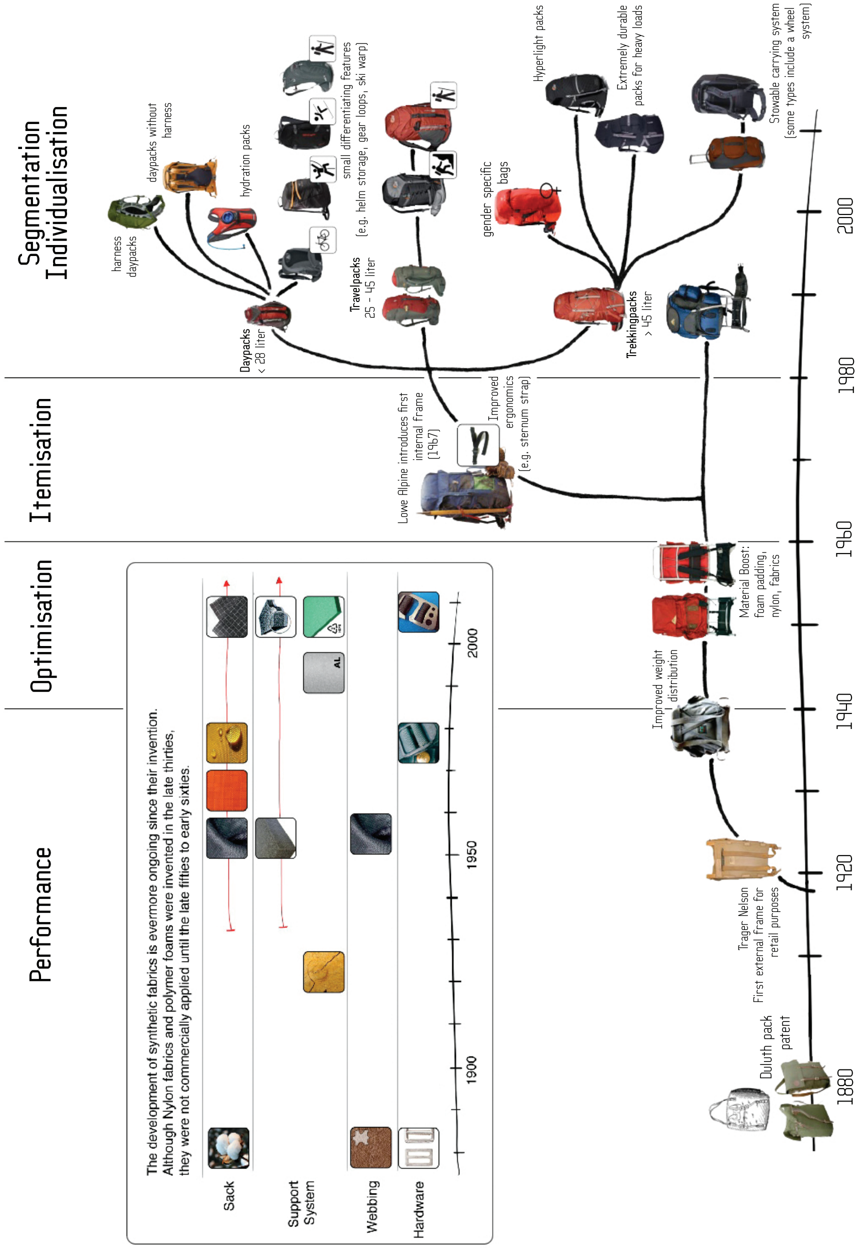


Figure 8.3. Product Family Tree of backpacks (Stam, 2012).

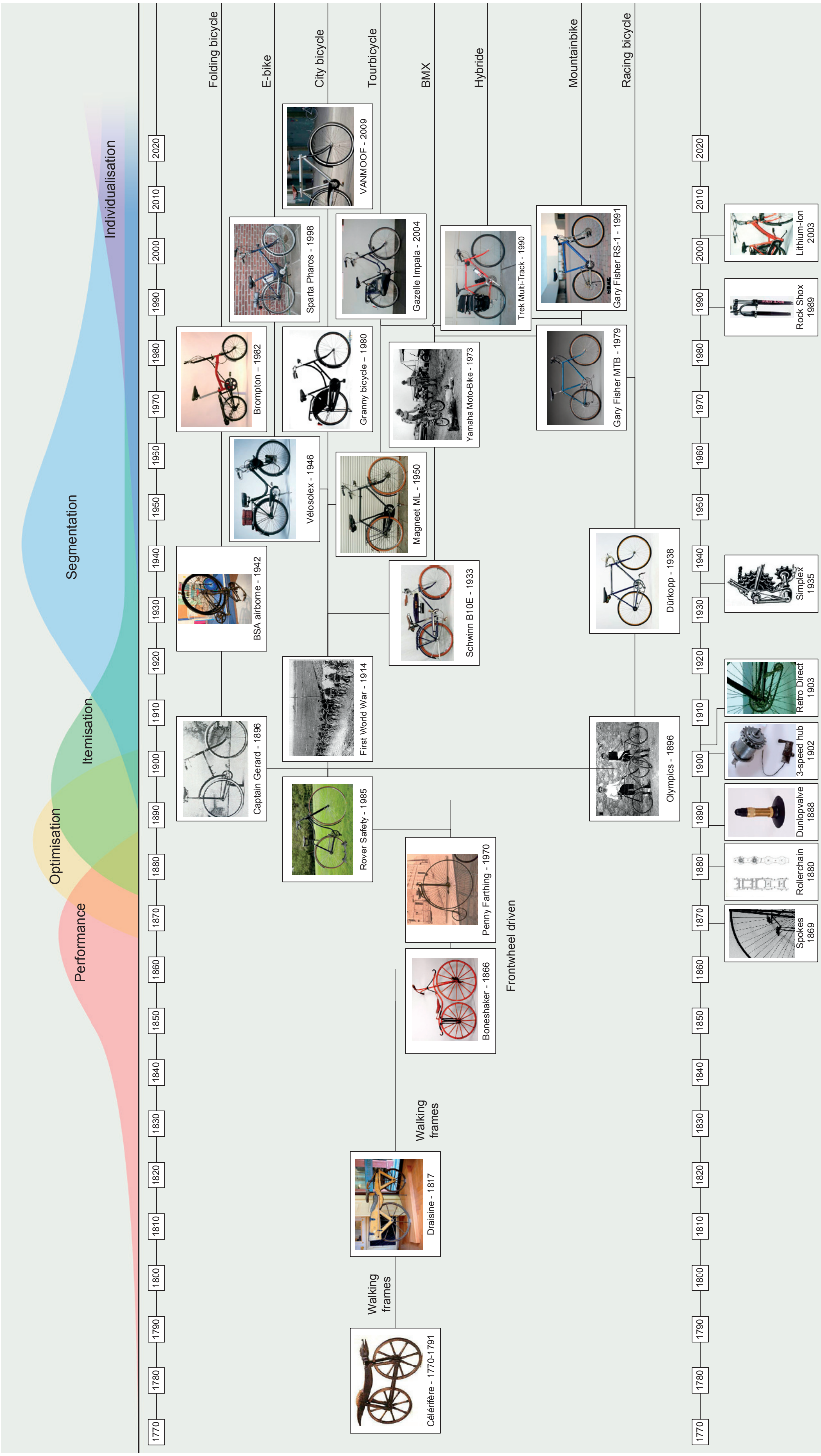


Figure 8.4. Product Family Tree of Bicycles (Bakker, 2013).

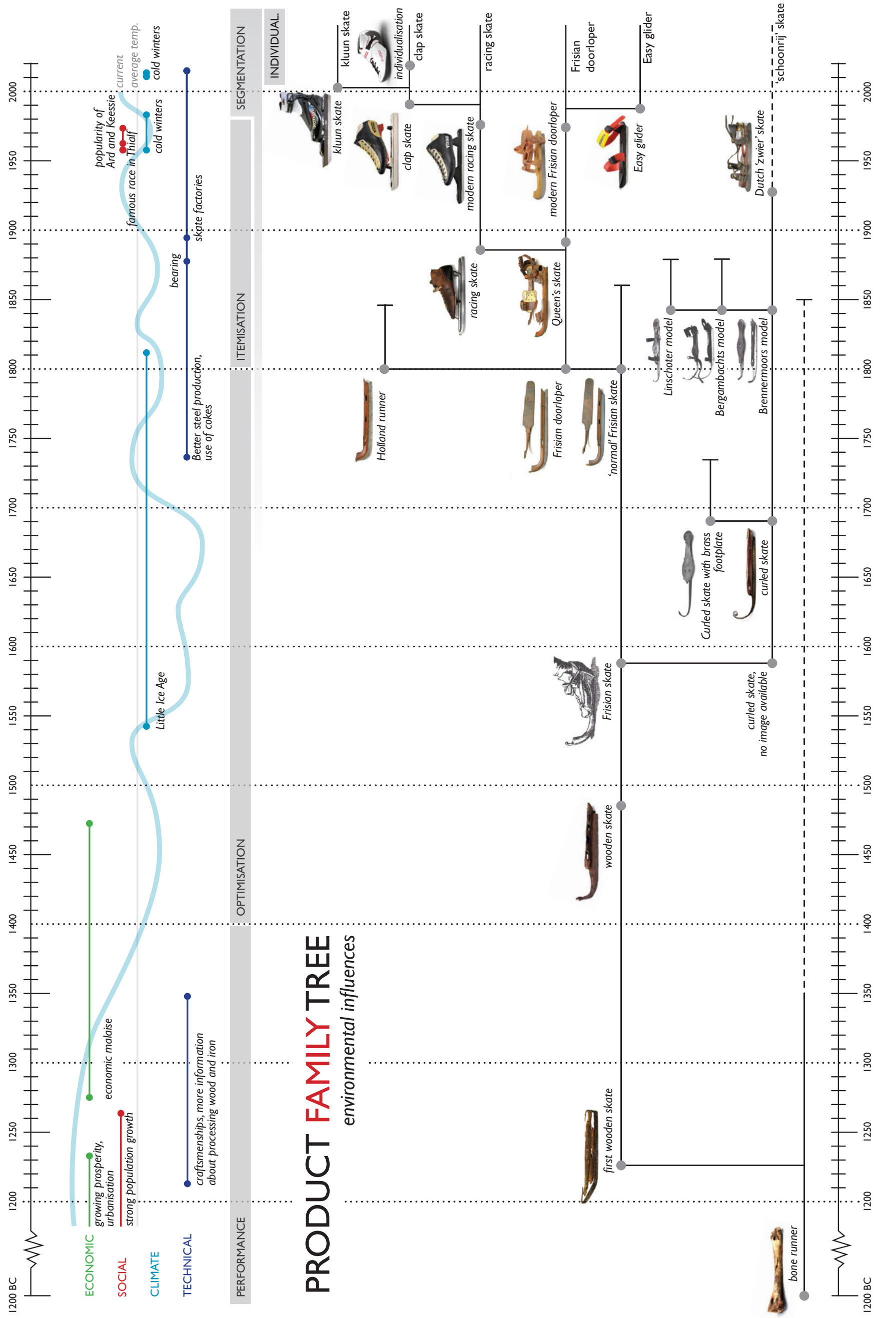


Figure 8.5. Product Family Tree of ice skates juxtaposed with ecosystem including temperature changes related to climate change (Offringa, 2014).

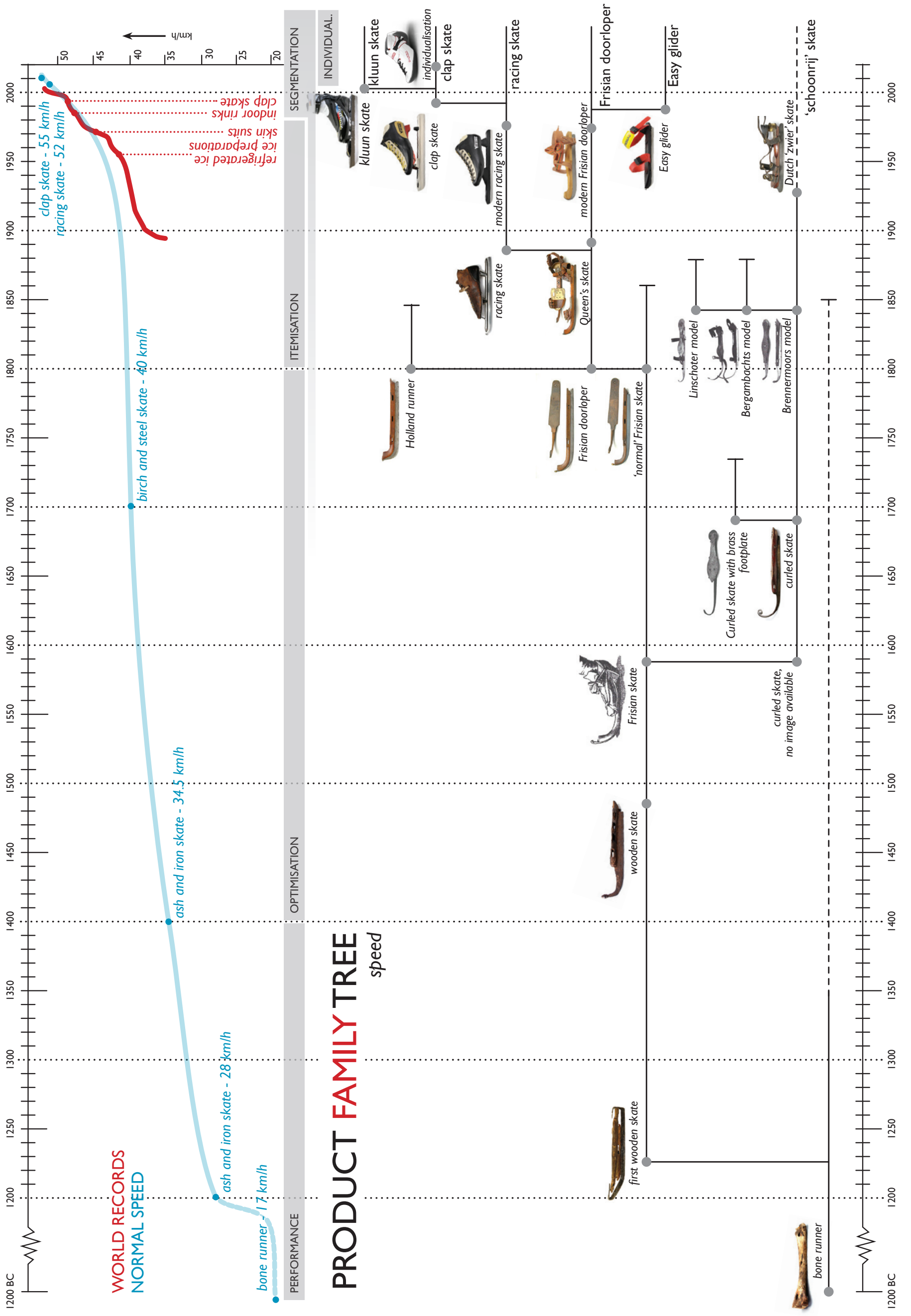


Figure 8.6. Product Family Tree of ice skates juxtaposed with speed achieved (Offringa, 2014).

