Technology monitor 2018

A new perspective on breakthrough technologies:

3D printing, Blockchain, Self-driving car, and Augmented Reality

STT Netherlands
Study Centre for
Technology Trends

TU Delft

June 2018, final report

Roland Ortt (Delft University of Technology)
Bram Dees (Delft University of Technology)

Table of contents

Preface

We hardly need to point out that technology is changing our society. We could not imagine living without electricity, cars, airplanes, paracetamol or the Internet. We experience the consequences of those technology every moment of the day. How we eat, work and communicate is to a large extent based on the use of those technologies. As we said: we cannot live without them.

So we know the consequences of those technologies. But do we also know how they originate? We ever had the first idea or patent? Which organizations played a crucial role in the development of the technology? What where the first products that were based on the technology? And what factors played a role in the development. In short: what did the pattern of the technology development look like?

These questions are the basis of the study that researchers of the Technology, Policy and Management faculty of Delft University of Technology conducted on behalf of the Netherlands Centre for Technology Trends. They examined four so-called technological breakthroughs and looked at how they developed over time. The technologies in questions are blockchain, 3D printing, the self-driving car and Augmented Reality. They looked at when the breakthroughs were first invented, when the first prototypes were developed and when market diffusion started.

As such, the development pattern can be divided into three phases:

1. The development phase: between invention and initial introduction.
2. The adaptation phase: between initial introduction and the start of industrial production and large-scale diffusion.
3. The stabilization phase: after the start of industrial production and large-scale diffusion.

In addition to examining the temporal pattern, the researchers also mapped the factors that play a role in the development of technological breakthroughs. These factors are conditions that have to be met to allow the development of the technology to continue, like knowledge about the technology, socio-cultural aspects, product performance and regulations.

These factors show that technology development is not an automatic process. Technologies do not just fall from the sky, nor are they the result of a random process. Using these factors, it becomes clear that technology development can be monitored, explained and managed. And given the socio-economic importance of breakthrough technologies, that is more than good news.

It is the intention of the Netherlands Study Centre for Technology Trends to conduct research into the development of technological breakthroughs on an annual basis. That way, the development of potential technologies can be monitored and the factors that affect their development can be mapped and inventoried. As such, the Technology Monitor can become a long-term tool for innovation managers, product managers and policy-makers to bring society to the next technological level!

June 2018, Dr. Patrick van der Duin,
Director Netherlands Study Centre for Technology Trends

1. Introduction

The Study Centre for Technology Trends (STT) conducts broad futures studies on the crossroads of technology and society. Those crossroads can be approached from a social perspective. Society is a large unit to study, which is why it is divided into various domains. In most cases, the futures explorations are conducted from the point of view of such social domains, like education, healthcare, industry and security. STT's reports often include an exploration in one of those domains, as a building block of a multidisciplinary picture of society as a whole. In each domain, technological developments play a role. The interplay of the broader social influences and developments in specific domains is an important basis for an exploration at the crossroads of technology and society in the existing work at STT.

However, the crossroads of technology and society can also be approached from the perspective of new technological developments. As such, new technological developments together present a large unit of research, which is why they are divided into separate technologies, like gene therapy, robotics, blockchain and self-driving cars. Each of those technologies develops and diffused over a longer time period, in which the technologies are often applied in various domains. The interplay of the broader social influences and the developments in specific domains, and their joint effect on the development and diffusion of a technology are an important basis for an exploration at the crossroads of technology and society that complements the existing work in STT.

In domains like education or healthcare, different technologies are applied that set changes in motion. In turn, new technologies like the Internet, developed and diffused by being applied in various consecutive domains. In some cases, technology even creates new social domains or combinations of domains. In short, if we want to examine the crossroads of technology and society, we need complementary perspectives, including social domains as well as new technological developments.

This report describes a 'Technology Monitor', in which socially significant new technological developments are examined. That means that, in addition to focusing on the technologies themselves, we also look at how the technological developments are studied.
This report focuses on three research questions:

- Which technological breakthroughs can be expected to lead to fundamental change in society?
- What is the current status regarding the development and diffusion of those potential technological breakthroughs?
- What conditions have to be met for the technologies in questions to become actual breakthroughs?

1.1 Methodology

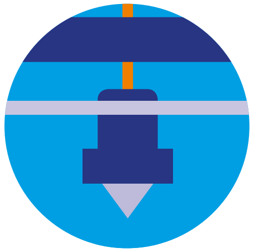
Technology is a broad concept that can include many things, which is why, in this report, to answer the first research question, an approach is presented for providing an unequivocal definition of a technology, which is then applied to four selected technological breakthroughs.

To map the development and diffusion of those technologies, we use an initial model, which describes a pattern of development and diffusion of technological breakthroughs over time. The model, which includes a pattern that distinguishes three generic phases, is used to indicate how technology was developed and applied in the past, and how it could continue to develop in the future. To answer the question as to the status of the development and diffusion of the technological breakthrough, we will use the pattern to visualize the consecutive applications of the breakthrough over time. As such, the model is used to answer the second research question.

The pattern of development and diffusion is the outcome of the interplay of a large number of factors that ultimately determine the change. To explain the changes in time, this report uses a second model that represents the large number of factors that set technological change in motion. Those factors are presented as a dashboard representing conditions for large-scale diffusion. So if large-scale diffusion has not yet begun, this method can be used to determine which conditions have not yet been met. As such, the model is used to answer the third research question.

1.2 The four breakthrough technologies

Based on a short study, a list was created of possible technological breakthroughs, taking into account the aggregation level on which the technology is defined and current expectations regarding the technology. If the aggregation level is too high, it is impossible to define clear milestones in the development and diffusion, because it involves families of technologies. On the other hand, if the aggregation level is too low, that can result in oversimplification. By selecting technologies of which current expectations are high and which are on the verge of large-scale diffusion, it is possible to include both the development so far and use the models to outline the near future. From a long list of technological breakthroughs, four technological breakthroughs were selected for closer examination: blockchain, 3D printing, the self-driving car and Augmented Reality.



3D printing

Blockchain

Self-driving car

Augmented Reality

2. Approach

In this report, three research questions are answered, using a different approach or model, which are discussed in the following paragraphs.

- The first research question is: **What are the technological breakthroughs that can be expected to lead to fundamental changes in society?** To answer that question, in the first paragraph, a method is presented that enables us to unequivocally define a technological breakthrough.
- The second research question is: **What is the current status regarding the development and diffusion of the four selected potential technological breakthroughs?** To answer that question, a model is presented in the second paragraph to indicate the current state of the development and diffusion of a technological breakthrough.
- The third research question is: **What are the conditions that determine whether or not a technology will break through?** To answer that question, a dashboard is presented in the third paragraph that includes the main factors for the development and diffusion of technological breakthroughs.

The final paragraph contains a brief outline of how the approach to defining breakthrough technologies and the two models can be applied together to map a technological change.

2.1 Method for defining breakthrough technologies

What is it that turns a technology into a technological breakthrough? A wide range of applications and structural change!

Technological breakthroughs are technologies that can be expected to result in fundamental change in society, which is determined on the basis of two aspects. Firstly, fundamental change means that the technology can be applied in multiple domains of our daily lives or in multiple industries. In the past, electro-motors were applied in several industries, in particular in all manufacturing industries. A technological breakthrough like the electro-motor is a technology that has a broad range of applications. Secondly, fundamental change means that a structural change is set in motion in each of those domains or industries and that the technology does more than merely replace a component or element of an existing chain or method, leaving the overall approach intact, and can also lead to a fundamental restructuring of the way things are done in that domain or industry. Again, the electro-motor is a good example. At first, it was seen in industry as an alternative to the steam engine, which itself had been a similar technological breakthrough a century earlier. The application of electro-motors instead of steam engines led to a new organization of factories. Efficient steam engines were huge and to use the forces optimally, all kinds of complicated switching mechanisms, with wheels and long leather straps, were used to power multiple industrial processes within one factory with one steam engine. So all the different processes were placed side by side. The electro-motor, on the other hand, could be reduced in size without losing efficiency, which meant that one electro-motor could be used for each process, making it possible to separated sub-processes. As such, the electro-motor led to a restructuring of industrial processes.

The definition of a technology

Often, a term used to refer to one technology, in practice refers to multiple technologies. In addition, people often use more than one term for the same technology. The term 3D printing, for instance, on closer inspection often refers to a family of different technologies, like joining consecutive sheets of material or heating and hardening of the powder or a material in consecutive layers. Working with different materials, like concrete, metal, chocolate and plastic, requires fundamentally different technologies. In addition, it turns out that other terms are also used to refer to that family of 3D printers, for instance 'additive manufacturing'.

If a technology has not been defined unequivocally, there is confusion about the question as to when that technology was invented, when it was first applied and when the large-scale application of that technology started or will start. In addition, it is unclear what the current status is of the conditions for large-scale diffusion. In short, it is impossible to answer questions regarding the status of a technological breakthrough and what the conditions are for further development and diffusion with having an unequivocal definition of the technology in question.

An unequivocal definition is created by describing the following aspects of a technology (a similar definition is described by Arthur (2009)):

1. The technological principle;
2. The functionality;
3. The components.

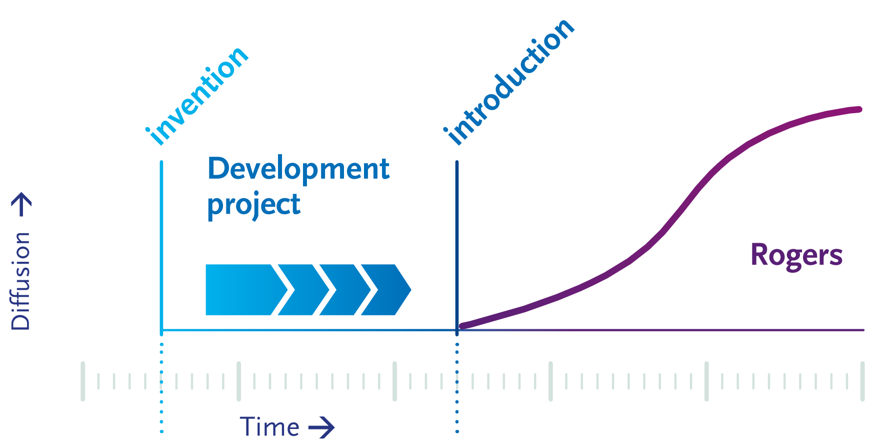
These aspects make it clear how the linguistic confusion around technology is created. The self-driving car, one of the four technologies we selected, is defined in terms of its functionality. However, it has not been determined on what technological principle that 'self-driving' is based or what the elements of the technology are, and nor has the 'self-driving' functionality been defined unequivocally. If you Google the words 'autonomous vehicle', you will find cars, but also airplanes, boats and submarines. If you browse Wikipedia for the history of self-driving cars, it would appear that the first autonomous cars were driving around in the 1920's. In a later chapter of this report, we will define the self-driving car based on the three aspects listed above, which will allow us to clearly indicate when the technology was first demonstrated (the invention) and applied (the market introduction).

2.2 Model for representing the development and diffusion of breakthroughs

The standard model: development project and diffusion pattern

The current, much used and broadly applied standard model of the development and diffusion of a technological breakthrough consists of two parts. The first part describes the development of the breakthrough as a development project, while the second part describes the diffusion of the breakthrough after market introduction. Both parts of this model (the 'innovation-diffusion' model), have been described at great length and are a standard element of scientific literature.

Figure 2.1: The innovation-diffusion model



The development project is often seen as a collection of consecutive phases, like idea generation and selection, conceptualization and selection, product development, production development, the development of a marketing plan and, ultimately, market introduction and implementation. This is known as the 'stage-gate model' (Cooper, 1990) (see the representation of the project phases in the figure shown above, between invention and introduction). Variations of the stage-gate model have also been proposed, like an agile project approach, ad hoc approaches and hybrid combinations.

For many technological breakthroughs, the diffusion has been examined by adding the consecutive sales or implementations of those breakthroughs, resulting in a cumulative adoption pattern that looks like a kind of S-curve (see the curve after introduction in figure 2.1): at first, adoption increases slowly, after which it accelerates and then slows down and reaches a ceiling once the complete collection of possible customers, the potential market, has been served.