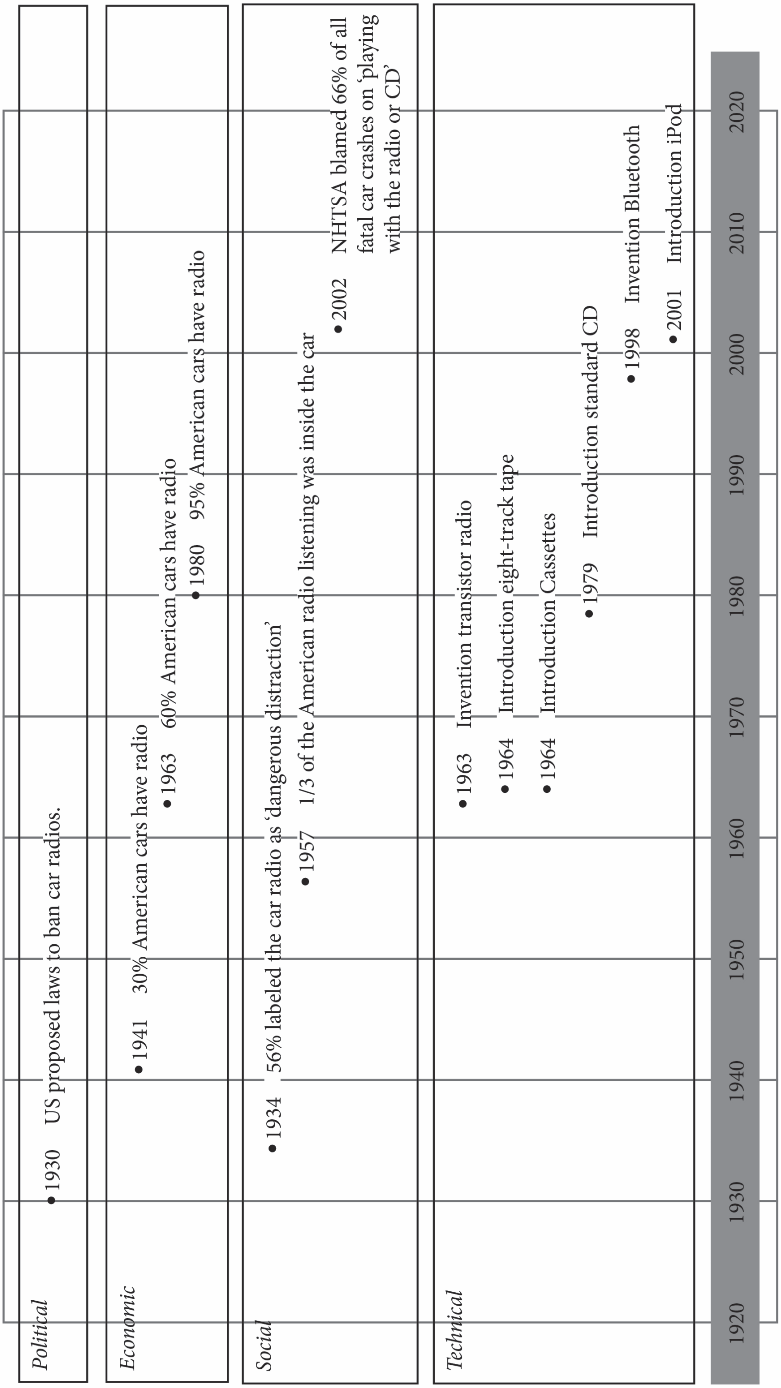
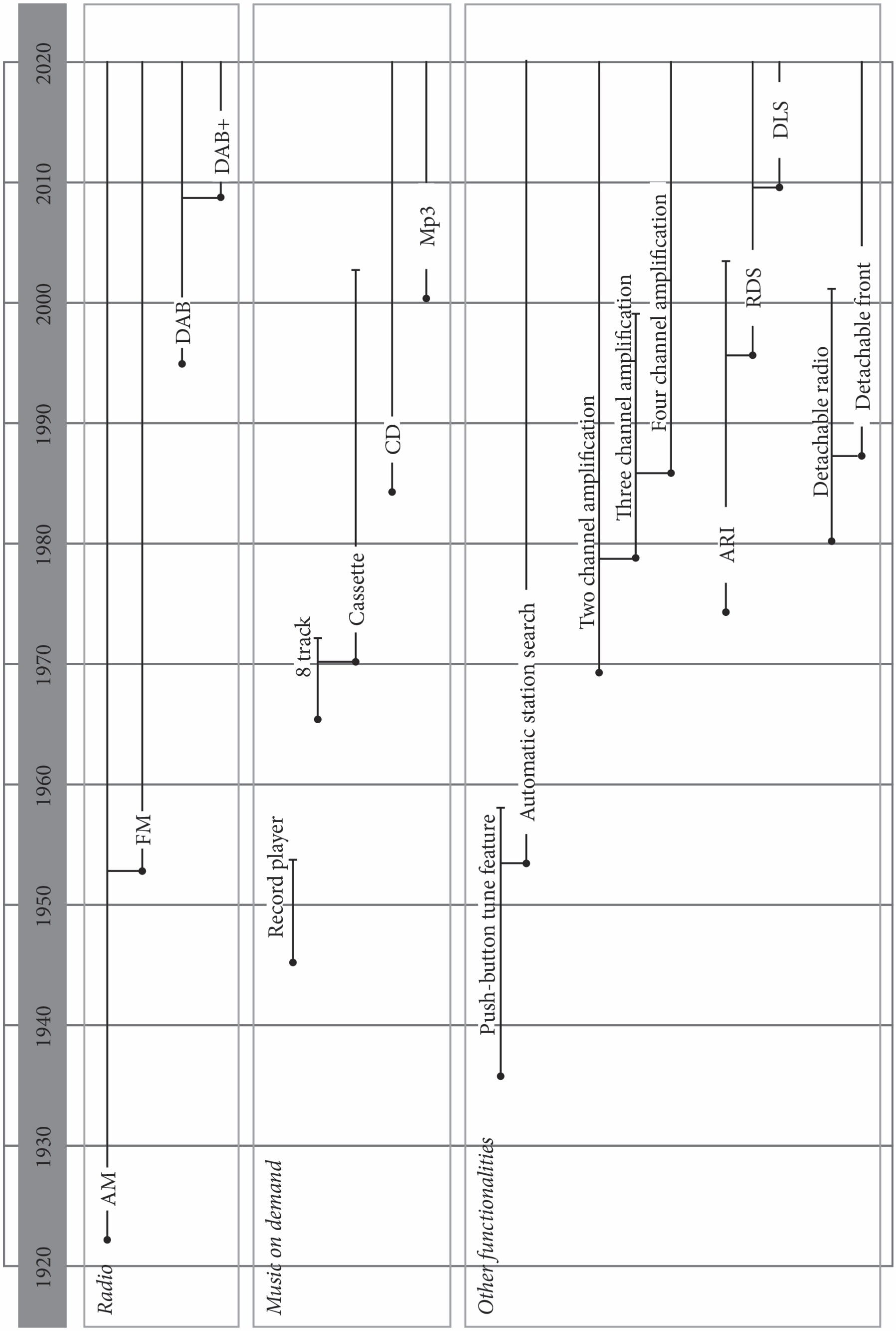


Figure 8.7. Product Family Tree of car radios (Hoogsteder, 2015).


1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
Radio
AM
FM
DAB
DAB+
Music on demand
Record player
8 track
Cassette
CD
Mp3
Other functionalities
Push-button tune feature
Automatic station search
Two channel amplification
Three channel amplification
Four channel amplification
ARI
RDS
DLS
Detachable radio
Detachable front

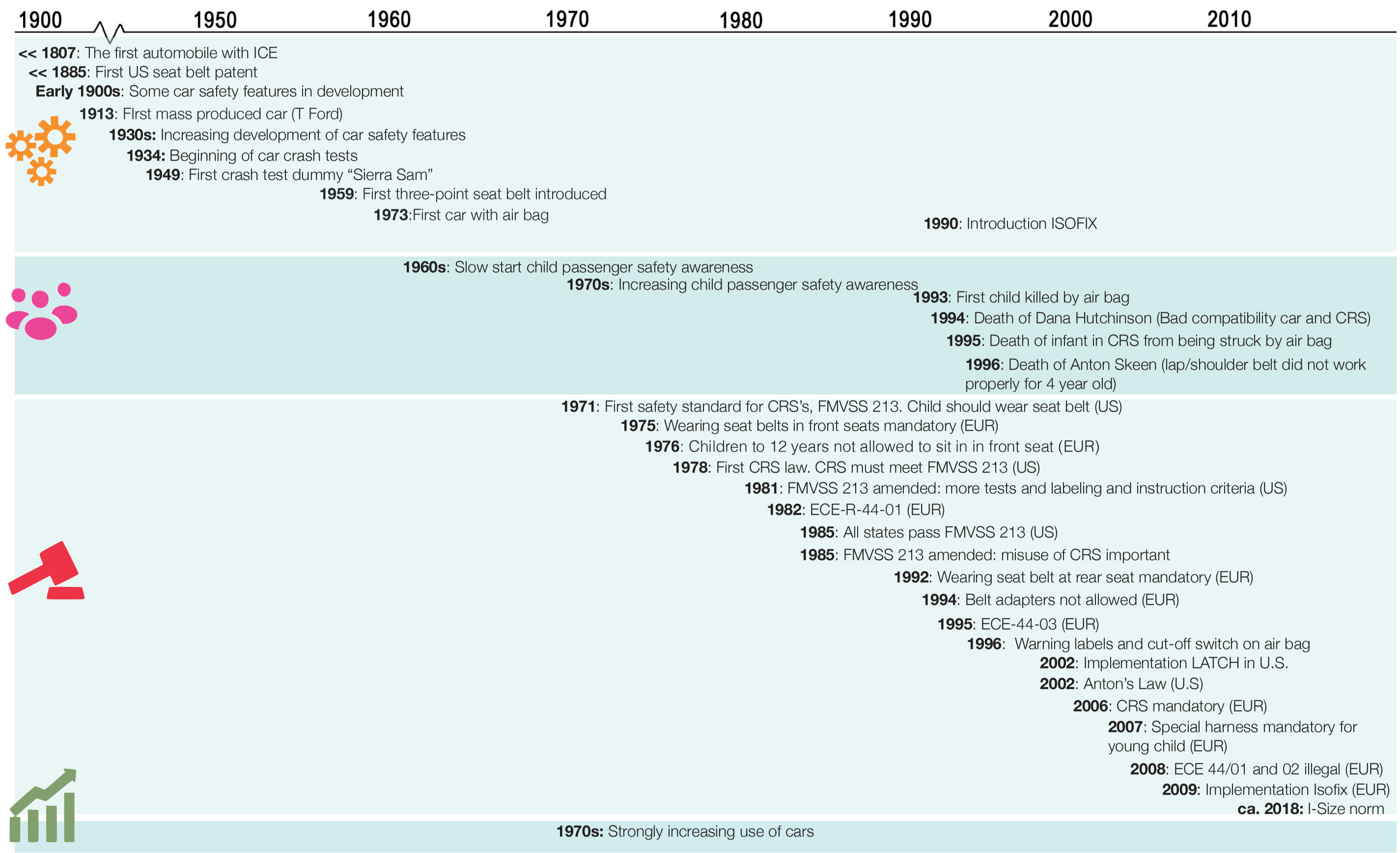


Figure 8.8a. Ecosystem of child restraint systems development (Reigersman, 2014a).