It would appear that the two elements together create a logical and complete model for looking at where potential breakthroughs are located at a given point in time. It is noteworthy that the standard model, consisting of a development project and diffusion, is implicitly based on a number of assumptions:

- The development of a product on the basis of the new technology is a project that, provided it is properly managed, will lead to success.
- Diffusion of the technological products is a measure of that success. If the diffusion is lagging, something went wrong in the development project: for instance, the wrong idea was selected, or an idea was worked out in the wrong way, or it was manufactured or introduced in the wrong way.

As such, the success of a technological breakthrough is ascribed to the quality of research (the performance of the technology) and of management (the product form, marketing mix and introduction strategy).

Why is this standard model not (always) correct?

When the development and diffusion of a technological breakthrough is described as a historical phenomenon, the picture that emerges is different than the standard model.

What if the development and diffusion are followed from the moment of invention? In that case, an invention is defined as the first time the technology is demonstrated. To determine the moment of invention accurately, it is important to come up with a clear definition of the breakthrough (see paragraph 2.1). Prior to the moment of invention, lots of things are happening, like ideas and patents being deposited, fundamental research into the technological principle behind a breakthrough, etc. We focus on all that is happening from the invention on. After documenting over 100 technological breakthroughs from their invention on, we notice the following (Ortt, 2010):

Between invention and introduction, there is more than one development project

- The time between invention and initial introduction includes a period that is often many times longer than the period that is needed to complete a development project.
- Instead of one coordinated development project, there are often multiple related, but not coordinated, development processes taking place at sites in different organisations. It is impossible to see the combination of those processes as one project.
- In a large part of the phase between invention and introduction, people do not work only in development projects. It often takes a while for a technology to acquire the price/quality required to allow for introduction in the form of a product. That often requires fundamental research that has a completely different structure than a development project. Sometimes, the technology has advanced far enough but it is impossible to locate funds within the organizations involved for the development of a project. Sometimes, there is no urgent reason for the further development of a technology, which can end up being 'shelved' for years.

In short: the development between invention and initial introduction is different from a project.

After introduction, there is no steady diffusion, and that includes successful breakthroughs!

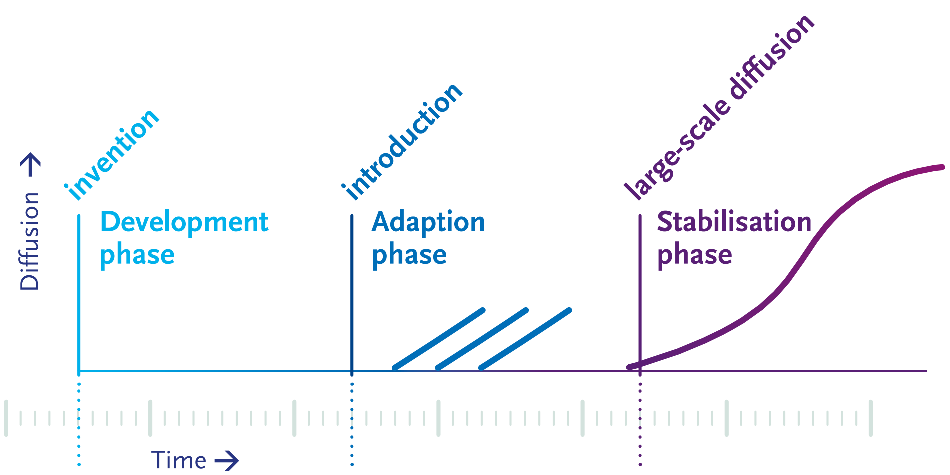
- The diffusion of many breakthroughs does indeed have an S-shaped diffusion pattern, which appears to support the second part of the standard model. However, on closer inspection, it also turns out that there is an enormous amount of time between the initial introduction of a breakthrough and the start of that S-shaped diffusion curve. In short, although that diffusion curve does occur with successful breakthroughs, it almost never starts immediately after introduction.
- Instead of a successful diffusion, there are often multiple small-scale, sometimes less than successful, applications of technological breakthroughs. Those applications do not confirm the lack of success (as the standard model implies), but they are a result of the fact that the technological breakthrough and its market applications have to be explored, understood and developed together with all complementary products and services and all other conditions. Often, it takes more time to develop those conditions that it takes to develop the technology itself.
- In about 80% of all breakthroughs we examined in our study in the course of 15 years, prior to their large-scale diffusion, in the form of an S-shaped diffusion curve, there is a prolonged phase of niche applications (Ortt, 2010).

In short: a small-scale and chaotic start of the diffusion of a technological breakthrough is not always a sign that the technology in question has no potential. In fact, it is often a more logical start for something that is completely new and the result of the complex interaction of constructing a system, competition with other technologies and competition between different forms of the same technology.

The new model: the pattern of development and diffusion

These important objections to the standard model have inspired to form a modified model that forms a more realistic representation of the development and diffusion of a technological breakthrough in the course of time.

Figure 2.2: The pattern of development and diffusion of technological breakthroughs



In the model, three milestones in time are distinguished:

1. **The invention.**
   The first demonstration of the functioning of the technological breakthrough.
2. **The first introduction in the market.**
   The first time that the technological breakthrough is applied, sold or implemented.
3. **The start of the industrial production and large-scale diffusion and implementation of the technological breakthrough.**

Using the three milestones, we can distinguish three consecutive phases:

- The development phase between invention and initial introduction. The invention is the demonstration of a functional principle that, in many cases, is not ready for production and market introduction. The development phase often includes research designed to improve the principle, and there are often one or more development processes to create a product on the basis of the principle.
- The adaptation phase between initial introduction and the start of industrial production and large-scale diffusion. This phase often includes a trial-and-error process in which different variations of the product are introduced in a variety of market niches, in essence creating an adjustment (adaptation) between the product, different consumer groups and different applications. Ultimately, the adaptation can lead to a kind of standard product.
- The stabilization phase starts with industrial production and large-scale diffusion. This phase starts with a sort of standard product that can be produced on a large scale and that is applied and diffused on a large scale. The product variations and applications have in essence stabilized.

Notes on the new model

The new model complements the standard innovation-diffusion model. The new model indicates, unlike the standard model, that there is more time between invention and diffusion than the time that is needed for a development project. The new model clearly indicates, unlike the standard model, that diffusion often does not begin with an S-curve, but with a process of small-scale diffusion in consecutive niche applications.

In each phase of the model, many actors play a role. Groups of actors work together to form a coherent system of complementary products and services, and a network of suppliers and distributors. In addition, there can also be competition with groups of actors that marketed the previous technology (technology competition) or groups that want to market the same new technology in a different form (design competition). Also, the technology can still perform below expectations, or applications of the technology may not be clear yet, and different actors also play a role there. These mechanisms are some of the reasons that the second phase can take on a chaotic character.

Innovation takes place throughout the entire pattern, not only at the start. Those innovation processes can relate to technology, to the components, products or systems that are made with the technology, to the marketing mix, to the production and to the entire organization, the business model surrounding the technology or even the nature of the network or collaborating companies. Unlike what is often thought, the innovation activity (in terms of the number of parties that go through an innovation process or in terms of the investments in innovation processes at a certain moment) often increases during the pattern. The idea often is that there is a kind of logical order in which the development of the principle and innovation take place first, that lead to a new product, after which the product diffuses in the market. This so-called pipeline model diverges strongly, however, from practice, in which innovation-related activity increases rather than decreases later on in the process. The economic explanation for that is that innovation only gets started when there is a large market of consumers, so that investments in innovation do indeed yield results, something that is far less certain at the beginning of the process.

There are various scenarios for the shape of the pattern of development and diffusion, scenarios that distinguish themselves by different phase lengths. There are examples of breakthroughs in which the first phase lasted almost a century, like fax machines and the material PVC, and examples in which that phase lasted less than a year, like dynamite. The same applies to the second phase. Depending on the length of the phase, it is possible to distinguish different scenarios, as shown in the examples listed below.

In the first scenario, a development is terminated prematurely during the first or second phase, prior to the start of large-scale diffusion. An example of that is the pattern of the electro-mechanical television systems that, after small-scale sales in the 1930s, completely phased out because fully electronic systems became the standard. There is no 'natural law' that the pattern is always traversed completely, the development and diffusion can stop at any point, for instance if the technology is outdated prematurely.

A second scenario is the scenario in which our model yields the standard innovation-diffusion model! In that case, the development phase is just as long as a development project and the adaptation phase is cancelled completely. As such, the new model includes the standard model as a special case. Earlier research teaches us that the standard model only occurs in 20% of technological breakthroughs (Ortt, 2010).

Although all these forms of realism fit the model of the pattern, it is a simplification and it is important to understand what causes that and what that means in practice. The cause is simple: the model is formed based on historical cases and that gives a 'hindsight bias'. In practice, that means that an even more chaotic pattern emerges that the stylized evolutionary pattern as presented. In one of the best innovation management studies, the Minnesota studies (Van de Ven et al., 2009), researchers monitored innovation projects in companies, which never worked on one innovation, but on different versions at the same time. If one of those versions becomes a success, that pattern can, in retrospect, be built up, but that means that people also forget how much work was done on versions 'that did not make it'. It is interesting to note that those Minnesota studies never produced a mainstream model. Were the findings too complicated, or were the findings not concrete enough to know what had to be done? Probably both.

Assumptions and limitations of the model

Every model is a simplification of reality. The method of simplification depends on the goal for which the model is intended, which shifts the emphasis to different aspects and reality is simplified into a different direction. The simplification is also a result of the (limited) available knowledge at a certain moment in time. But the standard innovation-diffusion model is really outdated: there is new knowledge that indicates the actual course of the pattern of development and diffusion of technological breakthroughs, and the new model that is based on that knowledge includes the standard model as a special case.

The new model in turn is also a simplification of reality. To represent the simplification, it is important to make the assumptions of the model explicit. If the model's assumptions have not been met, the model is an unusable simplification. And as such, making the assumptions explicit also gives direction to future research.

The main assumptions of the new model:

Assumption 1: The technology can be defined unequivocally (using the method described above in paragraph 2.1). Looking back when analyzing a historical case, defining a technology is a lot easier. In practice, there are often multiple research and development projects, and it is unclear as yet what a certain technology actually is. For instance, when Baekeland invented Bakelite, he was not sure whether it was a construction material (plastic), a varnish or a type of glue. Later, it became clear how his invention was perceived in practice (Bijker, 1995).

Assumption 2: The defined technology keeps changing, but remains within the definition during the entire pattern. If the technology changes so quickly that a new technology has been invented or introduced before the first phase has been completed and development of the earlier technology is halted, the result is a chaotic situation in which the model cannot be used.

Assumption 3: The milestones in time (1. Invention, 2. Initial introduction and 3. Start of industrial production and large-scale diffusion), can be recorded in time with an accuracy that is greater than the length of the phases between the milestones. So if the invention and initial introduction cannot be determined more accurately than in a time interval that is greater than the time between these milestones, the result is a chaotic situation in which the model is unusable.

2.3 Model for representing conditions for large-scale diffusion

The model discussed above is a passive description of the pattern of development and diffusion of technological breakthroughs. To explain, or perhaps even predict, the pattern, more information is needed. After thorough research, we were able to compile a list of factors that can form a barrier to the development and diffusion of the technological breakthrough. The available factors have been divided into fourteen categories. Seven of those categories make up the social, economic and technical system: they are the core factors. The other seven factors can influence the core factors.

An example shows why those influencing factors are so important. If a core factor is missing, for instance because there are no consumers, a large-scale diffusion is not possible. There may be different causes: it can be because knowledge is lacking among consumers about the technology and its applications or because the technology is expensive. Knowledge of these factors is important to explain and predict the pattern.

This collection of factors represents a significant extension of the factors Rogers uses to explain diffusion in the standard innovation-diffusion model. Rogers primarily looks at factors on the demand side of the market, in particular the characteristics of the (potential) consumers, and how those consumers perceive the innovation. That is understandable when you know the origin of the diffusion theory. Rogers was an agricultural sociologist conducting research in the 1960s into the acceptance of 'hybrid corn', a new type of corn, among farmers in the United States. Because all the factors on the supply side were in order, attention rightly focused on the demand side of the market. However, when everyone started using the diffusion model in other situations as well, they failed to check whether the supply-side factors were actually in order in those particular cases as well and whether they were important in terms of diffusion. In essence, a model that was first developed for a special situation, was then simply applied to all possible situations without modification.

The two tables below contain a description of the fourteen factors: the seven core factors and the seven influencing factors.

Table 2.1: Core factors for a large-scale diffusion of breakthrough technologies

Core factors	Description
1 **Product performance**	A product (with all its components and software) with a performance and quality (in absolute terms or relative to competing products) is needed for a large-scale diffusion. A poor performance, quality or unintended side-effects of, or accidents with, products may stand in the way of large-scale diffusion.
2 **Product price**	The price of a product includes financial and non-financial investments (for instance time and effort) to acquire and use a product. A product (with all its components and software) with a reasonable price (in absolute terms or relative to competing products) is needed for a large-scale diffusion. A high price may stand in the way of large-scale diffusion.

3 **Production system**	A production system that can deliver large quantities of products of sufficient quality and performance (in absolute terms or relative to competing products) is needed for a large-scale diffusion. The absence of such a system, unintended side-effects of, or accidents with, production may stand in the way of large-scale diffusion.
4 **Complementary products and services**	Complementary products and services for the development, production, distribution, adoption, use, repair, maintenance and discarding of products are needed for a large-scale diffusion. Absent or incompatible system components, unintended side-effects of, or accidents with, complementary products or services may stand in the way of large-scale diffusion.
5 **Actors and network formation**	Availability of necessary actors and enough coordination of their activities for the development, production, distribution, adoption, use, repair, maintenance and discarding of products are needed for a large-scale diffusion. Coordination can be emergent and implicit (for instance market mechanism) or formal and explicit (for instance an industry association). If certain actors or coordination mechanisms are needed but missing, that can stand in the way of large-scale diffusion.
6 **Customers**	Customers are needed for a large-scale diffusion. Customers have to have knowledge of the product and its use and be willing and able to pay for and use the product. If there are no customers, that will stand in the way of large-scale diffusion.
7 **Standards, rules and laws**	Standards, rules and laws with regard to the product, production, complementary products and services and how actors (on the demand and supply side of the market) have to handle the product and the surrounding socio-technical system are needed for a large-scale diffusion. Absence of standards, rules and laws can stand in the way of large-scale diffusion.

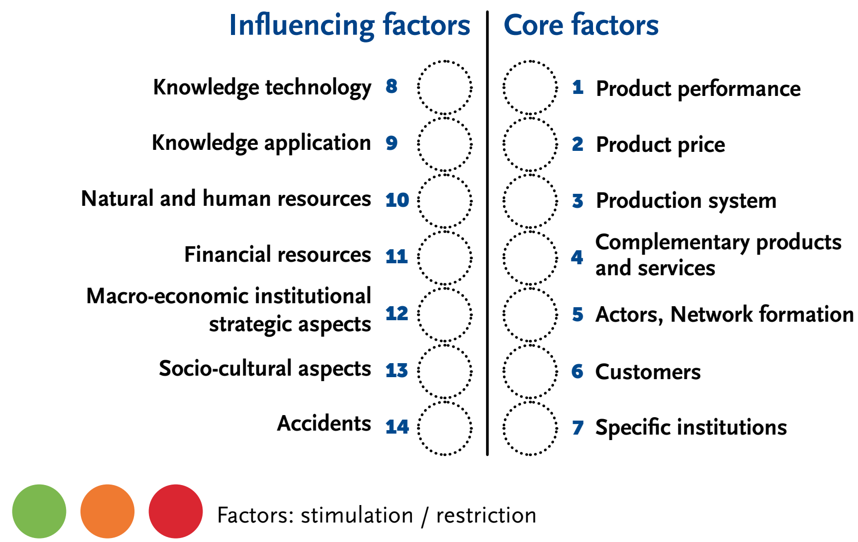
Table 2.2: Influencing factors for a large-scale diffusion of breakthrough technologies

Influencing factors	Description
8 **Knowledge of technology**	This includes fundamental and applied knowledge of the technology. Fundamental knowledge relates to technological principles in the product, production, complementary products and services and the surrounding socio-technical system. Applied knowledge relates to knowledge needed for the development (design), production and management of technological principles. If relevant actors lack important knowledge of technology for their role, that can stand in the way of a large-scale diffusion.
9 **Knowledge of applications**	This includes knowledge of potential applications, knowledge of the market (structure) and the actors involved. This knowledge is needed for all actors, including customers, to form strategies, formulate product requirements and to find other actors. If relevant actors lack important knowledge of applications for their role, that can stand in the way of a large-scale diffusion.
10 **Employees and resources**	The availability of employees with sufficient knowledge and skills, and the availability of resources and inputs of components and materials, are needed for the production and the use of a product, for production, complementary products and services. Organizations with a role in providing these aspects, like trade unions, are also included here. A lack of these forms of input may stand in the way of a large-scale diffusion.
11 **Financial resources**	Financial resources and the organizations (for instance banks) or platforms (for instance crowd funding) needed to provide those resources are needed for the development and diffusion of new products, production systems, complementary products and services, and for the adoption, implementation and maintenance of the products. A lack of financial resources among the actors on the supply and demand side of the market can stand in the way of a large-scale diffusion.

12 **Macro-economic and strategic aspects**	Macro-economic and strategic aspects refer to the overall economic situation in a country or industry, like a recession or sector-wide stagnation. Strategic aspects refer to the interests of countries and industries. Macro-economic and strategic aspects of countries and industries can stand in the way of a large-scale diffusion.
13 **Socio-cultural aspects**	Socio-cultural aspects refer to the values in a certain culture or industry. They include methods and habits in an industry or country and can also relate to interest groups outside the supply chain. These aspects are often less formalized that the formal standards, rules and laws. Socio-cultural aspects can stand in the way of a large-scale diffusion.
14 **Accidents and unexpected events**	This category includes accidents and events outside the socio-technical system with a major impact, like wars, nuclear accidents, natural disasters or political revolutions. These matters, or the risk of them occurring, can stand in the way of large-scale diffusion.

The factors form a dashboard. The status of the factors can be seen as slowing down further development and large-scale diffusion, or not slowing them down at all, or in between. Those three options have been translated for each factor in a traffic sign: a factor is slowing down (red), not slowing down (green), or in between (yellow). As such, the dashboard as a whole is a collection of traffic lights that allow you to see the status at a glance.

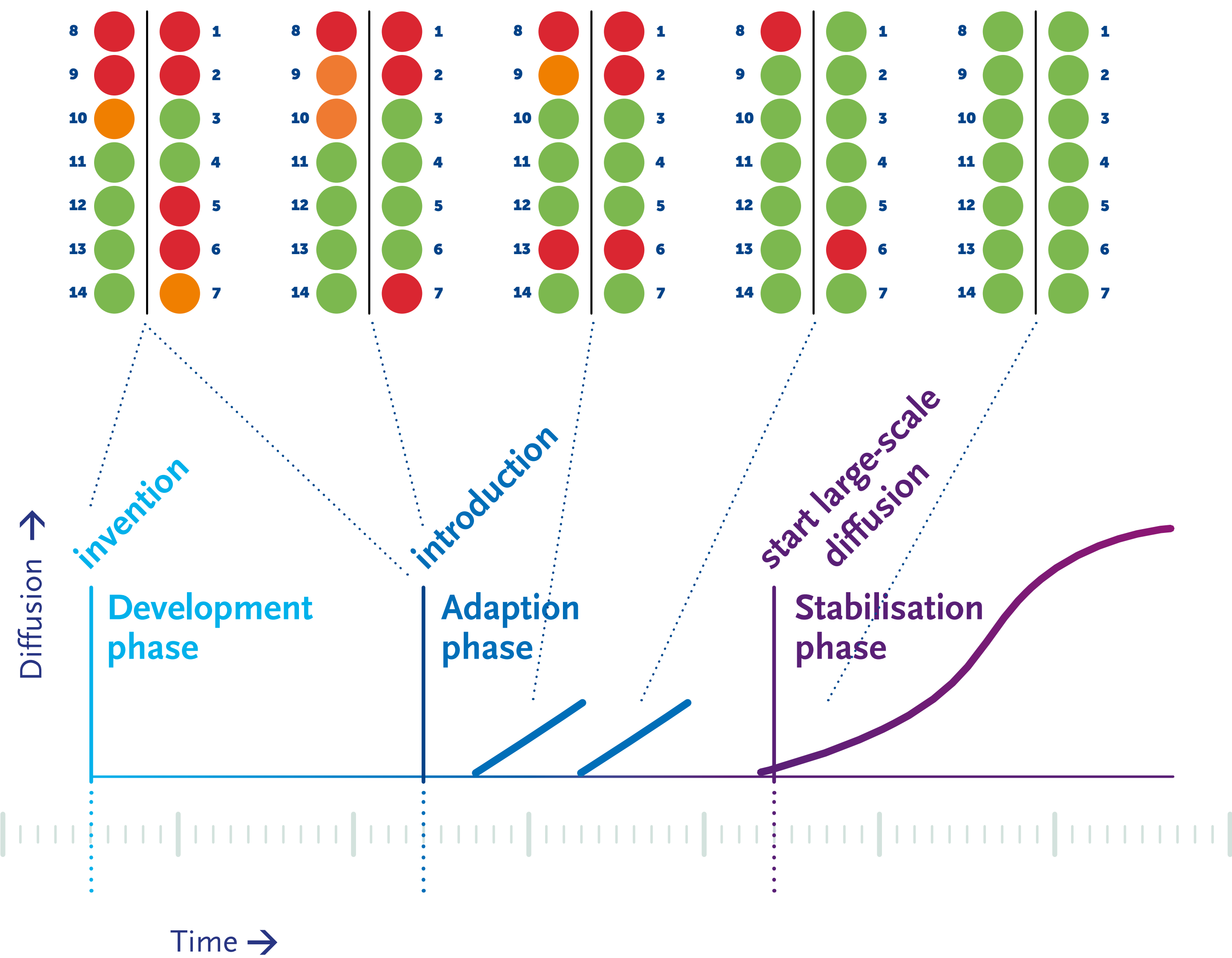
Figuur 2.3: Dashboard with factors that are important to large-scale diffusion



2.4 The combination of methods

In this chapter, we started by describing what a technological breakthrough is and how such a breakthrough can be defined as a research unit. Secondly, a model was presented that indicates, on a timeline, how the pattern of development and diffusion of technological breakthroughs unfolds. The model in question offers a historical perspective, indicates where the breakthrough stands at the moment and how it will further be developed and diffused. Thirdly, a model was described in which important social, technical and economic factors and their main influencing factors are described. The model indicates the current status of the technological breakthrough and shows which conditions have to be met for a likely large-scale diffusion. Figure 2.4 shows how the combination of methods is used. The pattern for Double Clutch Technology (DCT), which makes it possible to shift gears more smoothly and quickly, is shown. At various points, it is indicated which factors slowed down (red) and which factors facilitated (green) the further development and large-scale diffusion.

Figure 2.4: The combination of models indicates how factors for large-scale diffusion change over time throughout the development and diffusion pattern of a technological breakthrough



3D printing

3. 3D printing

There are dreams aplenty. When you are on vacation, instantly being able to print the clothes you want to wear that day. Going to Mars and being able to print exactly what you need and later recycle the material to print other tools. Printing living organs to solve the shortage of donors. How long before all that is possible? In this chapter, we discuss the development and diffusion of 3D printing.

3.1 Definition

Functionality

3D printing is a production technique with which an object is made from a 3D model by adding material layer by layer.

Operational principles

The American Society for Testing and Materials (ASTM) defines seven different categories in 3D printing (ASTM, 2015):

1. **Binder jetting:** binding ink is injected in a pattern onto a powder to bind the layer of powder.
2. **Direct energy deposition:** thermal energy is used to melt material and then blend it together.
3. **Material extrusion:** material is added selectively through a nozzle.
4. **Material jetting:** drops of building material is placed selectively.
5. **Powder bed fusion:** a layer of powder is melted together selectively with thermal energy.
6. **Sheet lamination:** sheets of material are joined together to create an object.
7. **Vat photopolymerization:** a liquid photopolymer is solidified selectively under the influence of light.