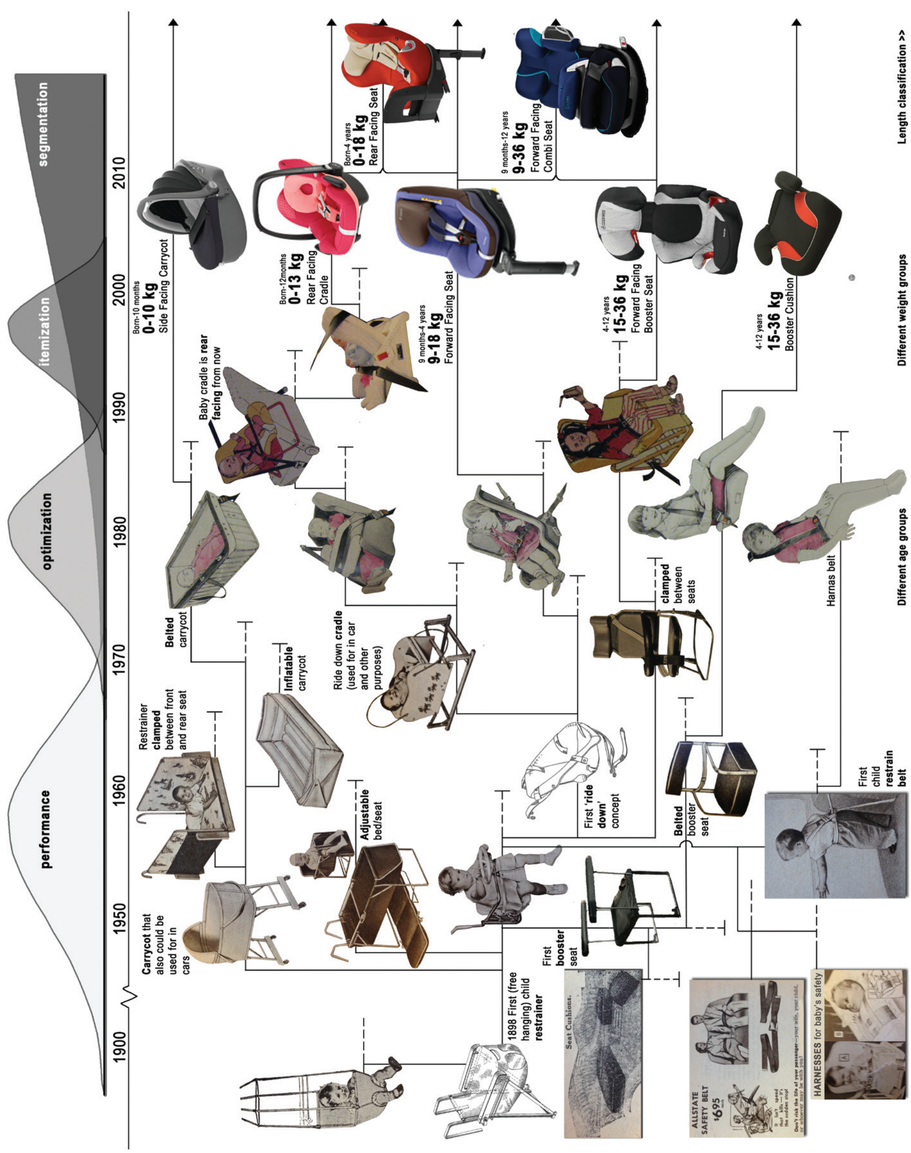


Figure 8.8b. Product Family Tree of child restraint systems (Reigersman, 2014a).

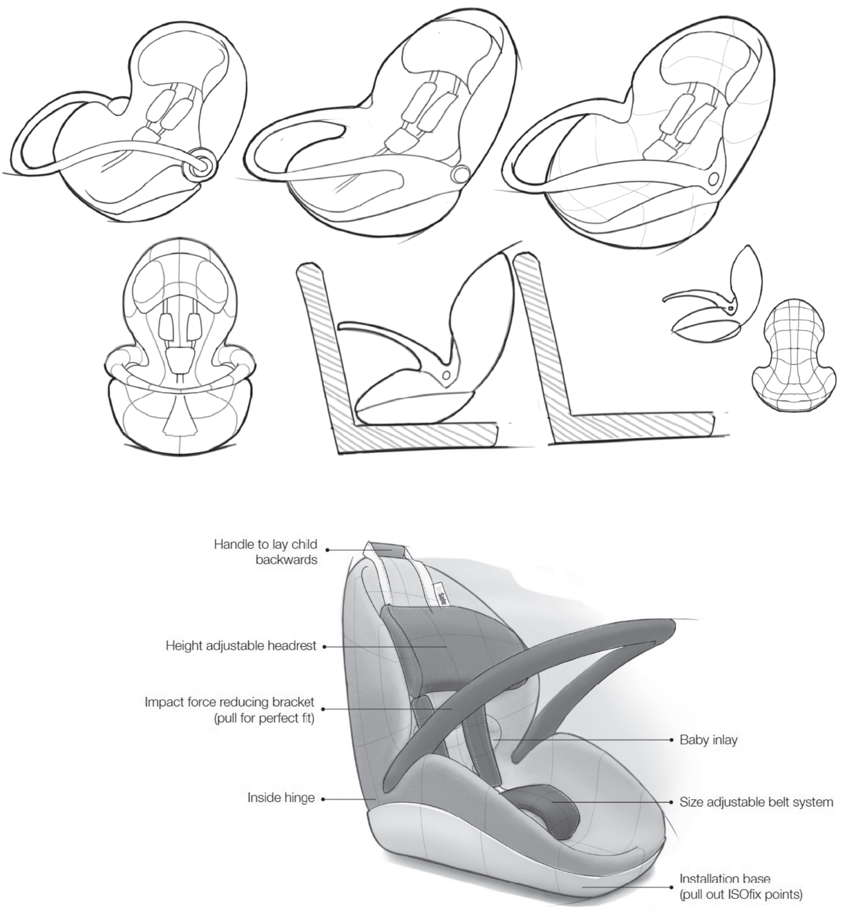


Figure 8.9. Design sketches for an evolutionary next version of a child restraint system (Reigersman, 2014b).

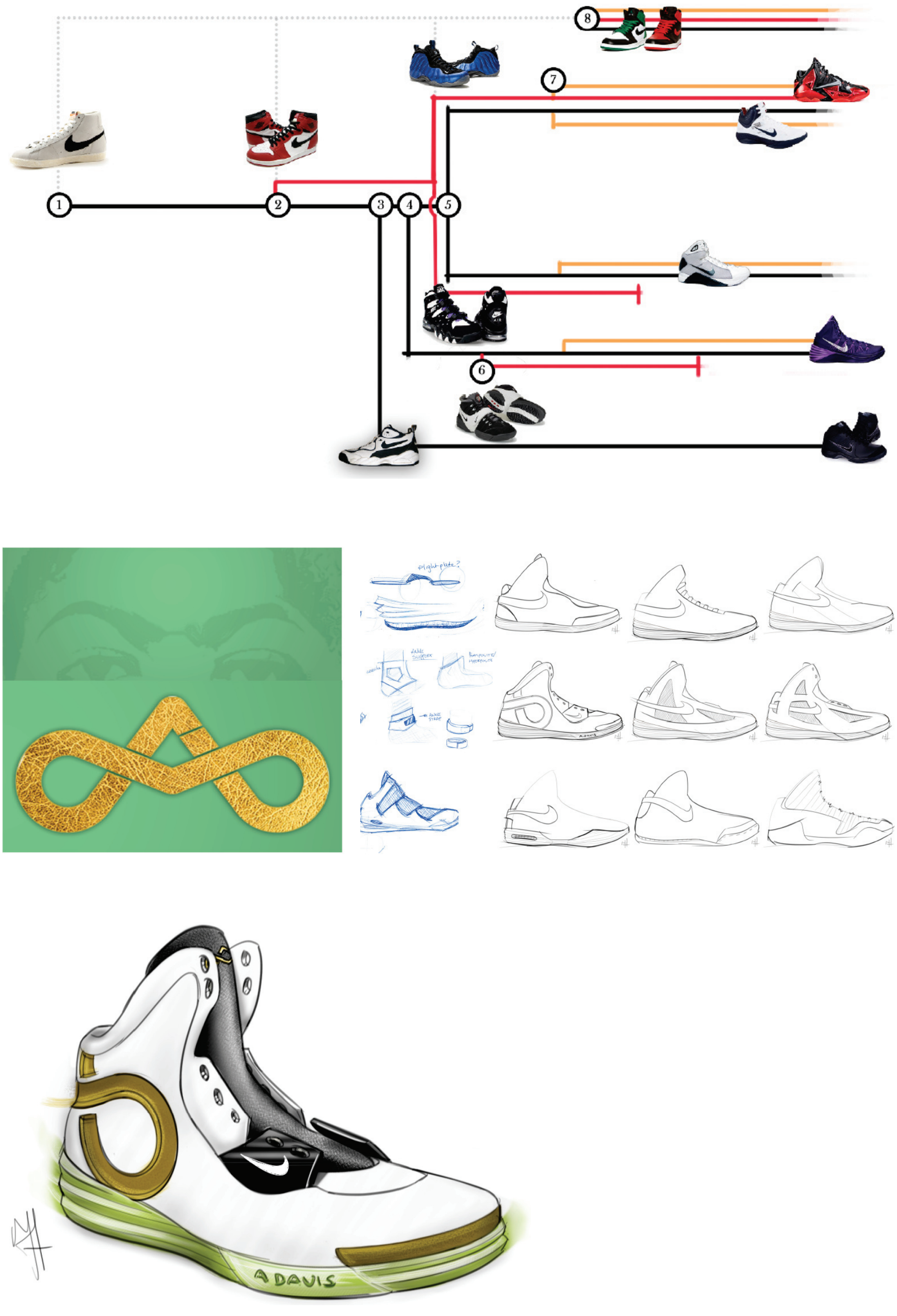


Figure 8.10. Product Family Tree of basketball shoes (top), design sketch of a visual marker (mid left), various design sketches for basketball shoes (mid right) and a sketch of the resulting design for the proposed basketball shoe (bottom) (Michel, 2014a: 2014b).

9

Consumer Magazines

9.0 Introduction

This thesis uses *Consumentengids*, a publication by the Dutch consumer organization Consumentenbond, as the primary source of information on the development of products investigated in case studies. The comparative surveys or product tests provide an independent and detailed overview of products in focus to support consumers who need to make informed decisions. The volumes of the magazine available from 1959 onwards provide a historic record of developments in consumer goods, their technical performance and sales prices as well as topics like related controversies, legislation and standardisation.

At the start of this PhD project, in the spring of 2010, a complete collection of all volumes of Consumentengids was established as a research archive. This was based on the assumption that this archive would provide a rich source of information on the development of consumer products through time. Using this archive, an index of all product tests published since 1959 was compiled in order to select those products most suitable for further investigation of case studies. The following criteria were used to identify suitability; 1) the tests published needs covering at least two decades, 2) at least 10 tests were published. Based on these criteria, the Child Restraint Systems (CRS) was first selected for further research in a case study. It appeared to be impossible to quantify the price-performance development of CRS over time. The root cause for this is the fact that there is no clear unit to express the performance of the basic function of CRS (to provide safety to child passengers in cars during driving in general, and in the event of a collision in particular). This prompted need to define a next criterion for case selection, namely to quantify the price-performance development over time. The Compact Fluorescent Lamps (CFL) appeared to comply with all three criteria and was therefore selected as a second case study.

In addition to these two case studies, students who followed the course Evolutionary Product Development between 2011 and 2015 (see also Appendix A) used a copy of the archive stored at the library of the University of Twente.

As only comparative surveys from the Dutch consumer magazine were used, the information reviewed reflects, strictly speaking, only the evolution of these products in the Netherlands. This section reviews the relevance of using the product tests published in Consumentengids for studying the evolution of products in general and the two cases studied for this research project in particular. This chapter also provides information on consumer organisations, their international organisation and their role and influence on the development of products in general.

9.1 Consumer Magazines as a Primary Source of Information

Although consumer magazines like Consumentengids do not provide a complete record of the historical development of consumer products tested, a lot of information regarding the evolution of products investigated can be found in these publications. The following section provides an overview of advantages and limitations experienced in this research project.

9.1.1 Advantages

- Consumer organizations like Consumentenbond review products independently and are aimed at advancing the interests of consumers. There is no commercial interest in promoting specific products or manufacturers.
- Although not scientific in intent and approach, tests are executed in a systematic fashion. Test protocols are often aligned with consumer organizations of other countries. An explanation of how different scoring elements contribute to a final score is commonly included.
- Price information is commonly included, which allows a picture to be constructed of how prices developed through the years. In this research project, no other source has been discovered that provides as rich and systematic a source of information for this purpose.
- A wide range of products and services is being tested in consumer magazines. An overview of items included in the annual index of *Consumentengids* has been constructed for this research project. This provided a list of over 2,000 lines that includes many products commonly referred to as brown and white goods, as well as tests relating to food, housing, sleep and insurance policies.
- Product tests provide an overview of products available in the market and features/functionality. This allows a reconstruction in time of how features/functionality disseminate in the market through time. In this research project, no other source was discovered that provides a source of information that is as rich and systematic for this purpose.
- Tests are often executed together with sister organizations from other countries. The various consumer organisations subsequently publish the data that is relevant for their territory. In general, the products tested are available in several countries. This means that the information from Consumentengids on these products is valid for more countries than the Netherlands only (see also information on ICRT in section 9.3).
- Consumer magazines are a freely accessible source of information. The Koninklijke Bibliotheek, the National Library of the Netherlands, has a collection of *Consumentengids* issues dating back to 1959 that can be accessed for research purposes.

9.1.2 Limitations

- Consumer magazines do not, in general, provide test results on new types of products in their first product phase (performance). This implies that other sources are needed to reconstruct a picture of the early stages of development of new types of products.
- The evolution of products from the introduction of a new type into a family of advanced versions took many decades for the cases investigated. Only a few products in *Consumentengids* have been tested over more than two decades. This implies that other sources are needed to reconstruct a picture of the complete development of products.
- Consumer organizations were established in the 20th century (see also section 9.3). Earliest issues of their reports did only include simple test results. Many product families are rooted in times before consumer organizations were established. This implies that, for these products, information on these earlier periods cannot be drawn from consumer magazines.
- The test protocols, and the formats in which the tests results are published, vary over time. This limits the extent to which information from different tests can be compared.
- Although internationally linked to other consumer organizations (see also section 9.3), the information published with test results only concerns those products available on the national market. National focus reduces the scope of products included in tests. In the case of many products it is known that there are national differences in types offered as well as in taste preferences amongst buyers. Well-known examples of these differences are, for example, found in cars that tend to be larger in the USA then in Europe, or washing machines for which horizontal axis types dominate in continental Europe while vertical axis machines dominate in the USA.
- Information on market shares of different vendors of particular products is not available in consumer magazines. Hence, the test results published do not indicate the relative importance of different products on the market.
- Information on the level of adoption of a product is not available in consumer magazines.

9.2 Relevance of Using Consumer Magazines in this Research Project

Popular belief holds that the ‘market’ where consumers buy their products is the environment where most evolutionary selection of products takes place. However, selective pressure is not only applied by consumer choice. Selective forces in the evolution of products are applied by a variety of social groups. For example, governments that produce (national and international) legislation and commercial organisations (manufacturers,

Figure 9.1. Front pages of Consumentengids January 1971 (top left), March 1985 (top right), December 2001 (bottom left) and June 2015 (bottom right).

retailers etc.) that compete (nationally and internationally) play a major role. Consumer organisations occupy a special place amongst these social groups. Individual consumers do not have much of a say in their contacts with large manufacturers. Therefore, consumer organisations have been founded to act as proxy for interests of individual consumers. As such, the different consumer organisations can be regarded as proxies for consumers in the different national markets. In this thesis it has been observed that there is at least one case (the child restraint system) of which consumer organisations influenced the development.

9.2.1 Time Scope

The first consumer organisation was founded in the USA in 1936. In Europe, consumer organisations were first founded in the 1950s (see also section 9.3). In the introduction to this chapter it was mentioned that a threshold of two decades and ten test results has been used to select cases to be investigated. In the case of child restraint systems (CRS) over four decades of test review information has been collected from Consumentengids, and over two decades for the compact fluorescent lamp. Retrospectively it can be concluded that information recovered was very useful. However, looking back at this research project, it is clear that, for these specific products, one needs to include information from many decades, if not from more than a century, to develop a complete picture of how these product families evolved over time. For other types of products the time one needs to take into account to overlook how a product family evolves from its start in the performance phase into the segmentation phase might be different. As product life cycles have become generally shorter, new types of products introduced today (specifically those including microelectronics and software) are expected to evolve faster.

9.2.2 Geographical Coverage

In biological evolution, the term 'allopatric speciation' is used for a process where new species arise from existing ones due to the geographic isolation of populations (see also footnote 8 in Chapter 1). This thesis has explored evolution in products and, to that end, describes how it differs in many ways from biological evolution. For the evolution of technology and products, geographic isolation can also be a cause of different evolutionary paths. One example is found in user preferences (as mentioned before for cars and washing machines) that are known to vary per geographic region. Legislation varies per region. This thesis mentions differences in legislation concerning CRS and (the phasing out of) GLS incandescent lamps. However, the extent to which legislations differ and the consequences this has for the evolution of products has not been investigated here.
Another known example of effects of geographic isolation for the evolution of products is found in infrastructures that, once established, become nearly impossible to change. The electric grid that roughly divides the world into 110 Volts and 220 Volts networks and requires matching electric equipment forms a case example of this.

Markets are known to differ per geographical region. However, differences have become smaller over time. People have been travelling to trade products and exchange ideas for many millennia. In general, one can say that the connectedness of economies and cultures across the world has grown rapidly over the last decades as a result of political changes (end of the cold war) and advances in transportation (aviation, container transport) as well as the advent of *information and communication technologies* (internet, email). The increased connectedness reduces differences between (same types of) products used on different continents. Nevertheless, differences between national markets still exist today. This thesis only reviews products that are less than 150 years old. During the last 150 years both information and products were freely exchanged between the North American market and the European markets. It is therefore safe to assume here that, in the case of the products investigated, geographical isolation did not play a role to such an extent that the main features of the evolution observed in the tests published in Consumentengids would not occur in geographies outside the Netherlands.

The next section discusses the relevance of *Consumentengids* as a main source of information for the two case studies published in this thesis.

9.2.3 Relevance for the Child Restraint Systems Case

For the Child Restraint Systems the level of car use per inhabitant strongly influences the demand for these seats. In the 1930s car ownership rose to over 200 vehicles per 1,000 people in the USA (see also Figure 7.1). At this point in time, some Child Restraint Systems were already available on the USA market. Publications by catalogues like Sears in the years 1923 to 1960 (Reigersman, 2014a) show examples of these first Child Restraint Systems being available on the market. With the USA being the first market to adopt the car on a large scale, it comes as no surprise that the first Child Restraint Systems also developed in this market.

In around 1970 car ownership levels in Western Europe approached the level seen in the USA in the early 1930s. At this point in time, the demand for Child Restraint Systems in Europe also increased rapidly. As a consequence, more manufacturers introduced their own designs and Child Restraint Systems rapidly became more diverse. At this time international trade and communication reached levels that supported the easy exchange of information and product designs as well. One particular Child Restraint System, the Maxi Cosi infant seat, has been described as an example of a product that was imported from the USA to Europe and then underwent further development. From 1990s onwards, when the internationalisation of trade rapidly increased, multinationals sold similar products around the world. Consumer organisations, standardisation and legislation bodies exchanged information internationally. As a consequence, Child Restraint

Systems sold around the world are quite similar in terms of construction, functionality and features, although regional taste and legislative differences are known to exist. Longer use of rearwards facing seats in Scandinavian countries is an example of this.

This thesis uses references to Child Restraint Systems from 1970 through to 2010 from *Consumentengids* and one reference to *Consumer Reports* from 1972. For *Consumentengids* it is known that no test results of Child Restraint Systems predate the 1970 report. The PED shown in Figure 7.15 starts in 1898 and shows considerable branching from the late 1940s until 1970, indicating that quite a few variants were developed. From 1970 onwards the awareness of the need for safety technologies in cars increased and this had an effect on the market for Child Restraint Systems, which started to develop. Manufacturers produced more designs. Consumer organisations started to pay attention to child passenger safety from the early 1970s. Test results used in this thesis do not cover the first product phase (performance) where Child Restraint Systems enter the market as a new type of product. Other sources have been used for this phase, like commercial catalogues by Sears and various Internet resources. Test results have been available since 1970 when the optimization phase best describes the stage of development of Child Restraint Systems. Consumer organisations are known to have played a role in the evolution of Child Restraint Systems. Ronald Vroman, an automotive expert employed at Consumentenbond since 1985, has also sat on the board of Euro NCAP since 1997 and has been an ANEC consultant since 2003. Vroman was interviewed as part of this research project and was kind enough to review this chapter. Obviously the presence of such experts at internationally linked organisations like Consumentenbond, Euro NCAP and ANEC supports international knowledge dissemination and acts as a catalyst for raising European standards in this product family.
The test results on Child Restraint Systems from *Consumentengids* have provided a lot of information which enables us to qualify and quantify the evolution over four decades since 1970. Most Child Restraint Systems tested in *Consumentengids* in the 1970s appear to be manufactured outside the Netherlands and imported as their names refer to known CRS manufacturers like Storchenmühle (Germany), Kettler (Germany), Britax (UK). The test results also mention some products manufactured in the Netherlands, like the Rimo seat. However, this appears to be a smaller group and associated brands and companies have not been continued into later decades. However, the Maxi Cosi seat that became popular from the 1980s is manufactured in the Netherlands and sold throughout Europe. Clearly there has been, and still is, an active international trade in Child Restraint Systems. Over the last decades, there was a consolidation amongst

manufacturers who are all selling on many national markets. According to Vroman, the Dutch CRSs market has always been very international with only few local products.

Vroman also noted that CRS have, for a long time, been tested together with international sister organisations and automotive interest groups. Clearly, the Child Restraint Systems reviewed in *Consumentengids* represent at least an important share, if not the majority of the evolution that has taken place in Child Restraint Systems since 1970.

9.2.4 Relevance for the Compact Fluorescent Lamps Case

Compact Fluorescent Lamps were invented in the second half of the 1970s in reaction to a changing attitude towards pollution and the use of natural resources. The first Compact Fluorescent Lamp (CFL) was brought onto the market in 1981 by Philips, a globally leading manufacturer of electric lighting products with its headquarters in the Netherlands.
This thesis uses test results from *Consumentengids* dated between 1984 and 2013.
For the CFL, given that the Netherlands has been a lead market in CFL sales per capita (Menanteau and Lefebvre, 2000), and is the home market of Philips (a leading CFL manufacturer) and given that the same CFL technology is used throughout the world, the expectation is that the historical development pictured and the statements made in *Consumentengids* are valid for most geographies. Especially for the evolution of the CFL, *Consumentengids* has proven to be a very valuable source because it provided information that facilitated the quantifying of price-performance development (see also Figure 7.34 and Figure 7.35).

Besides *Consumentengids,* there is a wide body of policy, scientific and patent literature on lighting technology in general. Many scientific publications are available on the topic of lighting technology, of which this thesis has used ten. Four of these were dedicated to Compact Fluorescent Lamps only. A particularly interesting publication is by Bijker (1997) who used the case of bulbs and fluorescent lighting (in addition to Bakelite and bicycles) to write extensively about the social construction of technology. What is more, Light's labour's lost (Waide and Tanishima, 2006), the policy publication by International Energy Agency, provided an extensive overview of all types of information relevant to energy-efficient lighting technologies, programmes and policies. These sources have been a crucial complement to *Consumentengids* in researching the evolution of lighting technologies that produced the Compact Florescent Lamp, in addition to many other lighting products.

Country	Name of organisation	Name of publication	Established in year	Amount of members (2013)	Population	Level of membership
USA	Consumers Union	Consumer Reports	1936	7,300,000	319,000,000	2.3%
UK	Consumers' Association	Which?	1957	614,000	63,742,977	1.0%
France	Union Fédérale des Consommateurs	Que Choisir	1951	500,000	66,259,012	0.8%
Germany	Stiftung Warentest	Test	1964	462,000	80,996,685	0.6%
Netherlands	Consumentenbond	Consumentengids	1953	486,000	16,877,351	2.9%
Belgium	Test Aankoop	Test Aankoop	1957	320,000	10,449,361	3.1%

Table 9.1. Consumer organisations with publications featuring comparative surveys or product tests.

9.3 Consumer Organisations

Consumer organisation first appeared at the start of the 20th century in the USA. Consumers Reports (formerly known as Consumer Union) based in the USA served the first and largest consumer market. It is by far the oldest and largest of the consumer organisations (Table 9.1). Consumer organisations are defined as advocacy groups that seek to organise, inform and protect the interests of consumers. This not only includes organisations that publish above mentioned product tests, but involves a much wider groups of organisations like umbrella organisations and specific lobby groups. Most are national organizations, in addition to a few international ones like:

- Consumers International (CI), the world federation of consumer groups, with 220 member organisations in 115 countries, founded in 1960.
- Bureau Européen des Union de Consumateurs (BEUC) that acts as an umbrella organisation that represents its members at European level, founded in 1962.
- ANEC, the European Association for the Co-ordination of Consumer Representation in Standardisation, that represents the European consumer interests in the creation of technical standards, especially those developed to support the implementation of European laws and public policies. ANEC was founded in 1995.
- ICRT (International Consumer Research and Testing), a global consortium of more than 35 consumer organisations dedicated to carrying out joint research and testing in the consumer interest. ICRT was founded in 1990, but builds on a tradition of cooperation between national consumer organisations dating back to 1968.

Consumer organisations operate in various ways such as campaigning, litigation, lobbying or acting as a watchdog. In general, consumer organisations cooperate internationally to create a stronger voice to lobby for shared interests. Several consumer organisations from the industrialised countries publish comparative surveys or tests of products and services in magazines, and nowadays on websites. Most of them cooperate via ICRT, which develops common test programmes and evaluation methods, and also operates a database for storing and retrieving standardized information on product tests. In the case of many consumer goods, exactly the same versions are sold in different countries. Therefore, ICRT offers efficiency to its participants by performing product tests of which results are shared for publication. Participants also share information produced by their own product test via the ICRT database. Major ICRT members are: Association des Consommateurs Test-Achats SC (Belgium), Consumentenbond (The Netherlands), Consumer Reports (USA), Stiftung Warentest (Germany), UFC - Que Choisir (France), Which? (UK). Although, in general, publications in *Consumentengids* do not make clear the extent to which information is shared with other organisations, it is clear that information is actively exchanged. As a consequence, information published in comparative surveys or product tests is often relevant to more countries than only the one targeted by a specific consumer magazine.