Components

To begin with, a basis is needed on which printing can take place, a substrate to which the material sticks, but from which the end product can later be removed. The printing material is placed onto that substrate, often with the use of a heat source (warmth or light). Around that, the most striking part of the 3D printer is visible: the construction designed to get the substrate and the product, the material and the energy, in the right place and give it the right speed.

Using CAD software, a 3D scanner or photogrammetry software, a 3D model can be made, which is then exported via an STL file (Surface Tessellation Language or Standard Tesselation Language) and converted by a so-called slicer into G-code. It is the G-code that controls all the movements of the 3D printer and starts the actual printing process.

3D printing and 'additive manufacturing'

3D printing is an additive production method, in which material is continuously added, unlike non-additive production methods in which material is shaped, for instance through melting and pressing, or removed, like in the manufacturing of drills and saws. The term 'additive manufacturing' (AM) is often used to refer to 3D printing, but strictly speaking, it could also include other production methods. Both terms are used, whereby AM is more common in technical circles, and 3D printing among the general public (Bourrell, 2016).

3.2 Pattern and applications

There are a number of old descriptions of methods for making 3D objects, like photographing the object from all sides to be able to create a good likeness in stone, and building an object using well-placed welding drops. Then, in 1981, Kodama published an article in which he reports on a 'rapid prototyping' system on the basis of a photopolymer that hardens when exposed to light. He has a functional system and used it to print multiple products. In 1984, Charles Hull developed a stereolithographic system for which he receives a patent in 1986, the same year he starts a company for 3D printers: 3D Systems Corporation (Steenhuis & Pretorius, 2015). However, he is not the first, Helisys was the first company in 1985, the same year Denken was founded in Japan (Bourell, 2016).

Helisys and Denken sold their first system in 1991 and 1993, respectively. 3D Systems beat them to it, when the SLA-1 was first sold in 1988. In the following years, other 3D printing methods are developed. DTM develops a form of powder bed fusion, Soligen is the first with binder jetting and, in 1998, directed energy deposition is marketed by Optomec (Bourell, 2016).

3D printing emerged from 'Rapid Prototyping'. In some cases, designers in the car industry had to wait two months for a prototype, but thanks to 3D printing, that was reduced to about two days, which meant that iterations could follow each other far more quickly. The real enthusiasts have been 3D printing for themselves for quite some time now, with printers they developed themselves. So what was the moment when the first 3D home printer was marketed? That was a gradual, incremental process. It was in 2006 that a printer was marketed from the Fab@Home project, which was a milestone in genuinely cheap printing at home (Bourell, 2016). In 2010, that was followed by the first car with a printed body (Stratasys, 2010), after which more car parts started being printed, initially with the exception of the powertrain. The fashion industry also started experimenting, first with shoes, bikinis and dresses (Resins Online, 2013). Printing houses and other buildings is coming ever closer via the 3D Print Canal House in Amsterdam that began in 2013 (3D Print Canal House, 2016), the company Winsun, which printed a multi-story apartment building in 2015 (Architect Magazine, 2015) and via projects from other companies and organizations. Possibilities in the medical world have created high expectations. In 2013, the jawbone of a patient was replaced successfully by a 3D printed jawbone, after his jawbone had been badly damaged in an accident (Hu & Yin, 2014). Shortly after that, there were applications in prosthetics, hearing aids and printed teeth: in particular objects that had to be tailor-made. Food is also printed, and 3D printing increases freedom in the design of, for example, candy and pasta, as well as pizzas (Wong, 2014). Thanks to 3D printing, it is now also possible to repair damaged parts, print the skeletons of extinct species and print souvenirs for sales. Airplane parts often have complex shapes to make them light as well as able to withstand strong forces. When legislation and regulations had been sorted out, the first printed flying part was put in production. The Boeing 787 Dreamliner has some 30 printed parts (Bourell, 2016). It appears that the main advantage for airline engineering is the ability to reduce the number of parts by replacing them with a single 3D printed part.

Table 3.1: Successive applications for 3D printing

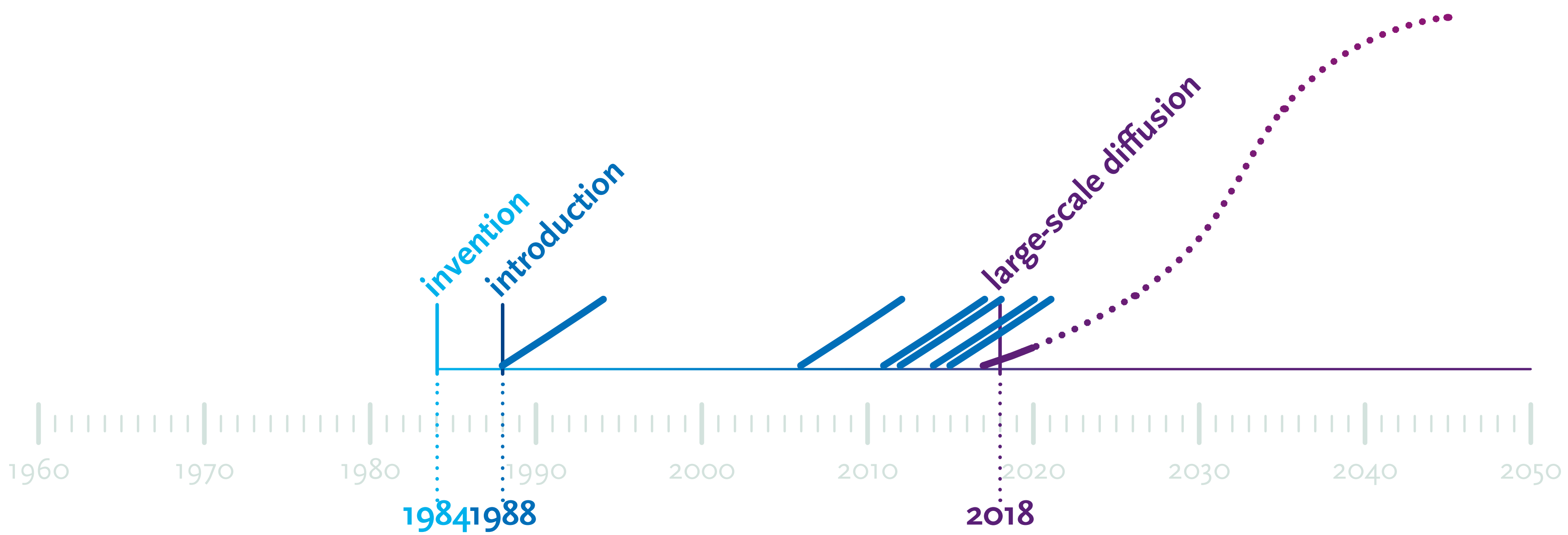
Year	Application	Explanation
1988	Rapid Prototyping	Prototypes of new designs
2006	Printing at home	Complete freedom
2010	Cars	Body
2013	Clothing	Shoes, bikinis and dresses
2013	Construction	All buildings
2013	Medical	Bone, prosthetics, hearing aids, teeth
2014	Food	Chocolate, candy, pasta, pizza
2014	Cultural heritage	3D models, repairs, souvenirs
2015	Airplane parts	Various parts

Future applications that are in the pipeline are even more impressive than the examples listed above. A lot can be done once it becomes possible to print at micro- or even nano-level. Some sources mention volume-based AM, in which an object is not printed layer by layer, but where each point of the object is printed at the same time, so that the process does not take hours or weeks, but mere seconds. The medical applications can be expanded enormously by something that is sometimes referred to as 4D printing, or printing living cells: from printing genes to printing organs and, one day, perhaps entire organisms.

In addition, there are developments to find more printable materials, for instance because they need to be harder, stronger or more wear-resistant, and it is also important to have as little tension as possible in a printed product. When printing is done using heat, that can create tension in the material, which is a problem that could be solved by using larger dimensions but, for instance in the airline industry, that can be undesirable. Also, different materials are increasingly combined in individual printers and products. The first printed products had a somewhat ribbed surface due to the layered printing. Finding a material that does not have to be treated afterwards can help reduce costs.

From 2010 to 2015, the 3D printer market grew with an average 30% per year (Bourell, 2016), during the crisis. It has been estimated that about 10% of companies use 3D printing for prototypes or production in 2014 (Ortt, 2017), and some expect the industrial side of the market along to represent a market value of 21 billion by 2010, while the consumer market recently increased by over 100% in a single year (Steenhuis & Pretorius, 2015). Looking at the list of applications in Table 3.1, there are also signs of strong growth between 2010 and 2015. However, many applications involved testing, first trials and experiments, which often required licenses and other one-time permissions, with legislation lagging further and further behind, resulting in a situation where applications were explored, without reaching their full potential. As we will see in the next paragraph, many of those objections have now been removed and, although some applications are not yet ready for a mass market, many of them are. The start of large-scale diffusion of 3D printing is now, in 2018.

Figure 3.1: Pattern of development and diffusion of 3D printing



The time between invention in 1984 and the initial market introduction in 1988 was not long. However, since then, it took about 30 years of developing, experimenting and niche applications to prepare 3D printing for large-scale diffusion. That is relatively long, compared to a large number of other historical cases (Ortt, 2010), but it is understandable when we realize what changes 3D printing brings about in value chains and supply chains, which will also prove to be relevant in the paragraph about conditions.

3.3 Conditions

Knowledge of technology

We have reached a point where some airplane parts can be printed, the first printed buildings have been erected and people can print what they want at home. Important developments are still expected in the printing quality and materials (Lu, 2015), which will lead to new performances, but even without those developments and with current knowledge, 3D printing has a lot of potential advantages.

Knowledge of applications

The understanding and use of 3D printing has already resulted in the use of 3D-printed products, but that is not the same as a large-scale implementation in a company. 3D printing will lead to major changes, both in the internal processes in production companies and in supply chains (Ortt, 2017). That next step is a complex step that has yet to be taken.

Employees and raw materials

3D printing mostly uses available 3D software to operate a machine via G-code, which is also used, for instance, in CNC machines. In that sense, there are plenty of people with the necessary knowledge and experience to operate 3D printers without problems. And while the lack of 3D models used to be a limitation with regard to the consumer market, open source projects, like the RepRap project (more about which later), are quickly changing that.

Financial resources

Ortt (2017) lists a number of financial barriers to large-scale diffusion of 3D printers: major investments and high material and maintenance costs. However, while these factors tend to slow down the process, there are also positive signals, like the many studies into aspects of 3D printing backed by funding and the large number of companies that uses or sells printed products.

Macroeconomic and strategic aspects

The major changes in value chains and supply chains companies have to undergo before realizing the full potential of 3D printing take up a long time. Many companies have already begun the process and business models have already been developed for the large-scale application of 3D printing.

Socio-cultural aspects

3D printing can be (part of) the response to the demand for unique, personal products and can contribute to sustainability (Wilkinson & Cope, 2015). Because that fits existing trends, in socio-cultural terms, not much resistance is to be expected to large-scale diffusion, with two possible exceptions: the printing of living cells results in various ethical discussion that will require compromises (Lu, 2015) and the possibility to print weapons will create problems. Once we reach those points, it will become clear whether the general public will embrace or reject those applications of 3D printing.

Accidents and unexpected events

No major events have been identified that appear to slow down the large-scale diffusion of 3D printing. On the other hand, there have been events that had a positive effect, like a speech by US President Obama in 2012, which led to an acceleration of many developments (Bourell, 2016).

Product performance

Despite the fact that there are a number of markets where 3D printing has immediate benefits, for instance the market for hearing aids (Ortt, 2017), the low-quality, user-unfriendly slow printing needed a lot of development. Although not the standard, there are printers with a resolution of 1,600 dpi (dots per inch) that are able to print a layer that is 16 micrometers thick. Metal printing is able to process a few kilograms per hour (Lu, 2015) and an average CNC machine is able to process a higher quantity than that. Bourell (2016) also points out that 3D printing is very fast when it comes to prototypes, but still very slow when it comes to production. In itself, the slowness of 3D printing is not a reason to claim that the large-scale diffusion has not yet begun, because existing designs are insufficient for comparing non-additive production methods and 3D printing. GE was able to replace twenty parts in a jet engine by one 3D-printed part (Lu, 2015), which compensates the higher costs per individual component.