9.3.1 Consumentenbond

In 1953, Consumentenbond was established as the Dutch consumer organisation. The first issues of its publication Consumentengids, including product tests, were published at the end of the 1950s. At its peak, in 1997, Consumentenbond had 650,000 members representing one in nine Dutch families. This level of membership is the highest ever achieved by any consumer organisation anywhere in the world. The 2013 annual report mentions that the number of members fell towards 486,000. The membership population is aging and accretion from younger generations is low. At time of writing the number of members has stabilized according to Vroman.
One of the reasons for low accretion in younger generations is attributed to more freely available product information on the Internet and specifically the price comparison service sites. Younger generations are avid users of online information, which explains why they are less attracted to paper publications like *Consumentengids*. According to Vroman, Internet has also become the main channel for Consumentenbond to disseminate its information. Publications on the Consumentenbond site have even become a source for articles in the paper publication. One of the particular advantages of the Internet as a platform for publishing test results is that it can be updated when new results become available.

9.4 Conclusion

This research project has shown that consumer magazines in general and *Consumentengids* specifically are a useful and rich source of information for the study of product evolution. However, there are also limitations, which make it necessary to use additional sources of information when studying the evolutionary history of products. The main conclusions regarding the usefulness and relevance of consumer magazines for studying the evolution of products are listed below.

First, consumer magazines provide information on how the performance and prices of different products offered compare mutually for the period in which the review is published. This allows the quantification of price and performance development over time, as displayed in the CFL case. In the Child Restraint Systems case, performance cannot be quantified in absolute numbers. Nevertheless, the test results can be used to analyse relative performance in a family of products at a certain moment in time, as well as over a period of time.

Second, this research has shown that consumer magazines can be used to study when particular features of products become available on the market and what different brands and types of products are offered at a particular moment in time in a market covered by the magazine. This information is an indicator of the product phase a particular product family is in. A first example of this was observed for fan heaters that first did not include thermostats. Later on some products tested did include thermostats and, finally, not having a thermostat became a disqualifier in a test (Ehlhardt, 1995). Another example was observed for child restraint seats where, at a certain moment, segments (age, weight, length), ease of installation and availability of a manual were included in the test results.

Third, this research project also found a number of limitations in the use of consumer magazines when studying the evolutionary history of products. The most notable in the context of this study are the absence of test results in the early phase of the evolution of products (performance phase), the absence on relative market shares of major vendors and the absence of information on the level of adoption of a particular product.

All in all it can be concluded that *Consumentengids* and probably other consumer magazines as well, provide a rich source of information that can be used to study the evolution of products. Nevertheless, it is clear that a consumer magazine as the only source does not suffice.

10

Conclusions and Recommendations

10.0 Introduction

The last chapter of this thesis will reflect on the research project and recount the findings presented in previous chapters. Conclusions drawn from the research objectives and questions are presented first. Then the analytical framework presented in this thesis is discussed in terms of strength and weakness as well as the context of its use in general and education setting for those who are (going to become) involved in the development of new (types of) products. As closure for this research project recommendations for further research will be discussed.

10.1 Research Objectives and Questions

The research objective of this study is to contribute to the understanding of *how new (types of) products come about and develop through time into a family of more advanced versions*. Investigating whether and to what extent the evolutionary metaphor can be used to realise the research objective has been a starting point of this project.

The evolution theory that explains how biological life evolves and new types of organisms or species originate by a process of variation, selection and retention of traits captured in genes has been able to develop over more than one and a half centuries. Although the exact origins of life remain a mystery, the ideas on evolution have provided an explanation for the way life has evolved and species originate. Furthermore it has given rise to field of genetic engineering that allows us to modify the traits of organisms deliberately.
For the world of made, the meme has been postulated in analogy to the gene. However, the meme has not provided similar explanatory leverage and has been parked in this thesis as a philosophical concept. Nevertheless, it has been shown that the various schools of thought described in Chapter 3 provide a solid literature base that confirms that *'technological innovation can be described as an evolutionary process'* (proposition P1). In particular, publications from the field that is referred to as 'Science Policy and Innovation Studies' have shown to be very valuable in creating an overview of the innovation patterns and mechanisms, as well as to provide a nomenclature to describe innovation phenomena from an evolutionary perspective. In addition two cases (telephone and electric bicycle) have been elaborated in Chapter 4 to show that technological innovation can be described as an evolutionary process. It appears that accumulation of know-how and know-what builds a fundament on which new (types of) products emerge. Individual inventors as well as collectives each contribute small steps to this fundament. However, it is this process of accumulation

that over time results in product families, as well as roots for new ones. A 'Theory of Product Evolution' is proposed in order to build on the groundwork of scholars described in Chapter 3, as well as on the observation that technological innovation can be described as an evolutionary process explaining how new (types of) products emerge (Chapter 4).

The cases studies of Child Restraint Systems, General Lighting Solutions and Compact Fluorescent Lamps have investigated in depth how new types of products come about and develop over time into a family of advanced versions. For all product families investigated by the researcher and a range of other product families investigated by students, it appears possible to map similar lineage relations from current products back to the start of the family. It has been shown that, on each occasion, these products start as a simple version that builds on products developed earlier or accumulated knowledge, here referred to as roots. From this first-of-a-kind or new type of product, a product family then develops over time. Slowly but surely the product is advanced in terms of functionality and price performance ratio. Once products reach what Eger (2007a) defines as the segmentation phase, the Product Family Tree shows various branches existing at the same time, targeting different types of use, each characterized by different dominant designs. It was noted that the products analysed in case studies emerged after the industrial revolution. Although not systematically investigated, this research project has not provided clues suggesting that evolution in post-industrial revolution products behaved different than in pre-industrial revolution products.
For the cases studied it has been shown that *'the emergence of new types of products, and their subsequent development into families of advanced types can be described as an evolutionary process'* (proposition P2). For the cases studied and the work by students it has been shown that *'evolution in products can be visualised as a Product Family Tree'* (proposition P3). It has also been shown, for the cases studied, that these products do not evolve in splendid isolation but are influenced by a context and that *'the influences of a context on the evolution of a product can be mapped as an ecosystem'* (proposition P4). In fact, the ecosystem appears to be part and parcel of the evolution of these products. This implies for these cases that *'to understand how products evolve, one needs to analyse the interaction between a product family and ecosystem over time'* (proposition P5).

Therefore it can be stated that juxtaposing a Product Family Tree with an ecosystem in a Product Evolution Diagram contributes to the understanding of how new (types of) products come about and develop through time into a family of more advanced versions. As such, the use of the Product Evolution

Diagram leads to two findings. First, it is this process of accumulation over time that results in evolving product families. Individual inventors and collectives again and again contribute small steps to this process and do not explain for the origin of product families. Second, the ecosystem is part and parcel of the evolution of products.

10.2 The Product Evolution Diagram

A *'Theory of Product Evolution'* is proposed that holds that new (types of) products emerge as a nested hierarchy of system, subsystems and components on the fundaments laid by previous developments through a process of variation, selection and retention. This theory employs the *Product Evolution Diagram* as an analytical framework to reconstruct development history of a product family. Building on many schools of thought, it intends to provide a product centric perspective and act as concise and recognizable reference for those involved in the development of new products. It has provided a view on different stages as well as typical patterns in the development of a product family.

The strength of the Product Evolution Diagram lies in the fact that it facilitates the display of a highly complex development history as a graphical narrative that visualises patterns in the development history of product families. It enables us to 'frame the development history of a product family' on a single page. Without this graphical overview that clarifies how newer types build on earlier versions and both context and product influence each other, it is hard to appreciate the complexity of the evolution of product families. As such, the Product Evolution Diagram contributes to the understanding of how new types of products come about and develop over time into product families. It has been noted in this thesis that personas perform a similar function by providing concise access to results of marketing research.

The Product Evolution Diagram has two weaknesses. First, according to current insight it is impossible to reconstruct unambiguous lineage in product families similar to how the phylogenetic tree allows for biological organisms. The Product Family Tree instead should be regarded as a schematic lineage overview based on appearance, similar as the Linnaean family tree did for biological life. Second, although a method used to scan the environment in strategic management studies (PEST) is presented to identify different types of factors from the context that influence the evolution of a product, it is never clear whether all the relevant factors that constitute the ecosystem have been taken into account.

10.3 Education and the use of the Product Evolution Diagram

Although it seems obvious that industrial design engineers and others involved in the development of products understand how new products come about, the way this process has been described in this thesis and referred to as the *'Theory of Product Evolution'* is new. This holds especially for the perspective that describes how new types of products come about and develop through time into a family of more advanced types. Besides, the analytical framework provided by the Product Evolution Diagram is instrumental in making explicit that the role of the context or ecosystem in the evolution of products cannot be ignored.

Traditionally, the approach in new product development is forward looking. The product in focus is regarded as a new and self-contained case, rather than a next variant in a family of related products that has been evolving over many years. Although it is commonly accepted that most innovations or new products come about on the basis of incremental steps, evolutionary product development (Eger, 2007a) is still a first-of-a-kind design approach that takes the typical phases a product evolves through as starting point for investigating the solution space for a next (evolutionary) version of the product. The evolutionary product development approach lacked both an analytical framework that builds on the school of thought referred to as Science Policy and Innovation Studies, and a visual means of mapping the development history of products. The Product Evolution Diagram was developed to complement evolutionary product development with this analytical framework as well as providing a firm embedding in Science Policy and Innovation Studies literature.
Student work has shown they are well capable of applying the Product Evolution Diagram and have indeed applied it in 143 cases. Besides that, it appears that students successfully use the evolutionary product development approach as a start for designing a next evolutionary version of a product. However, the success of products developed by this approach in the market has not been investigated yet.

The study of industrial design engineering has been set up as a practical discipline, which however, lacks a solid scientific connection to the field of Science Policy and Innovation Studies. Engineering studies in general largely aim for utilitarian rather than intellectual development.
The assumption that a better understanding of how new (types of) products come about and develop through time into families of advanced versions and will ultimately lead to a more successful and efficient process of new product development was one of the starting points of this research project. The researcher of this project realizes that this thought is in vain. The future

will show whether the thoughts elaborated in this thesis will be picked up at all, let alone whether it will have any effect on the process of new product development or the success of products developed with it.

10.4 Recommendations

More case studies would help test the general validity and usefulness of the *'Product Evolution Theory'* and its analytical framework, the Product Evolution Diagram. As regards to these case studies it would be valuable to explore both successful products and those that for one reason or another have not become successful. Besides it would be valuable to explore cases from different technological domains (e.g. mechanical, electronic, software) with different complexities, and used in different settings. Further exploration of the Product Evolution Diagram could, for example, elaborate drawing conventions used to draw the Product Family Tree. Research could also focus on whether a linear time scale is most appropriate in a Product Evolution Diagram, or if a logarithmic scale would be more appropriate for certain cases.

Currently, it is not known whether products, developed according to the evolutionary product development approach, are on average more successful in the market than those developed by conventional methods. What is more, it is unknown whether the evolutionary product development approach itself is more efficient than conventional methods. In the context of reflecting specifically on this research project it is yet unclear to what extent the Product Evolution Diagram as analytical framework contributes to more successful designers and designs. Research into these topics will contribute to a better understanding of value of the approach. It will probably also provide clues for further improvement of the method.

Last but not least, research could assess to what extent the Product Evolution Diagram can contribute to exploring the most probable solution space for products in the near future. Such research could function alongside tools like roadmapping and personas that are now commonly used in strategy, planning, and execution of new product development. Today's context shapes future products and tomorrow's products, at least most of them, build on today's products. Both these elements are mapped in the Product Evolution Diagram.

11

Summary

How do new (types of) products come about? To what extent does the genius of the inventor play a decisive role in these events? Is there perhaps another explanation for the way products come about and develop over time? To what extent can the evolutionary metaphor be used to describe technological innovation? Can we describe a (evolutionary) relationship between the first product and the most recent products? These are some of the questions discussed in this thesis.

The formal starting point of this study is described in Chapter 1. It states the research objective of this study as being to contribute to the understanding of *how new (types of) products come about and develop through time into a family of more advanced versions*. To that end the aim is to provide an analytical framework that can be used to study how particular products come about and develop over time. The framework developed in this research project has been used in the course Evolutionary Product Development and complements the product phases theory.

While writing about the topic of *product evolution* it became apparent that available terms and definitions were insufficient to describe unambiguously all the matters investigated. Chapter 2 was therefore added and includes new and enhanced definitions. It is assumed here that these definitions provide a nomenclature that contributes to the general understanding of the way in which new (types of) products come about.

Many authors have discussed patterns and mechanisms of innovation and provided analytical tools to investigate them. Chapter 3 describes different relevant schools of thought, in particular those that have used evolutionary metaphors to describe the process of innovation. These schools of thought target domains such as economics, sociology, science policy, innovation studies and industrial design engineering. The variety of schools of thought listed indicates the number of angles from which one can view the process of innovation. It appears that innovation cannot rightfully be described from a single perspective. Moreover, technology is often the subject of analysis and less so products in which technologies aggregate to provide functionality in a context of use. Therefore, this thesis takes a product centric perspective using the maxim that products *"are both the means and the ends of technology"* (Basalla, 1988; p.30).