Product price

When only a few copies have to be produced, a 3D-printed object is often cheaper than a non-printed one, for instance in the case involving hearing aids. As production figures rise, the costs per part are reduced in the case of traditional production methods, while they stay virtually identical when 3D printing is used. To allow 3D printing to compete more effectively with other production methods, the costs per printed part have to be reduced. The costs involved include mainly the costs for the 3D printer and the printing materials. Other factors that affect overall costs are the printing speed, increasing complexity of the object and waste reduction of the material (Bourell, 2016). Initially, the costs of 3D printing were very high, but that is changing now, in part thanks to patents that are expiring (Ortt, 2017). Meanwhile, 3D printing systems are already competitive with serial sizes of up 10,000 items (Steenhuis & Pretorius, 2015).

Other financial benefits of 3D printing are reduced transportation costs when it is possible to print on site, for instance a reduction of the number of spare parts a mechanic has to pack, or printing on a construction site. Lu (2015) looks beyond that and points to the possibility of consumers co-designing and printing their products at home. That will reduce design times, render transportation obsolete and provide consumers with unique products.

Production system

The price of 3D printers is falling steadily and sales figures are rising. Production of 3D printers does not appear to slow down their diffusion, while the printers themselves do have a potentially revolutionary impact on production systems.

Complementary products and services

Although CAD software can be used to create 3D models, that software was used before to make technical drawings, which means that much of the transition towards 3D printing of those models has already been made, which means it has contributed to the diffusion of 3D printing. The step towards creating a more user-friendly and simple operating of 3D printers is much bigger, and there is still work to be done (Ortt, 2017). Sharing 3D models is important with consumer printers, because not everybody has design software and the knowledge on how to use it. That is why Makerbot, manufacturer of consumer printers, has set up the Makerbot Thingiverse, where users can share there 3D models with others, after which people can build on each other's models. At the moment, over a million designs are already available on the Thingiverse (Makerbot Industries, 2018). For now, platforms that bring supply and demand together to offer creative designs and solutions to customers quickly are few and far between, which means that consumers as yet have little influence on market supply and demand or on the available designs, and there are few opportunities for working on that with a low threshold, because the associated software has not yet reached that level. User-friendly software for the operation of 3D printers has developed quite a bit, but for many users, design software remains too complex.

Actors and network formation

The greatest potential influence of network formation is the possibility for consumers to take part in the design and production process to allow them to buy unique personal products that are at the same time sustainable, for instance through the use of recycled material or the reduction of transportation. The abovementioned Thingiverse platform is a good example. Another example is the RepRap project, which started in 2005 and was aimed at creating a printer that was able to make all or most of the own parts. RepRap stands for 'Replicating Rapid Prototyper' (Steenhuis & Pretorius, 2015). This open source project has had an influence on the movement away from 'rapid prototyping' towards printing as a production process (Wilkinson & Cope, 2015).

Customers

Because most of the people working on the technology were hobbyists, technical challenges were no problem. Solving them was part of the fun involved in creating a 3D printer. To reach the mass market, operating the printers has to be simple and user-friendly and, at the moment, the software needed to make that happen has not yet been developed (Lu, 2015; Ortt, 2017). There have been serious developments, and that is reflected in the strong recent growth of the market, and there appears to be no shortage of users.

Standards, regulation and legislation

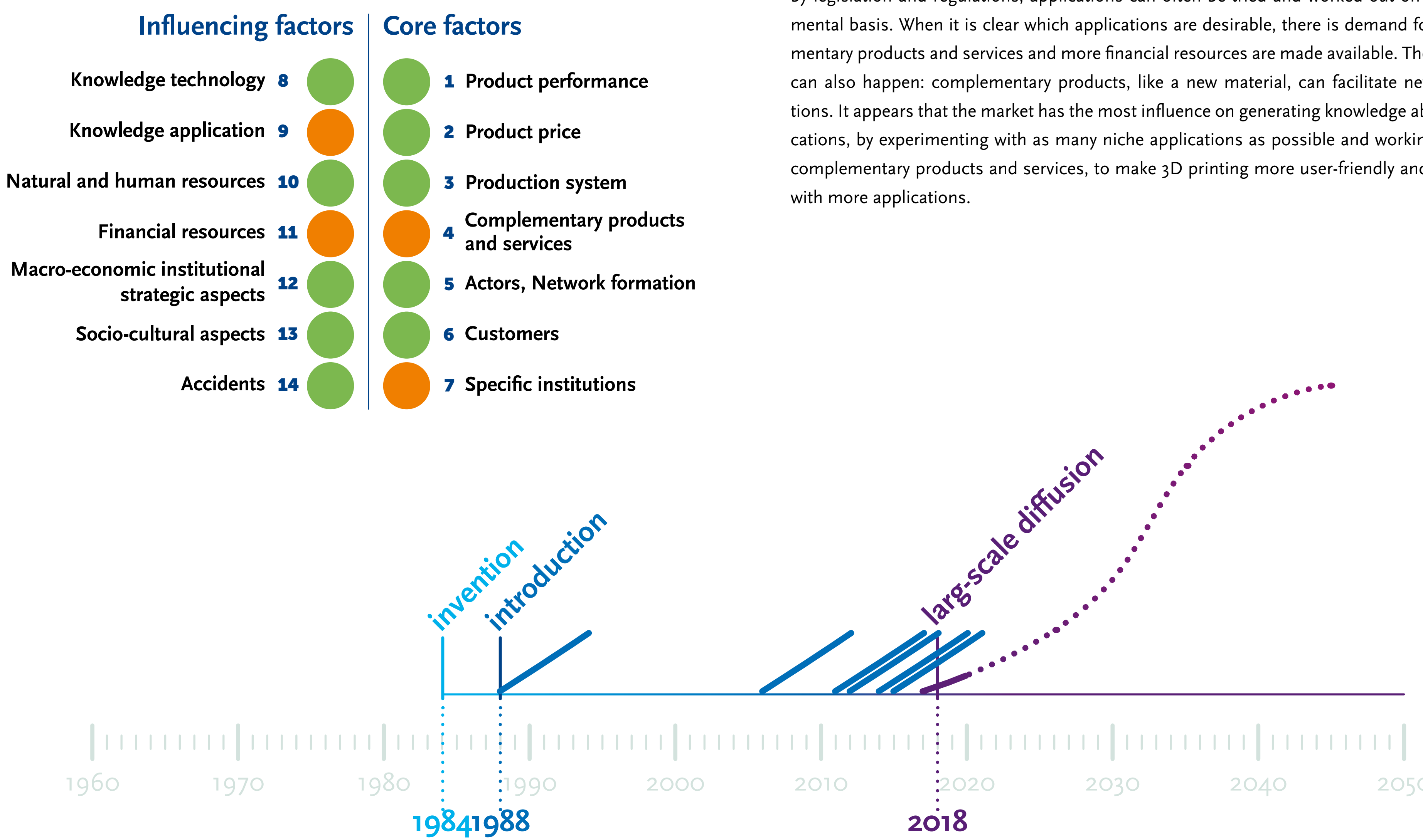
The first patents for 3D printing, which were issued from 1984 on (Steenhuis & Pretorius, 2015), have already expired, which has had a positive impact on market growth, for instance through lower prices for 3D printers. In 2012, the China 3D Printing Technology Industry Alliance was founded and, in 2014, 3D printing was included in two different national innovation programs in China (Hu & Yin, 2014). In 2012, President Obama spoke about Us Manufacturing Innovation Institutes, the first of which was founded the same year, with a focus on 3D printing. Not only that institute, but in particular the publicity thanks to Obama has had international consequences for all kinds of institutes and organizations that started working with 3D printing more (Bourell, 2016). There are, however, still many challenges as far as legislation and regulation are concerned. New safety requirements have to be defined and observed for all applications. Cars are now allowed to drive with printed parts, airplanes also have printed components, but it is often difficult to prove the quality of printed parts. In the construction industry, for example, it is still a difficult process. And there are concerns about the (illegal) printing of weapons, which is difficult to monitor, because the online sharing of components is hard to prevent. Finally, there is little jurisprudence in this area: initially, there was usually one organization responsible for designing, making and distributing a product (Bourell, 2016), but that could now change dramatically.

Table 3.2: Overview of the conditions for 3D printing

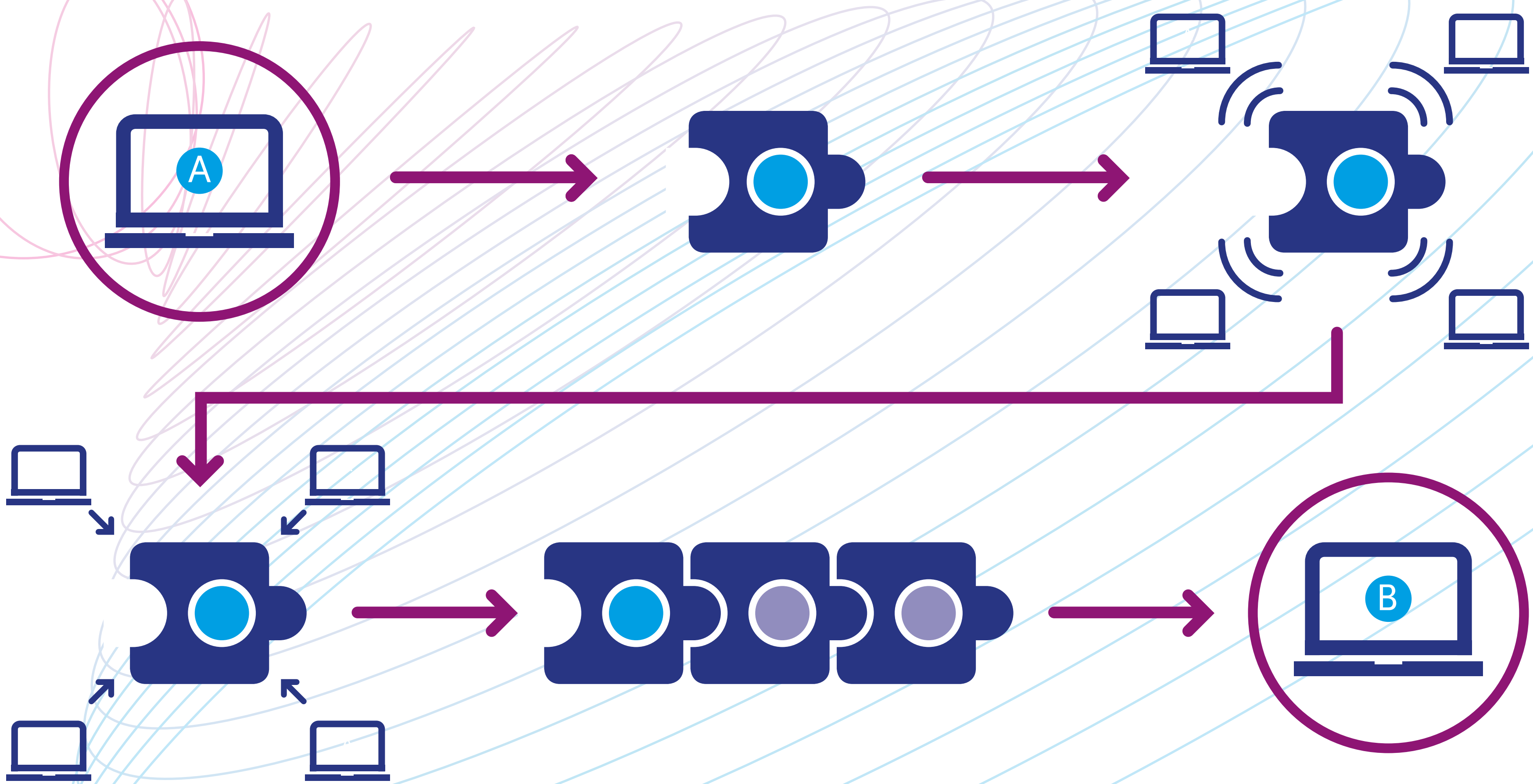
Influencing factors	Core factors
8 Knowledge technology	1 Product performance
9 Knowledge application	2 Product price
10 Natural and human resources	3 Production system
11 Financial resources	4 Complementary products and services
12 Macro-economic institutional strategic aspects	5 Actors, Network formation
13 Socio-cultural aspects	6 Customers
14 Accidents	7 Specific institutions

In the overview of the conditions that serve as necessary requirements for large-scale diffusion, we see that none of them are red. However, some of them are not green yet and an improvement of the conditions in question could lead to an accelerated diffusion. Each application of 3D printers has different parameters, including the printing materials, the other requirements of printed products and additional safety requirements. Apart from the limitations imposed by legislation and regulations, applications can often be tried and worked out on an experimental basis. When it is clear which applications are desirable, there is demand for complementary products and services and more financial resources are made available. The opposite can also happen: complementary products, like a new material, can facilitate new applications. It appears that the market has the most influence on generating knowledge about applications, by experimenting with as many niche applications as possible and working hard on complementary products and services, to make 3D printing more user-friendly and come up with more applications.