Products have been around since the Stone Age. The first simple tools were superseded by slightly more advanced versions. It has been asserted that new products appear to originate from know-how (to make) and know-what (functionality to provide) and are developed based on earlier products. The accumulation of this knowledge provides the foundation from which new (types of) products can emerge. In this process, technology in itself appears to be a means to an end. Chapter 4 explores two cases of evolving products. It appears that examining technological innovation in a (sub)system supports an understanding of the way products evolve as the outcome of innovations at different levels that converges into dominant designs. The first case explores how, over the decades, the design of the telephone changed along with innovations in telephone network technology. A (product) system diagram is introduced that show how products can be analysed as a nested hierarchy of systems, subsystems and components each of which is subject to technology cycles. The second case explores how innovation in subsystems continues to drive evolution in (electric) bicycles.

Investigating how products evolve over time implies relating later versions to earlier ones. The concept of lineage is derived from the world of life where it is used to describe how a sequence of species evolved from a predecessor. An introduction to the development of biological classification and lineage is provided in Chapter 5, which also includes an illustration of how lineage concepts have also been applied to human culture and explains how these differ from biological lineage. In Chapter 3 the concept of the meme (Dawkins, 1976) is discussed as a unit for carrying cultural information in analogy to the gene as a unit for carrying biological information. According to Edmonds (2005), memetics has not been very successful in providing 'explanatory leverage upon observed phenomena'. Therefore, memes and memetics have been put to one side and considered a philosophical concept that will not, at this point, contribute to the research objective stated in this thesis.

In Chapter 6 the *Product Evolution Theory* is proposed that holds that new (types of) products emerge on the fundaments laid by previous developments through a process of variation, selection and retention. This theory employs the *Product Evolution Diagram* as an analytical framework to reconstruct the development history of a product family and picture it as a graphical narrative. The Product Evolution Diagram consists of two elements: the ecosystem and the Product Family Tree. The *ecosystem* is the element in the diagram used to map the context that influences the evolving product family. The case studies (Chapter 7) reveal that the ecosystem is part and parcel of the evolution of products. The other element, the *Product Family Tree*, depicts the products through time as a lineage. The Product Family Tree reveals five patterns that appear to be typical for the way new types of products come about. First, all products build on previously developed products or accumulated knowledge, referred to here as the *roots*. Second, any new product family commences with a first product referred to as the *base*. Third, not all product branches are perpetuated and some therefore lead to *dead ends*. Fourth, product families evolve over time into *branches* that cater to different segments of the market in which dominant designs represent the most successful architectures. Fifth, the combination of the Product Family Tree and the ecosystem reveals the *mutual influence* between the context and the evolving product.

In Chapter 7 this thesis studies two cases of products that came about and developed through time into a family of more advanced versions. The first case recounts how a first child restraint system (CRS) emerged before car designers got rid of the horseless carriage syndrome. Once the mass production of cars had started with the Ford model T, car use quickly increased. Once car ownership increased to a level of more than 100 vehicles per thousand people in the 1920s, CRSs patents, production and use took off in the USA. In Europe it took four more decades to reach a similar level of car ownership and, as it appears, the start of a market for CRSs. In the meantime, passive car safety technologies emerged. First the design of car safety belts improved and their use became general practice. Then active car safety technologies also emerged, like the Anti-lock Braking System (ABS) and the Electronic Stability Control (ESC). These developments influenced the expectations of child-passenger safety and therefore created a situation in which the market for CRSs could take off. A wide range of actors helped to evolve CRS perception and designs. An English couple patented a first safety-oriented CRS with the aim being to provide children with a level of safety comparable to that of the level of safety already provided at that point to adults. A Swedish professor in biomechanics invented the rear-facing CRS inspired by seats used in the Gemini space programme. Legislation was introduced and started to place higher demands on CRSs and influenced their design. Consumer organisations tested CRS performance and started to influence legislation. A trade in CRSs emerged and travelling salesmen ensured international dissemination as well as further development. It appears that the whole of influences denoted here as the ecosystem has been part and parcel of the evolution of CRSs.
The architecture of CRSs evolved over the decades into three segments. The first is a rear-facing cradle type intended for babies. The second type provides a forward-facing seat with its own five-point belt harness intended for toddlers. The third type is referred to as a booster seat that elevates children so that they can use the car's own three-point belt system. These architectures are closely related to international standardisation and safety programmes, which have continued to develop until the time of writing.

The second case study investigates electric lighting products. The incandescent lamp that evolved into a design known as the General Lighting Solution (GLS) is one of the first major applications that prompted consumers to use electricity. The invention of the incandescent lamp is rooted in many decades of technology development. In 1879 two inventors on different sides of the Atlantic Ocean independently patented and commercialised an incandescent lamp using a carbon filament. The point is made that no fewer than 22 inventors of incandescent lamps prior to Swan and Edison (Friedel and Israel, 1985) have been identified. Clearly the invention of the incandescent lamp was not the work of a single genius or a stand-alone event. This major technological development built on prior knowledge accumulation provided by many individuals and collectives over the course of many years.

The incandescent lamp was further improved in terms of life span, efficacy and cost price. The inventions of the drawn tungsten filament and the Edison screw base turned out to be important elements of the dominant design that became known as the GLS incandescent lamp. The GLS incandescent lamp became a main consumer of electric energy. Meanwhile gas discharge lighting technology developed that quickly became more efficient than the incandescent lighting technology. Its main incarnation became known as the fluorescent lamp or fluorescent tube, which is generally shaped as a long straight thin tube. However, as result of a series of conditions, gas discharge lighting technology did not succeed in developing a similar position as the GLS incandescent lamp did in the Western consumer market.

About a century after the invention and commercialisation of the incandescent lamp, the perception of the availability of natural resources dramatically changed and inspired two competing lighting technology manufacturers to invent an energy efficient alternative to the infamously inefficient GLS incandescent lamp. The result was a more conveniently shaped incarnation of the exiting fluorescent tube, which became known as the Compact Fluorescent Lamp (CFL). Although it was first assumed that, once introduced, the CFL would become a serious competitor to the GLS incandescent lamp, it transpired that consumers still preferred the incumbent two decades later. It was only after climate change mitigation efforts discussed in the Kyoto protocol that legislation was introduced that phased out the use of the GLS incandescent lamps.

The cases of the CRS and CFL illustrate that the process of evolution in products cannot be understood if described in technology terms only. The ecosystem that constitutes contextual factors like societal change, economic development and legislation has been shown to be part and parcel of their evolution.

Between 2011 and 2015 the ideas described in this thesis have been presented to students following a course Evolutionary Product Development at the University of Twente. During this course, the Product Evolution

Diagram was offered to these students as a framework for analysing the historical development of products. Chapter 8 provides examples of work by these students from which it can be concluded that they are able to use the analytical framework provided. Students already used visual mapping techniques before the Product Evolution Diagram or elements of it were introduced. This may come as no surprise, as students of industrial design engineering are trained to use visual elements in their work.
It appears that students do not always apply the Product Evolution Diagram in exactly the same way as suggested in lectures. Furthermore, these students have provided interesting ways of visualizing particular aspects like 'enabling technologies' and 'parameters' that can be regarded as interesting additions. Besides the academic objectives of this research project, it should be noted that students who followed the course in Evolutionary Product Development have shown that they are able to derive valuable design directions from their analytical work.

This thesis uses *Consumentengids*, a publication by the Dutch consumer organization Consumentenbond, as the primary source of information on the development of products investigated in case studies. Chapter 9 provides an overview of lessons learned regarding the use of consumer magazines as a primary source of information for the type of research presented here. The advantages listed include the wide range of topics investigated in comparative surveys, the inclusion of price information and the good availability of issues of Consumentengids. The limitations listed include, for example, that the comparative surveys in general do not include those products that recently came about as new types of product, the test and reporting protocols vary over time and only a few products have been tested over a sufficiently long period (decades) to allow a reconstruction of an image of the development of products.
Chapter 9 provides an overview of criteria used to select the two products investigated and reflects on the relevance of using Consumentengids for those case studies. It concludes that consumer magazines in general and Consumentengids specifically are a rich source of information for the study of the evolution of products. These magazines provide valuable information on price, performance and features of products available in the market at time of publication.
However, there are limitations that make it necessary to use additional sources. The most notable limitation listed is the absence of information on products investigated in their early phase of evolution.

In Chapter 10 the research project is reviewed and rounded off with conclusions and recommendations. The initial project research objective was to contribute to the understanding of *how new (types of) products come* *about and develop through time into a family of more advanced versions*. The five propositions that frame the research project are briefly reflected upon. Based on the cases studied, the thesis argues that the ecosystem appears to be part and parcel of the evolution of products. This implies that *'to understand how products evolve, one needs to analyse the interaction between a product family and ecosystem over time'* (proposition P5). Therefore, juxtaposing a Product Family Tree with an ecosystem in a Product Evolution Diagram provides explanatory leverage for the research objective.

The strength of the Product Evolution Diagram is that it enables us to *'frame the development history of a product family'* on a single page. As such, the Product Evolution Diagram makes it possible to display a highly complex development history as a graphical narrative that visualises patterns in the development history of product families. Without this graphical overview, that clarifies how newer types build on earlier versions and both context and product influence each other, it is hard to appreciate the complexity of the evolution of product families.
The Product Evolution Diagram has two weaknesses. First, according to current insight, it is impossible to reconstruct lineage in product families unambiguously similarly to how the phylogenetic tree used in biology allows this for organisms. Second, although a method (PEST) is presented to identify different types of factors from the context that influence the evolution of a product, it is never clear whether all the relevant factors that constitute the ecosystem have been taken into account.

The assumption that a better understanding of how new (types of) products come about and develop through time into families of advanced versions will ultimately lead to a more successful and efficient process of new product development was one of the starting points of this research project. Nevertheless, it should be noted that only time will tell whether thoughts elaborated in this thesis make any useful contribution to the education of designers, the process of new product development or the products developed by them.

12

Samenvatting

Hoe ontstaan nieuwe (typen) producten? In welke mate speelt het genie van de individuele uitvinder hierbij een rol? Wat zijn andere verklaringen voor de manier waarop producten ontstaan en zich in de loop van de tijd ontwikkelen? In welke mate biedt een vergelijking met de evolutieleer een verklaring voor het proces van technologische innovatie? Kunnen we een (evolutionaire) relatie tussen een eerste product en de recentste versies daarvan beschrijven? Dit zijn enkele vragen die in dit proefschrift besproken worden.

Hoofdstuk 1 beschrijft het formele startpunt van dit onderzoek en verklaart het onderzoeksdoel van deze studie: *de manier waarop nieuwe (typen) producten ontstaan en zich in de loop der tijd ontwikkelen tot families van meer geavanceerde versies beter begrijpelijk te maken*. Het streven is om voor dat doel een analytisch instrument te ontwikkelen waarmee bestudeerd kan worden hoe specifieke producten ontstaan en zich door de tijd heen ontwikkelen. Het analytische instrument dat uit dit onderzoeksproject voortkomt, is gebruikt in het vak Evolutionaire Productontwikkeling en vult de productfasentheorie aan.

Al schrijvende over het onderwerp productevolutie werd duidelijk dat de beschikbare termen en definities niet toereikend waren om alle onderzochte zaken ondubbelzinnig te beschrijven. Daarom is hoofdstuk 2 toegevoegd, waarin nieuwe en ook aangescherpte definities zijn opgenomen. Het uitgangspunt hierbij is dat deze definities een nomenclatuur vormen die bijdraagt aan het algemene begrip van de manier waarop nieuwe (typen) producten ontstaan.

Al veel auteurs hebben innovatiepatronen en -mechanismen besproken en analytische instrumenten aangereikt om die te onderzoeken. Hoofdstuk 3 beschrijft verschillende denkrichtingen, met name die waarin vergelijkingen met de evolutieleer een verklaring bieden om het proces van innovatie te duiden. Deze denkrichtingen, ook wel scholen genoemd, richten zich in het algemeen op specifieke domeinen zoals economie, sociologie, wetenschapsbeleid, innovatiestudies en industrieel ontwerpen. De hoeveelheid opgesomde denkrichtingen geeft al enigszins aan vanuit hoeveel verschillende invalshoeken innovatie kan worden bestudeerd. Het is een duidelijke indicatie dat innovatie zich niet volledig laat beschrijven vanuit slechts één enkele invalshoek. Bovendien is over het algemeen de technologie het onderwerp van analyse en geldt dat in mindere mate voor de producten waarin die technologieën zich opstapelen om functioneel te worden in een bepaalde gebruiksomgeving. Daarom neemt dit proefschrift een perspectief in waarbij het product centraal staat, gebaseerd op de uitspraak dat producten *"zowel het middel als het doel van technologie"* zijn (Basalla, 1988; p. 30).

Producten zijn er al sinds de steentijd. De eerste eenvoudige gereedschappen werden opgevolgd door iets geavanceerdere varianten. Er wordt in dit proefschrift gesteld dat nieuwe producten mogelijk worden op basis van kennis over fabricage (het 'hoe') en functionaliteit (het 'wat') die ten behoeve van eerdere producten ontwikkeld zijn. Stapeling van deze kennis biedt een fundament waarop nieuwe (typen) producten kunnen ontstaan. In dit proces is technologie een middel dat wordt aangewend voor een bepaald doel. In hoofdstuk 4 worden twee voorbeelden van evoluerende producten onderzocht. Hierbij blijkt dat het beschouwen van technologische innovatie in (sub)systemen bijdraagt aan het begrip van de manier waarop producten evolueren als resultaat van innovatie op verschillende niveaus, die convergeert in dominante ontwerpoplossingen. Het eerste voorbeeld onderzoekt hoe in de loop van verschillende decennia het ontwerp van de telefoon veranderde samen met innovaties in de telefoonnetwerktechnologie. Hierbij wordt een (product) systeemdiagram geïntroduceerd waarmee producten geanalyseerd kunnen worden als een geneste hiërarchie van systemen, subsystemen en componenten die allemaal onderworpen zijn aan technologiecycli. In het tweede voorbeeld wordt bespiegeld hoe innovatie van elektrische fietsen gedreven wordt door innovatie in subsystemen.