Figure 3.2: The pattern and conditions for 3D printing



Blockchain



4. Blockchain

Probably, everyone in the Netherlands by now knows at least one person who says that cryptocurrencies are the future. While these enthusiasts keep promoting Bitcoin and other so-called 'altcoins', the public at large watching the news sees the exchange rate go up and down. In this chapter, we discuss the development and diffusion of the 'blockchain', the platform on which Bitcoin was built.

4.1 Definition

Functionality

A blockchain is an open, distributed database that can monitor transactions between parties in an efficient, verifiable and permanent way (Iansiti & Lakhani, 2017).

Operating principles

A blockchain protocol creates consensus in a network by verifying each transaction with prior transactions, and by adding the transaction to the chain if it matches earlier transactions. That way, users can never spend something they do not own. Via this system, information can be sent directly to another party, without a third party that carries out the transaction, while guaranteeing reliability. This results in secure transactions without requiring trust between sender and recipient. When a machine tries to send information in a way that violates the agreed rules, actions by that machine are limited or even ruled out. So changes can only be implemented via majority vote.

Components

First and foremost, a blockchain is defined in a protocol that contains the 'rules' for the actors in the network. Actors who want to be part of the blockchain will have to use that protocol. As such, the blockchain exists in a network of machines that are connected, usually via the Internet. In principle, all actors in the network can make a transaction, but a number of actors will have to check whether the information matches the history. When that confirmation is issued by a number of actors defined in the protocol, the new block is added to the chain. Each block consists of multiple elements, the first of which is the 'hash': the reference to the previous block to which the new block wants to be added. In addition, each block contains the date and time when the block was found. And finally, the block contains the transaction data, the information being sent.

Blockchain and cryptocurrencies

The prime association with the concept of blockchain is that of the cryptocurrencies, whereby the blockchain is used to send unique 'private keys' that we call Bitcoin, for example. At the moment, there are over 1500 cryptocurrencies that are based on this principle (CoinMarketCap, 2018). It is important to note that, in this report, the blockchain will be discussed in all its aspects, which means the blockchain can be used to store all kinds of identities (of products or people) and for each imaginable transaction for each random person or machine with access to the network. When physical objects get assigned a unique code, they can switch owners via the blockchain. Blockchains do not have to be public and can, for instance, also be used by the employees of a company to exchange information.

4.2 Pattern and applications

The first description of a series of documents, each with a non-forgeable time stamp, came from Haber and Stornetta (1991). The following year, the concept of the Merkle trees was included in a series of documents, making it possible to combine multiple documents in one block, and to check all documents at the same time for damage or alterations since they were sent (Bayer, Haber & Stornetta, 1992). That is the last milestone identified before publication of the invention in 2008. Between 1992 and 2008, no milestones were identified that are clearly at the basis of the invention of blockchain, although a number of people apparently worked on similar concept. David Chaum worked on DigiCash, Adam Back on Hashcash, after which B-money by Wei Dai and Bit gold by Nick Szabo are seen as predecessors of the Bitcoin. Looking back, it is clear that the various digital currencies used each other's solutions and continued from there, and it is also clear that the ideas of Nick Szabo were used for the Bitcoin. Szabo shared his ideas in a closed mailing in 1998 and first described them in public in 2005 (Cannucciari, 2016).

In 2008, Satoshi Nakamoto published the idea that was ultimately used to develop the bitcoin, and with it the underlying blockchain. Who Satoshi Nakamoto is? That is a complete mystery. Man, woman, or group, we do not know. We do know that Nakamoto used the ideas provided by Szabo as a foundation. Because we do not know whether Nakamoto first encountered the ideas in Szabo's closed mailing (Szabo, 2011), we have to conclude that the blockchain was invented between 1998 and 2008. A demonstration of the principle of the blockchain as we now know it in that ten-year period is not known. What we do know is that Nakamoto, after the publication in 2008, sought and found the cooperation of a number of developers, after which the Bitcoin was operational in 2009 (Cannucciari, 2016). It seems unlikely that, between 1998 and 2008, no other attempts were made beyond the theoretical publication. As such, the exact moment of invention is unknown, other than that it took place between 1998 and 2008. The entity of Satoshi Nakamoto first appeared in his publication in 2008 and we only know of the developments from that moment onwards. Nakamoto only had contact with developers online, both via forums and by e-mail, to work out the necessary software in the basis of the concept that had been formulated, and probably tested, by Satoshi Nakamoto (Cannucciari, 2016).

Soon after, the aforementioned introduction of the Bitcoin took place in 2009, when ten bitcoins were sent in January of that year, marking the first transaction ever. The first cryptocurrency had been born. It was only after that introduction that people realized that the underlying principle, the blockchain, could be used in many more applications.

In 2011, it became clear that the anonymous transactions of the Bitcoin can facilitate illegal activities. Silk Road was an online market for trading drugs, visiting the website was anonymous because it was located on the Dark Web and, thanks to Bitcoin, payments could be made anonymously. Other ideas, like paying artists every time their music is played or making an automatic payment on delivery of a package, can also be done through the blockchain. In 2014, the Ethereum platform was launched, enabling everyone to sign a contract on the blockchain, a so-called 'smart contract'. That application of the blockchain is also known as blockchain 2.0, because it has an even greater potential than cryptocurrencies when it comes to generating change. Meanwhile, cryptocurrencies are to a large extent set up and used independently of government authorities, although governments themselves also come up with more and more applications, for example the E-Dinar Coin that was introduced in 2018 by Tunisia as the first national cryptocurrency, quickly followed by Senegal, and by now, many countries are working on their own versions (iAfrikan News, 2016). The year 2017 saw the first international sale of land, as part of the much broader possibilities to trade properties via a smart contract. In this case, a little over 2 hectares of land in California was sold to a buyer from Norway.

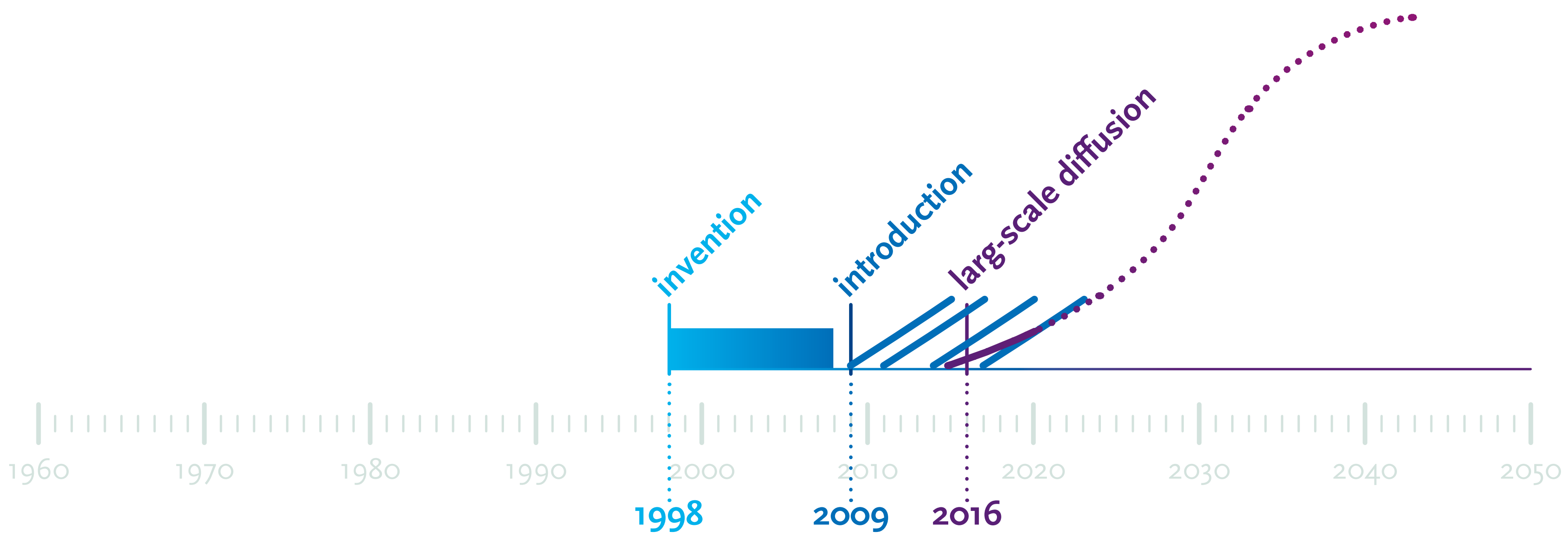
Table 4.1: Successive applications for Blockchain

Year	Application	Explanation
2009	Cryptocurrency	Bitcoin and may other cryptocurrencies
2011	Illegal activities	Trade in illegal drugs and arms
2014	Blockchain 2.0	For 'smart contracts'
2015	National cryptocurrencies	E-Dinar in Tunisia
2017	Real estate	Sale of land

The possibilities go much further. If everything that happens in networks can be verified, it is possible, for instance, to have online elections. Patient information can be stored in the blockchain and made available at the right time to the right people or authorities. Financial services will change fundamentally, because agreements are carried out directly and automatically. And the two billion people who right now have no access to financial services, for instance for lack of identification, can trade directly with anyone all over the world and all they need is a smartphone and an Internet connection.

So where in the pattern do we find ourselves right now? Is there a large-scale diffusion of is there a reason to assume that blockchain is still working on niche applications that may yet fail? As early as 2017, there was a solid base of an estimated three million users of cryptocurrencies worldwide (Gautham, 2017), after which it turned out, in November of that same year, that Coinbase, a platform on which the main cryptocurrencies are traded, has twelve million registered users. Together with the users of other platforms, they generate 12,000 transactions per hour for Bitcoin alone (Sedgwick, 2017). Accenture claimed that the adoption of blockchain technology surpassed 13.5 % in 2016 for companies in the financial sector (Accenture, 2017). The company Venture Outliers was able to identify some 1,250 start-ups worldwide that were working on blockchain, with over a third focusing on the financial market (Sandner, 2017). AngelList (2018) was able to compile an online list of 1,913 start-ups. The base for blockchain right now is so broad that it seems unthinkable that existing applications will not succeed and that S-curve will have to start again after implementation of a new application. In that sense, something unique is happening in the case of the blockchain. The first application is at the same time the basis for all further developments, and a platform has been created that turns out to be solid enough to be applied immediately in a very large number of ways. So is there a large-scale diffusion? Yes, we go along with Accenture's statement and claim that that point was reached in 2016. And have we witnessed the full potential consequences of the blockchain? Not at all, because cryptocurrencies are still hardly useable as a payment method and smart contracts are primarily applied in experimental settings. That observation could lead us to conclude that the full potential of the blockchain can have far-reaching consequences for almost the entire world population. It could also mean that the technology was hyped to such an extent that it will be very hard to meet expectations.

Figure 4.1: Pattern of development and diffusion of Blockchain



In a number of cases, it is difficult to pinpoint the exact moment a technology was invented. Different people can work on the same idea, media attention comes after the technology has been further developed or it started as a military application, so it stayed a secret. In that sense, the case of the blockchain is unique: the moment of invention itself has remained a secret! Ideas from 1998 were used and the first invention was published in 2008, and blockchain must have been invented somewhere in between. The first market introduction took place in 2009 when Bitcoins became available, followed by a period when governments, universities, research institutes, companies, start-ups and even the general public began developing applications for the blockchain. During that period, it became clear that the blockchain is a platform: the niche applications in the adaptation phase are all built on the blockchain and the blockchain itself is the basis that does not change. Large-scale diffusion started around 2016. The length of the phases is relatively short and large-scale diffusion especially means that the diffusion will continue until there is a better alternative. However, the period needed to implement all the applications could prove to be very lengthy.

4.3 Conditions

Knowledge of technology

Although the knowledge has not yet reached every organization for which it can be relevant, it appears that there is enough fundamental knowledge about the exact operation of the blockchain.

Knowledge of applications

Opinions and expectations vary from a revolution that is bigger than the rise of the Internet and will change our lives in a fundamental way, to a hype that will dissipate and fail to find many actual applications. That is a sign that knowledge about the application of blockchain is still lagging.

Employees and resources

As can be deduced from the number of start-ups, people are hard at work creating all kinds of blockchain applications. However, although people are learning to work with blockchain in those start-ups and in other projects, for now, the number of Solidity programmers (for smart contracts via the Ethereum platform) is nothing compared to the number of Java programmers.

Financial resources

The high expectations regarding blockchain appear to results in an abundance of financial resources. Overall investments in blockchain start-ups in 2016 has been estimated at 1.55 billion worldwide (Friedlmaier, Tumasjan & Welpe, 2016) and the total market capitalization of cryptocurrencies has long since surpassed 300 billion (CoinMarketCap, 2018).

Macro-economic and strategic aspects

In particular larger organizations, like governments, proceed with caution with the regulations of the blockchain applications, especially the cryptocurrencies, trying to find a balance between potential benefits and drawbacks (Pisa & Juden, 2017). And even if large organizations were to proceed with implementation, Iansiti & Lakhani (2017) point to the enormous change that, for instance, a law firm would have to go through to draw up all the agreements as smart contracts.

Socio-cultural aspects

The strongest negative sounds about blockchain have to do with the claim that expectations are so high that blockchain could never meet them, or the use of cryptocurrencies for illegal practices. There is a lot of discussion about the potential and application of blockchain, but there appears to be little resistance to the idea of global transactions and information exchange without a third party.

Accidents and unexpected events

The publication of Nakamoto appeared during the crisis in 2008, at a time when many people were losing faith in the existing financial systems and were looking for alternatives. Since then, the increasing value of the various cryptocurrencies has been all over the news, with a growing emphasis on how risky an investment cryptocurrencies are. It is intended as a payment method, but the current volatility will not allow that, while the DAO hack and hacking of platforms like CoinBase and Bitfinex also affect confidence in cryptocurrencies and possible blockchain as a whole. Also, Bitcoins are mentioned more and more often in relation to illegal practices, for instance the Silk Road online market.

Product performance

The concept of the blockchain is primarily used as a platform, and extended with the use of other applications. Objects of change are the division of voting rights within the network and ways to processing more information with less processing power.

Product price

By making intermediaries redundant, transactions all over the world can be done via the blockchain at lower transaction costs than are currently being charged by banks. At the moment, that is limited by the amount of information that can be processed in one block and by the volatility of the cryptocurrencies. When more information, and thus more transactions, can be added to the individual blocks in the blockchain, transaction costs are reduced more and will soon start to compete with the current costs the banks charge. However, unfortunately, the volatility of the cryptocurrencies sometimes results in the transfer of an incorrect amount, because the exchange rate changes too much during the entering and processing of the transaction. The potential cost reduction thanks to the elimination of intermediaries is present in all applications of the blockchain.

Production system

In the case of blockchain, there is not always an actual production. In most cases, the application is based on the existing Internet network and much of the software is open source. And although software is often developed for the individual applications, building on the blockchain serving as a platform, there are no indications that this production method could slow down the large-scale diffusion of blockchain. On the contrary, nowadays, it is very simple to develop an application on the blockchain oneself.

Complementary products and services

The blockchain itself is above all a platform, the value of which is above all related to the large number of radical applications that are based on that platform. In that sense, complementary products and services are indispensable, of which the more than 1,000 start-ups worldwide that are working on them are a good indication. In the diamond sector, the route of gems through complex supply chains are tracked using blockchain, the technology and services are provided ready-made (Iansiti & Lakhano, 2017). At the same time, the development of smart contracts is still in its early stages.

Actors and network formation

An organization that uses a public blockchain will have almost no influence on that blockchain (Pisa & Juden, 2017), while governments are often reluctant when it comes to cryptocurrencies in the first place. However, these problems for governments appear to have no negative effect on network formation. There are numerous examples of governments, universities, research centers, banks, businesses and other groups and organizations that join forces enthusiastically to work together on developments and implementations.

Customers

Anyone with an Internet connection can take part in a public blockchain, giving it an enormous potential. The average Bitcoin user is a 32-year old male libertarian who is motivated by curiosity, profit and politics (Guadamuz & Marsden, 2015). An experiment among MIT students in which 4.494 students were offered 100 dollars' worth of Bitcoin for free showed that 30% of the students had no interest. Of these students who accepted the offer, 20% sold their Bitcoins for dollars with a few weeks (Iansiti & Lakhani, 2017). Many people show an interest in blockchain, but often lacks the understanding needed to work with it.

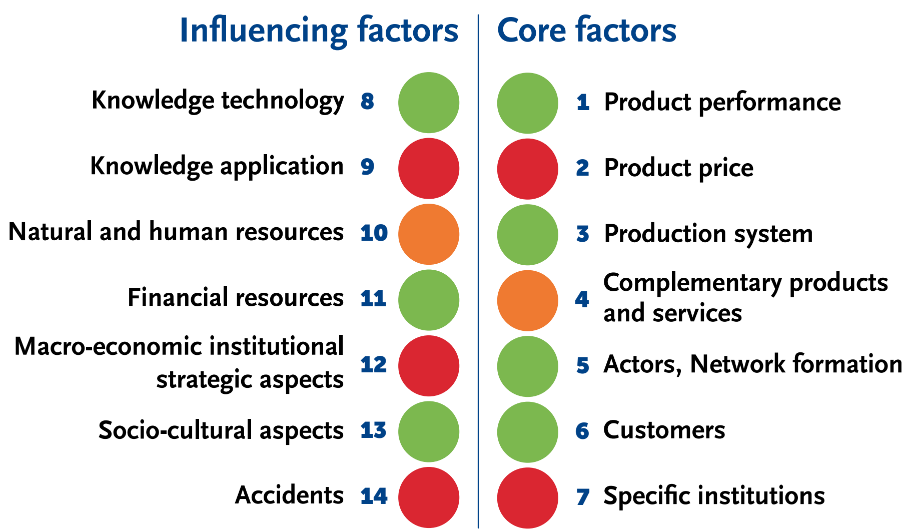
Standards, legislation and regulation

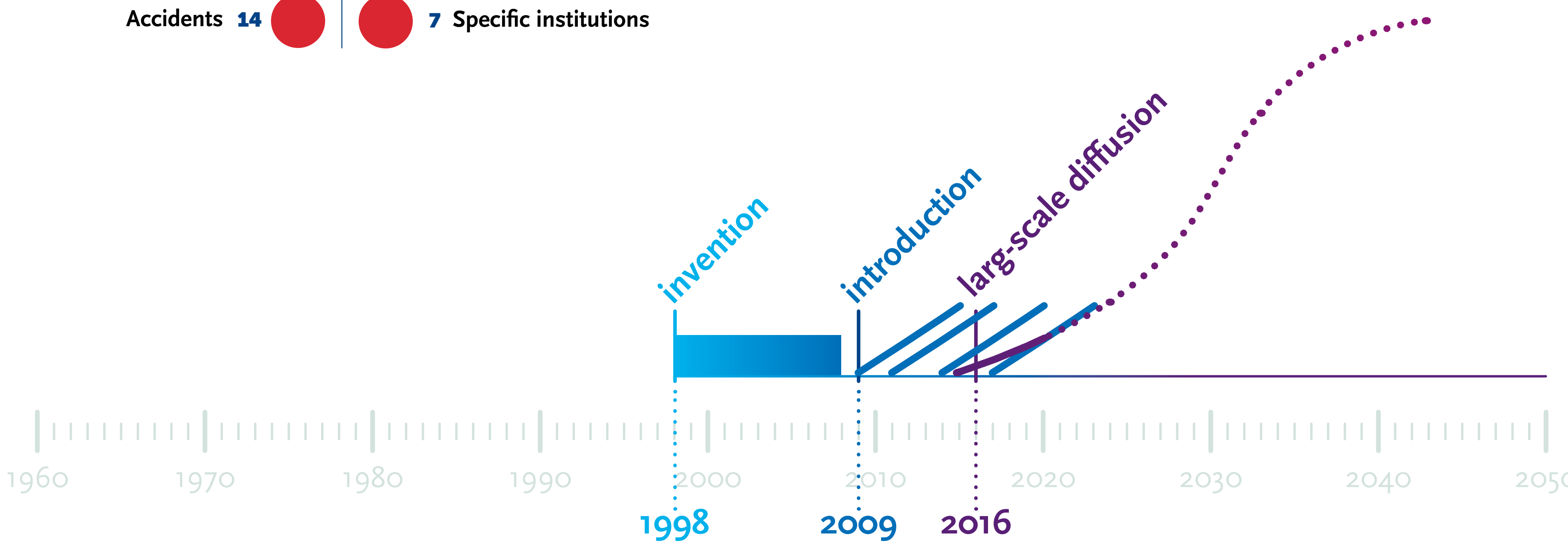
Many cryptocurrencies are made anonymously by users, which explains the criticism regarding their use for illegal practices. That makes political involvement and the development of policy for cryptocurrencies more difficult. A perhaps even bigger objection for governments is the loss of control of their monetary policy (Iansiti & Lakhani, 2017), making the reluctance of many governments and signals about possible bans on the use of cryptocurrencies understandable. That does not mean that governments are reluctant about all blockchain applications: for instance, Dubai has announced its intention to publish all government documents in blockchain by 2020 (Gupta, 2017).

Table 4.2: Overview of the conditions for Blockchain

Influencing factors	Core factors
8 Knowledge technology	1 Product performance
9 Knowledge application	2 Product price
10 Natural and human resources	3 Production system
11 Financial resources	4 Complementary products and services
12 Macro-economic institutional strategic aspects	5 Actors, Network formation
13 Socio-cultural aspects	6 Customers
14 Accidents	7 Specific institutions