Onderzoeken hoe producten in de loop van de tijd evolueren, impliceert dat men latere versies relateert aan eerdere versies. Hiervoor wordt het begrip 'afstamming' gebruikt, dat uit de biologie komt, waar het gebruikt wordt om te beschrijven hoe een reeks soorten is ontstaan uit een voorganger. Een introductie in de zich door de eeuwen heen ontwikkelende ideeën over biologische classificatie en afstamming is opgenomen in hoofdstuk 5. Hierin wordt ook uitgelegd hoe het begrip 'afstamming' wordt toegepast op menselijke cultuur en hoe het verschilt van biologische afstamming. In hoofdstuk 3 wordt het begrip 'meme' (Dawkins, 1976) besproken als drager van culturele informatie, analoog aan het gen als eenheid van biologische informatie. Volgens Edmonds (2005) is gebleken dat memetics niet succesvol is in het bieden van een "verklaring voor waargenomen fenomenen". Om die reden zijn de meme en memetics hier niet verder uitgewerkt en worden ze slechts beschouwd als filosofisch concepten die niet verder bijdragen aan de onderzoeksvragen die gesteld zijn in dit proefschrift.

In hoofdstuk 6 wordt de *productevolutietheorie* geïntroduceerd, die stelt dat nieuwe (typen) producten ontstaan uit het fundament dat door voorgaande ontwikkelingen is gelegd via een proces van variatie, selectie en retentie. Deze theorie gebruikt het *productevolutiediagram* als analytisch instrument voor de reconstructie van de historische ontwikkeling van een productfamilie en het afbeelden ervan in een grafische voorstelling. Het productevolutiediagram bestaat uit twee elementen: het ecosysteem en de productfamiliestamboom. Het *ecosysteem* is het deel van het diagram dat gebruikt wordt om de aspecten uit de omgeving vast te leggen die van invloed zijn op de evolutie van een productfamilie. De onderzochte casussen (hoofdstuk 7) laten zien dat het ecosysteem een essentieel onderdeel vormt van de evolutie van producten. Het andere onderdeel van het diagram, de *productfamiliestamboom*, beeldt producten af als een afstammingslijn. De productfamiliestamboom toont vijf patronen die typerend blijken te zijn voor de manier waarop nieuwe producten ontstaan. Ten eerste bouwen alle producten voort op voorgaande producten of kennis, hier aangeduid als *wortels*. Ten tweede begint elke nieuwe productfamilie met wat hier aangeduid wordt als de *stam*. Ten derde blijkt dat niet alle takken in een productfamilie worden gecontinueerd, maar dat sommigen *doodlopen*. Een vierde patroon in familiestambomen dat aangehaald wordt, is het ontstaan van *takken* die gericht zijn op verschillende marktsegmenten. Hierbij vertegenwoordigen de zogenaamde *dominant designs* de succesvolste productarchitecturen. En als vijfde wordt aangehaald dat de combinatie van de productfamiliestamboom en het ecosysteem de *wederzijdse invloed* van de omgeving en het evoluerende product laat zien.

In hoofdstuk 7 van dit proefschrift worden twee casussen onderzocht van producten die ontstaan en zich vervolgens in de loop van de tijd ontwikkelen tot families van geavanceerdere versies. De eerste casus verhaalt hoe (auto) kinderzitjes al ontstonden, reeds voordat auto-ontwerpers zich ontworstelden aan de paardenkoets vormgeving. Vanaf het moment dat de massaproductie van auto's van start ging met de Ford model T nam het autogebruik snel toe. Toen het autobezit in de jaren twintig van de vorige eeuw in de VS boven de 100 voertuigen per 1000 inwoners uitkwam, kwamen er snel patenten en begon de productie van kinderzitjes. In Europa zou het nog vier decennia duren voordat eenzelfde niveau van autobezit bereikt werd en er een markt voor kinderzitjes was. In de tussentijd kwam de passieve veiligheidstechnologie voor auto's opzetten. Als eerste werd de veiligheidsgordel geïntroduceerd, die na verloop van tijd algemeen werd. Vervolgens ontstond ook de zogenaamde actieve veiligheidstechnologie, zoals het antiblokkeersysteem (Engels: *Anti-lock Braking System* of ABS) en het elektronisch stabiliteitssysteem (Engels: *Electronic Stability Control* of ESC). Deze ontwikkelingen hebben vervolgens de verwachtingen over de veiligheid van kinderen in auto's beïnvloed en gezorgd voor een klimaat waarin de markt voor kinderzitjes zich kon gaan ontwikkelen. Een reeks actoren heeft vervolgens bijgedragen aan de zich verder ontwikkelende

beleving van kinderzitjes en de gebruikte vormgeving. Een Engels echtpaar patenteerde het eerste kinderzitje dat kinderen eenzelfde mate van veiligheid moest bieden als volwassenen. Een Zweedse professor in de biomechanica vond het achterwaarts gerichte kinderzitje uit, geïnspireerd op de stoelen die gebruikt werden in het Gemini-ruimteprogramma. Er kwam wetgeving op het gebied van kinderzitjes, die steeds hogere eisen ging stellen, wat weer van invloed was op de ontwerpen. Consumentenorganisaties gingen kinderzitjes testen en vervolgens de wetgeving beïnvloeden. Er ontstond een uitgebreide handel in kinderzitjes en handelsreizigers droegen bij aan de internationale verspreiding en de verdere ontwikkeling ervan. Uit dit soort voorbeelden blijkt hoe het geheel van invloeden uit de omgeving, hier aangeduid als het ecosysteem, onlosmakelijk verbonden is met de evolutie van kinderzitjes.
De productarchitectuur van kinderzitjes evolueerde in de loop der decennia tot verschillende segmenten. Het eerste omvat de achterwaarts gerichte wiegjes bedoeld voor baby's. Het tweede segment omvat voorwaarts gerichte zitjes met een eigen vijfpuntsriemharnas voor peuters. En het derde segment wordt aangeduid als zitverhogers en positioneert het kind zodanig dat het de driepuntsgordel die standaard in de auto zit kan gebruiken. Deze productarchitecturen zijn nauw verbonden met internationale standaardisatie- en veiligheidsprogramma's die op het moment van schrijven nog steeds in ontwikkeling waren.

De tweede casus onderzoekt elektrisch-lichtproducten. De gloeilamp, die evolueerde in een ontwerp dat in het Engels wordt aangeduid als de *General Lighting Solution* (GLS), is een van de eerste toepassingen die consumenten aanzetten tot het gebruik van elektriciteit. De uitvinding van de gloeilamp is geworteld in vele decennia van technologische ontwikkeling. In 1879 patenteerden en commercialiseerden twee uitvinders aan weerszijden van de Atlantische Oceaan, onafhankelijk van elkaar, een ontwerp voor een gloeilamp met een koolstoffilament. In de literatuur wordt opgemerkt dat er maar liefst 22 uitvinders van gloeilampen geïdentificeerd zijn die Swan en Edison voorgingen (Friedel en Israel, 1985). Het is duidelijk dat de uitvinding van de gloeilamp niet het werk is van een enkele uitvinder of een opzichzelfstaande gebeurtenis. Deze grote technologische ontwikkeling bouwt voort op voorgaande kennisstapeling, die tot stand kwam door bijdragen van een groot aantal individuele dan wel samenwerkende uitvinders over een periode van tientallen jaren.
De gloeilamp werd verder ontwikkeld en verbeterd wat betreft levensduur, effectiviteit en kostprijs. De uitvindingen van de gloeidraad van getrokken wolfraam en de schroeffitting bleken belangrijke elementen van het dominante design dat bekend zou worden als de GLS gloeilamp. De GLS gloeilamp werd een belangrijke verbruiker van elektrische energie.

In dezelfde periode werd de technologie voor gasontladingslampen ontwikkeld, die al snel efficiënter bleek te zijn dan de gloeilamptechnologie. De voornaamste verschijningsvorm daarvan werd bekend als de fluorescentielamp, in de volksmond tl-buis of tl-lamp genoemd (naar het Franse *tube luminescent*, oftewel lichtgevende buis). De voornaamste uitvoeringsvorm van de tl-buis is een lange, dunne, rechte buis. Maar door omstandigheden slaagde de gasontladingslamp er niet in om op de westerse consumentenmarkt eenzelfde positie te veroveren als de gloeilamp. Ongeveer een eeuw na de uitvinding en commercialisering van de gloeilamp veranderde de visie op de beschikbaarheid van natuurlijke hulpbronnen dramatisch. Dat zette twee concurrerende lampenfabrikanten aan tot de ontwikkeling van een energiezuinig alternatief voor de gloeilamp, die berucht was om zijn zeer lage efficiency. Het resultaat was een praktischer versie van de tl-buis, die in Nederland bekend werd als de spaarlamp (in het Engels *Compact Fluorescent Lamp*, vaak afgekort als CFL). Bij zijn introductie werd aangenomen dat de spaarlamp een geduchte concurrent zou worden van de gloeilamp. Na twee decennia bleek echter dat consumenten nog steeds de voorkeur gaven aan de gloeilamp. Pas nadat de discussie op gang kwam over maatregelen om klimaatverandering tegen te gaan en die maatregelen werden vastgelegd in het Kyotoprotocol, kwam er wetgeving geïntroduceerd om de gloeilamp geleidelijk af te schaffen.

De casussen van de het kinderzitje en de spaarlamp illustreren dat het proces van evolutie in producten niet goed begrepen kan worden als het alleen maar technologisch beschreven wordt. Het ecosysteem, dat omgevingsinvloeden zoals maatschappelijke verandering, economische ontwikkeling en wetgeving omvat, blijkt onlosmakelijk verbonden te zijn met, én een essentieel onderdeel te zijn van, de evolutie van deze producten.

Tussen 2011 en 2015 zijn de ideeën uit dit proefschrift gebruikt in een college aan studenten Industrieel Ontwerpen aan de Universiteit Twente. Gedurende dit college is het *productevolutiediagram* aangeboden als instrument om de historische ontwikkeling van producten te analyseren. Hoofdstuk 8 toont een aantal voorbeelden van werk van deze studenten, waaruit geconcludeerd kan worden dat zij het geboden analytische instrument goed kunnen toepassen. Deze studenten pasten vaak al visuele technieken toe voordat het productevolutiediagram of onderdelen ervan beschikbaar waren. Dit mag geen verrassing zijn, aangezien industrieel ontwerpers opgeleid worden om zaken te visualiseren en afbeeldingen in hun werk toe te passen.
Het blijkt dat de studenten het productevolutiediagram niet altijd op exact dezelfde manier toepassen als in het college wordt voorgesteld. Bovendien

blijken zij werkwijzen te gebruiken om bepaalde aspecten zoals *enabling technologies* en ‘parameters’ te visualiseren die een interessante aanvulling kunnen bieden. Naast een reflectie op de academische doelstellingen van dit onderzoek dient te worden opgemerkt dat studenten die het college Evolutionaire Productontwikkeling gevolgd hebben, goed in staat bleken waardevolle ontwerprichtingen af te leiden uit hun analyses.

Dit proefschrift gebruikt de *Consumentengids*, een uitgave van de Consumentenbond, als primaire bron van informatie in het onderzoek naar de ontwikkeling van producten zoals in de twee casussen beschreven is. Hoofdstuk 9 biedt een overzicht van lessen die getrokken zijn uit het gebruik van consumentenbladen als primaire bron van informatie voor het hier gepresenteerde type onderzoek. Als voordelen zijn genoemd het grote aantal onderwerpen dat in de producttesten behandeld wordt, de aanwezigheid van prijsinformatie én de goede beschikbaarheid van de *Consumentengids*. Genoemde nadelen zijn onder andere het feit dat ze over het algemeen geen voorbeelden bevatten van volkomen nieuwe, nog maar net op de markt verschenen producten, dat de test- en rapportageprotocollen in de loop van de tijd veranderen en dat slechts enkele producten worden getest over een periode die lang genoeg is (decennia) om een goed beeld te reconstrueren van de ontwikkeling van deze producten. Hoofdstuk 9 noemt bovendien de criteria op die zijn gebruikt voor de selectie van de casussen, alsook de relevantie van het gebruik van de *Consumentengids* ervoor. Geconcludeerd wordt dat consumentenbladen in het algemeen en de *Consumentengids* in het bijzonder een rijke bron van informatie bieden voor het onderzoek naar evolutie in producten. De tijdschriften bieden waardevolle informatie over prijs, prestaties en kenmerken van producten die op het moment van publicatie verkrijgbaar zijn. De beperkingen maken het echter nodig aanvullende informatiebronnen te gebruiken. De voornaamste beperking betreft het ontbreken van informatie over de te onderzoeken producten in de eerste fase van hun evolutie.

Hoofdstuk 10 biedt een reflectie op het onderzoek en bevat conclusies en aanbevelingen. Het project begint met een onderzoeksdoelstelling die ambieert bij te dragen aan het begrip van *de manier waarop nieuwe (typen) producten ontstaan en zich in de loop der tijd ontwikkelen tot families van geavanceerdere versies.* De vijf proposities die het onderzoek afbakenen, worden kort bespiegeld. Op basis van casussen beargumenteert dit proefschrift dat het ecosysteem onlosmakelijk verbonden met, alsook een essentieel onderdeel blijkt te zijn van de evolutie van producten. Dit impliceert dat *“voor het begrip van de manier waarop producten evolueren, men de interactie tussen de productfamilie en het ecosysteem over langere tijd dient te* *analyseren"* (propositie P5). Daarom biedt het naast elkaar plaatsen van de productfamiliestamboom en het ecosysteem in het productevolutiediagram een verklarende waarde voor de onderzoeksdoelstellingen.

De sterkte van het productevolutiediagram is dat het de gebruiker in staat stelt de *"ontwikkeling van een productfamilie vast te leggen"* op één pagina. Daardoor maakt dit diagram het mogelijk een zeer complexe ontwikkelingsgeschiedenis voor te stellen als een grafische verhaallijn die patronen in de evolutie van productfamilies vastlegt. Zonder deze grafische voorstelling, die goed laat zien hoe nieuwere producten voortbouwen op vroegere versies en hoe de omgeving en het product elkaar evolutionair beïnvloeden, is het moeilijk de complexiteit van de evolutie in productfamilies te bevatten.
Het productevolutiediagram heeft twee zwakheden. De eerste is dat het volgens huidige inzichten niet mogelijk is om ondubbelzinnig een afstammingslijn in een productfamilie te reconstrueren op een manier die vergelijkbaar is met de fylogenetische stamboom zoals die in de biologie voor organismen wordt gebruikt. De tweede is het feit dat het niet mogelijk is om met zekerheid vast te stellen dat alle relevante factoren uit het ecosysteem die de evolutie van een product beïnvloeden in acht genomen worden, ook al wordt een systematische methode (PEST) gebruikt om ze te identificeren.

Een van de uitgangspunten van dit onderzoek was de aanname dat een beter begrip van de manier waarop nieuwe (typen) producten ontstaan en zich in de loop der tijd ontwikkelen tot families van geavanceerdere versies, uiteindelijk bijdraagt aan een succesvoller en efficiënter proces van productontwikkeling. Toch wordt opgemerkt dat slechts de toekomst zal uitwijzen of de gedachtegangen die in dit proefschrift zijn uitgewerkt op enige wijze een bruikbare bijdrage zullen leveren aan het onderwijs aan industrieel ontwerpers, het proces van productontwikkeling of de producten die ermee ontwikkeld zijn.

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Appendix A

Student, Subject, Year, Case Occurrence

Student, Subject, Year, Case Occurrence

Below 143 students have participated in the course Evolutionary Product Development at University Twente between 2011 and 2015 investigating 82 different types of products. The course has been provided between 2005 and 2015. A list of all 294 students who participated and investigated a total of 170 different types of products is included in Eger & Ehlhardt (2017).

Name	Subject	Year	Case occurrence	
			2005-2015	2011-2015
Tol, Liza van	alarm clock	2015	2	1
Vries, Clareyne de	artificial cardiac pacemaker	2015	1	1
Andriessen, Rosanne	baby carrier	2015	1	1
Graat, Bob	baby monitor	2012	1	1
Stam, Liesbeth	backpack	2012	3	1
Voorde, Gijs ten	barbecue	2014	1	1
Michel, Maarten	basketball shoes	2014	2	2
Versteegh, Christiaan	basketball shoes	2011	2	2
Markerink, Willem-Sander	bathroom scales	2011	5	3
Schreurs, Marleen	bathroom scales	2014	5	3
Tibbe, Annemarie	bathroom scales	2012	5	3
Roodink, Wesley	beer packaging	2015	1	1
Bakker, Robbert	bicycle	2013	4	3
Hidding, Jet	bicycle	2012	4	3
Schoonderbeek, Anouk	bicycle	2015	4	3
Veldhuizen, Gilbert van	bicycle computer	2015	2	1
Bolding, Stefan	bicycle pump	2011	4	3
Haan, Robert-Jan den	bicycle pump	2012	4	3
Weerd, Henk de	bicycle pump	2014	4	3
Janssen, Fenna	binocular	2011	5	3
Vette, Frederiek de	binocular	2012	5	3
Vries, Wessel de	binocular	2013	5	3
Hoogsteder, Kay	car radio	2015	1	1
Rouwenhorst, Maartje	child bicycle seat	2015	2	1
Reigersman, Noor	child restraint system	2014	1	1
Geurds, Nina	child's bicycle	2012	2	2
Siepel, Anika	child's bicycle	2013	2	2
Maanen, Frank van	circular saw	2013	2	2
Titsing, Tineke	circular saw	2012	2	2

Name	Subject	Year	Case occurrence	
			2005-2015	2011-2015
Bootsveld, Jorien	coffee machine	2013	3	3
Dijkstra, Jurriën	coffee machine	2012	3	3
Heteren, Martijn van	coffee machine	2012	3	3
Voorde, Pien ten	compact camera	2011	2	2
Werf, Sam van der	compact camera	2014	2	2
Slob, Han	computer keyboard	2014	1	1
Snippert, Jeroen	computer monitor	2014	1	1
Slot, Jasper	computer mouse	2014	4	2
Zandt, Joep van de	computer mouse	2015	4	2
Martina, Dennis	cordless drill	2013	4	2
Wolf, Fernand de	cordless drill	2012	4	2
Eising, Tessa	deep fryer	2012	2	2
Taatgen, Rik	deep fryer, electric	2013	2	2
Rozema, Mart	desktop printer	2014	2	2
Visschedijk, Manou	desktop printer	2015	2	2
Al-shorachi, Albert	digital camera	2011	1	1
Reuvers, Remco	electric drill	2014	2	1
Swart, Lotte	electric fan	2015	1	1
Sesink, Anke	electric hand mixer	2014	1	1
Nifterik, Jan van	electric shaver	2013	5	2
Snippert, Bas	electric shaver	2012	5	2
Addink, Carmen	electric toothbrush	2011	6	6
Hout, Ruben van den	electric toothbrush	2015	6	6
Leusink, Erna	electric toothbrush	2014	6	6
Rasser, Haske	electric toothbrush	2013	6	6
Reijners, Ellen	electric toothbrush	2012	6	6
Bijkerk, Jennifer	electric toothbrush	2011	6	6
Anninga, Eelco	espresso machine	2014	5	3
Manen, Jorn van	espresso machine	2013	5	3
Vries, Gijs de	espresso machine	2013	5	3
Galen, Ronald van	food processor	2011	4	3
Korfage, Bas	food processor	2011	4	3
Otten, Gijs	food processor	2014	4	3
Grunsven, Kai van	football	2015	1	1
Sönmez, Gökhan	game controller	2015	3	1

Name	Subject	Year	Case occurrence	
			2005-2015	2011-2015
Kuiper, Kyan	hair dryer	2013	2	2
Joling, Kevin	headphones	2015	7	5
Meekhof, Linda	headphones	2014	7	5
Regeling, Kyle	headphones	2013	7	5
Schäffer, Laura	headphones	2012	7	5
Schouwenburg, Richard v.	headphones	2011	7	5
Ramaker, Freddy	home cinema	2014	1	1
Spikkert, Emmy	horse saddle	2014	1	1
Kopke, Melina	ice skate	2015	2	2
Offringa, Marleen	ice skate	2014	2	2
Egberts, Frank	jig saw	2012	4	2
Pris, Boris	jig saw	2014	4	2
Ewijk, Luuk van	kick scooter	2015	1	1
Heijs, Yannick	kitchen blender	2013	2	1
Boon, Liza	kitchen machine	2013	2	2
Groenendaal, Niek	kitchen machine	2012	2	2
Gommeren, Martijn	kitchen scales	2012	4	3
Knook, Eilien	kitchen scales	2013	4	3
Wit, Marlien de	kitchen scales	2014	4	3
Kruiper, Ruben	laptop	2013	2	2
Schuddeboom, Lisette	laptop	2013	2	2
Commandeur, Ard	lawn mower	2012	3	3
Kemp, Laurens	lawn mower	2011	3	3
Rassers, Pierre-Yves	lawn mower	2013	3	3
Smit, Jeroen	Living Colors	2013	1	1
Buijs, Amke	loudspeakers	2013	4	3
Korber, Matthias	loudspeakers	2011	4	3
Wiggers, Ellis	loudspeakers	2015	4	3
Evertzen, Renée	mattress	2014	1	1
Doppenberg, Alfred	mini audio system	2011	1	1
Blokker, Lara	mobile phone	2013	4	2
Kessel, Pleuni van	mobile phone	2013	4	2
Hofsink, Ashley	mp3 player	2013	2	1
Balk, Remco	navigation system	2013	3	3
Hengst, Thomas den	navigation system	2013	3	3

Name	Subject	Year	Case occurrence	
			2005-2015	2011-2015
Lohmeijer, Jannes	navigation system, car	2014	3	3
Theunissen, Rik	percolator	2011	1	1
Vissers, Judith	piano	2015	1	1
Wieringa, Rianne	pram	2015	1	1
Vries, Marleen de	pressure cooker	2012	2	2
Vriesen, Maarten	pressure cooker	2013	2	2
Kolkman, Lonneke	racing bicycle	2014	1	1
Eilering, Sanne	remote control	2011	3	2
Haar, Wouter van der	remote control	2015	3	2
Brilman, Bas	running shoes	2015	1	1
Baaijens, Ruud	sanding machine	2012	2	2
Henckel, Claudia	sewing machine	2014	3	2
Karsten, Rianne	sewing machine	2012	3	2
Beer, Manon de	slr camera	2011	4	3
Bijvank, Jessika	slr camera	2013	4	3
Donker, Jacques	slr camera	2011	4	3
Giesberts, Bob	smoke detector	2011	1	1
Dreissen, Cyriel	snowboard	2015	2	2
Lemmens, Pim	snowboard	2014	2	2
Houwers, Thomas	speaker box	2012	1	1
Bogt, Oscar ter	steam iron	2011	2	2
Molen, Pieta van der	steam iron	2012	2	2
Endert, Christiaan	suitcase	2012	2	2
Smulders, Laura	suitcase	2013	2	2
Waard, Paul de	television	2014	3	2
Zanten, Julian van	television	2013	3	2
Claus, Julian	thermometer, clinical	2015	2	1
Blankendaal, Hans	thermostat	2013	3	3
Wesselink, Alex	thermostat	2015	3	3
Witteveen, Gerrit	thermostat	2013	3	3
Bergsma, Job	toaster	2014	4	3
Hilgerink, Tom	toaster	2011	4	3
Veugelers, Puck	toaster	2014	4	3
Dijkstra, Minke	universal remote control	2013	1	1
Meijers, Franke	vacuum cleaner	2014	4	2

Name	Subject	Year	Case occurrence	
			2005-2015	2011-2015
Young, David	vacuum cleaner	2014	4	2
Braakhuis, Peter	vacuum cleaner, hand held	2011	4	3
Hout, Niek van den	vacuum cleaner, hand held	2015	4	3
Kodde, Annet	vacuum cleaner, hand held	2013	4	3
Gerrits, Abel	video game console	2014	1	1
Schol, Henri	washing machine	2012	1	1
Visscher, Pim	water cooker	2014	2	1
Valerio, Chiara	waterproof clothes	2012	1	1
Meer, Manon van der	wrist watch	2015	3	1

Curriculum Vitae

Huub Ehlhardt was born on 26 January 1971 in Zoeterwoude, the Netherlands. He studied Industrial Design Engineering at Delft University of Technology from 1989 to 1995. Since graduating with an MSc in Industrial Design Engineering he has worked in various roles in the manufacturing industry. Immediately after finishing his Master's project in 1995 he first worked as a predevelopment engineer at Philips Domestic Appliances and Personal Care. In 2001 he moved to TNO, the Netherlands Organisation for Applied Scientific Research (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek), where he worked as Value Management project leader in the department of Product Development at the Industrial Technology Institute. After that he returned briefly to Philips in 2005 as a new business development senior manager after which he joined PA Consulting Group as a management consultant in 2006.

He first met Prof. Dr ir. A.O. Eger in January 2010, to discuss ideas on *'Evolution and Innovation'* (see also preface). After a few meetings, Professor Eger kindly encouraged him to take up the PhD research project documented in this thesis at University of Twente, the Netherlands.

Parallel to his research project, he continued to work in various full-time jobs outside the academic world. In 2011 he moved to Philips Healthcare to take up a consulting role in the Product Cost Innovation programme. Organizational changes led to a move to Philips Innovation Services in 2012 where he has worked since, as a manager in the Procurement Engineering department.

This thesis presents a *Theory of Product Evolution* which builds on the work of many scholars who have described evolutionary patterns in innovation processes. It challenges the popular notion that we owe the availability of products solely to genius inventors. Instead arguments are presented to show that a process of variation, selection and retention driving the accumulation of 'know-how' (to make) and 'know-what' (function to realize) provide an explanation for the emergence of products and their subsequent development into families of advanced versions. This theory employs the *Product Evolution Diagram* as an analytical framework to reconstruct the development history of a product family and picture it as a graphical narrative.

Two retrospective case studies explore how products come about and develop over time into a family of advanced versions. The cases studied illustrate that the process of evolution in products cannot be understood if described in technology terms alone. It reveals that contextual factors are part and parcel of the evolution of products.

Product Evolution will be of interest to design students and professionals, as well as general readers who want to find out more about how new (types of) products emerge.