Figure 4.2: The pattern and the conditions for Blockchain

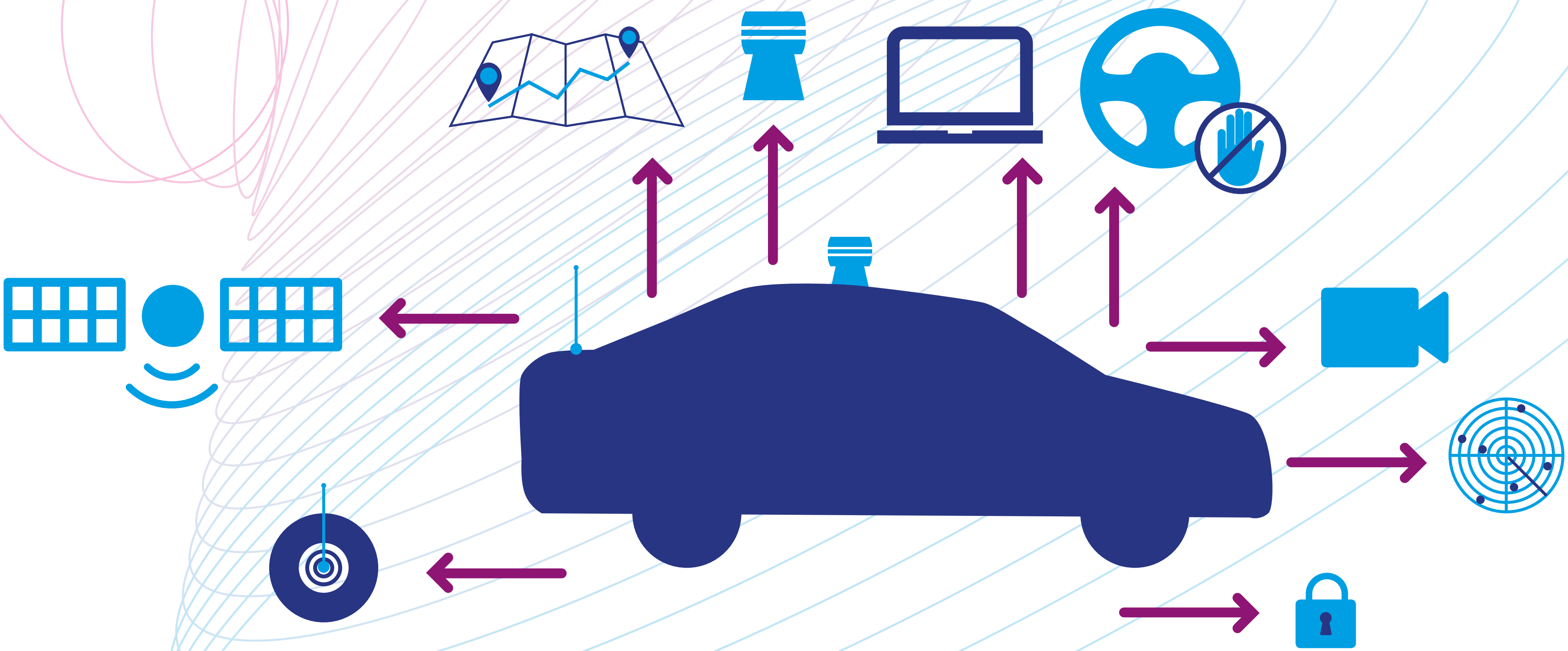




The conditions of this model have been presented as necessary conditions for large-scale distribution. And yet, in the section on 'Pattern', we stated that large-scale diffusion started around 2016, even though we see that not all conditions are green by far. First of all, that indicates that the development of blockchain is different from that of most other radically new technologies. Possible explanations for that are that blockchain is a platform and that high expectations may compensate certain flaws.

The public at large often appears to be enthusiastic about the applications of blockchain, without actually understanding either the blockchain or the applications. Not that that is really necessary, as we can see, for example, in the case of the Internet, but as long as applications are in the experimental phase, that will slow things down. The limited understanding of applications also means that companies are reluctant to use the blockchain in existing processes, in particular in the absence of legislation and regulation. Many governments are considering legislating the blockchain, but how and to what extent is still the subject of a worldwide discussion. As such, conditions that appear to be the most important in terms of influencing are the knowledge of applications through demonstrations and experiments, for instance in close consultation with governments and leading innovative organizations in the market.

Self-driving car



5. Self-driving car

Throughout the 21st century, people have thought about and experimented with self-driving cars. Around 1920, there were already radiographically operated cars on the road. Later, in the 1950s, there were cars that drove along electronic strips or other markings. Since the 1980s, there have been cars that drive autonomously. It looks like the self-driving car is about to make a breakthrough! In this chapter, we discuss the development and diffusion of the self-driving car.

5.1 Definition

Functionality

A self-driving car is a car that, after the desired destination has been entered, determines the route by itself and moves through regular traffic without the intervention of a human driver.

Operating principles and components

The self-driving car is a complex system that consists of multiple components, each based on their own technological principles. The first subsystem is the car itself. The second subsystem is the navigation system, often based on a combination of an electronic roadmap and GPS location (corrected or otherwise, for instance with DGPS or by measuring the distance based on the number of times the wheels have turned). Thirdly a variety of sensors, each based on their own technological principles: electronic cameras, radar, laser, sonar and infrared sensors, all of which have their own characteristics. Fourthly, a computer with software to combine all the signals from the sensors and the navigation system and then decide how to drive exactly. The software is often based on a self-learning algorithm. And finally, it is important for the signals from the computer to be transferred to the car, the accelerator, the steering wheel and the lights.

Self-driving and automatic car

A car that drives independently to and fro on a fixed and delineated trajectory is not a self-driving car in our definition. Long before the first self-driving car, there were vehicles, for instance on a fixed trajectory at airports, that drove back and forth automatically. Such vehicles use one fixed and programmed trajectory or an additional demarcation of a route, for instance using an electronic strip or other demarcation that is not found on public roads.

The self-driving car is a complex system that consists of various subsystems, which in turn are complex systems in their own right. It is striking that, prior to the first self-driving cars, but also afterwards, those subsystems became available for cars independent of one another. Cruise control is perhaps the first step, followed by 'adaptive cruise control', in which the speed is adjusted when the car gets too close to other cars, 'lane departure warning system', which indicates when the driver appears to be changing lanes without indication, 'parking assistance', which turns the steering wheel during parking (with the driver operating the accelerator), and 'automatic brake', which brakes automatically when there is an object or person in front of the car and the driver does not respond (quickly enough).

Because the level of autonomy of the self-driving car may vary, a system was formulated with levels of autonomy (TechRepublic, 2016).

Level 1: Driver operates the car using automated systems, like 'adaptive cruise control' and 'lane departure warning system' or 'parking assist'.

Level 2: The car can accelerate, break and steer independently, but the driver keeps paying attention and often keeps the hands on the steering wheel.

Level 3: The car can drive independently and the driver can do something else but, within a certain time frame and after a warning, has to be able to intervene.

Level 4: Driver does not have to do anything (can go to sleep). Driving is only allowed in special situations.

Level 5: The driver can no longer intervene, there is often no steering wheel in the car.

In this chapter, when we talk about a self-driving car, that car has to have at least a level 3 autonomy.

5.2 Pattern and applications

From the 1920s on, people experimented with automated vehicles. Initially, those vehicles where operated radiographically from another car driving nearby, as demonstrated in 1926 with the radiographically controlled car, the 'Linriccan Wonder', where the radio signals were transmitted to small electric motors that were used to control the movement of the car (Brimbaw, 2015).

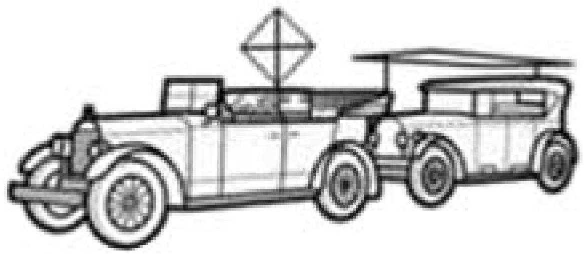


Illustration 5.1: The 'Linriccan Wonder', a radiographically operated car.

Later, electric cars were used that were operated via an electrical circuit that was embedded in the road, like the demonstration of the 'Phantom Car' at the 1939 World Exhibition. In the 1950s and 1960s, similar systems were further perfected and demonstrated on a small scale on public roads. Later, in the 1970s, the first estimates were made of the costs of a system with an electronic circuit in the road guiding the car. It was estimated that, thanks to the increased capacity of the roads (at least 50%) and a reduction in the number of accidents (with about 40%), investments in such a system could be recouped before the end of the century (Reynolds, 2001). That kind of system was never built and would now be hopelessly outdated, since self-driving cars do not need electronic systems embedded in the road.

In 1968, at the Vienna convention for road transit, a convention of which 70 countries were a member, a fundamental principle was laid down: the driver always has control and is also fully responsible for the way a vehicle behaves in traffic. This principle is a serious limitation for the self-driving car. The institutions, rules and laws will remain a limitation for a long time because they were all created with a traffic system in mind in which drivers determine the behavior of vehicles.

From the 1970s on, sectors other than the car industry also started working on components that are necessary for self-driving cars, including research into artificial intelligence and self-learning systems, which in turn provided input to computer algorithms for self-driving cars.

In the 1980s, the first self-driving cars appeared that meet our definitions: they were able to drive for longer periods of time without intervention from a driver. In 1983, the Terragator, an autonomous little car made by Carnegie Mellon University and designed to operate on rough terrain, was driving around independently. It was seen as the predecessor of autonomous vehicles that could be used for all kinds of applications: cleaning up hazardous waste (the builder, Whitaker, had been active in cleaning up after an accident in a nuclear reactor), exploring distant planets (the USA had already been to the moon), and carrying out underwater explorations. In 1986, Carnegie Mellon University demonstrated the Navlab, a self-driving van, already equipped with a laser scanner (Lidar) designed to map the environment. In addition, they were working on algorithms to process all the information and operate the car. In 1987, a self-driving Mercedes-Benz van was created by the Bundeswehr University in Munich with funds provided by the European Eureka Prometheus Project. The van was able 95% of the time to drive independently on the highway.

In Europe, research into the self-driving car was funded through Eureka (a collaboration of European government organizations) between 1987 and 1995. In the USA, DARPA (Defense Advanced Research Project Agency) started a project to develop an autonomous vehicle in collaboration with various parties. The vehicle had a laser sensor and electronic camera linked to a computer with which the vehicle moved independently at low speed through open terrain. The software used to process the input from all the sensors and operate the vehicle was created at the end of the 1980s by Carnegie Mellon University, using neural networks as a basis for operating the vehicle.

In the 1990s, the US Congress passed a law that encouraged USDOT (US Department of Transportation) to work together with partners and demonstrate a self-driving vehicle before 1997. At the end of the 1990s, funding for the project is cancelled due to a reduction of the research budget. Elsewhere, there are experiments in various locations with self-driving cars, which can drive ever faster, while an increasing percentage of them can really function autonomously in traffic. In the same period, a pilot is conducted with the ParkShuttle, a self-driving car that is deployed at Amsterdam Schiphol Airport and a business park in the Netherlands to transport passengers without a driver. Although the van is not autonomous according to our definition, and instead is guided along a demarcated trajectory with magnets embedded in the road, there were crossroads with pedestrians, cyclists and cars.

In the late 1990s, Toyota (1998) and Mercedes (1999) market Adaptive Cruise Control (ACC), an important component in the complex system of the self-driving car. ACC uses a laser to determine the distance to the next car and slows down automatically when that distance is too small. At that point, all major car manufacturer start research on the self-driving car.

In the first decade of this century, DARPA continues its development of self-driving cars. In 2004, 2005 and 2007, DARPA organizes Challenges, awarding $ 1 million to the vehicle that covers a 150 miles of desert the most quickly. Meanwhile, in 2005, Mercedes refines its ACC, called Distronic Plus, with the car being able to come to a full stop if necessary. It is demonstrated on a popular TV car show.

In 2008, for the first time a vehicle is marketed that is autonomous according to our definition. Up to that point, there were scientific projects and pilots, but now, for the first time, there was an actual sale. It was a self-driving truck that was used in a mine on a closed business site in Australia. The self-driving car is cost-saving and is used as part of a larger system in which various activities (drills, cranes, transportation) are carried out largely automatically and can be monitored remotely.

After that first introduction, around 2010, several prototypes are developed of self-driving cars, like the self-driving electronic cars by GM and Segway, and the self-driving Audi driving on mountainous terrain. In practice, more and more subsystems of autonomous driving are integrated in common car models, like adaptive cruise control, lane assist, parking assist and automatic brakes in the Mercedes S-class and the Infiniti Q50, indicating that the car industry has decided to introduce subsystems in top models. For instance, Mercedes continues to expand its S-class with more and more elements that increase the cars' autonomy.

In 2014, the second market introduction of a self-driving car took place, the Navia shuttle, an electrical cart that drives itself and can transport up to 8 passengers with a speed of 20 km per hour at airports, theme parks and pedestrian areas. In 2016, a self-driving taxi is introduced in Singapore.

It is interesting that newcomers enter the market with electric self-driving cars. Google is working on a self-driving car and Tesla introduced an electrical car that is prepared for autonomous driving. Tesla decides first to test and refine the software in its cars before introducing a self-driving car, or better yet: before installing the software for self-driving cars in existing cars. Next, Volvo produced a large number of Xc90s that are leased around Gothenburg and are allowed to drive autonomously there. In 2017, Audi marketed a self-driving A8. An overview of the applications is presented in the table below.

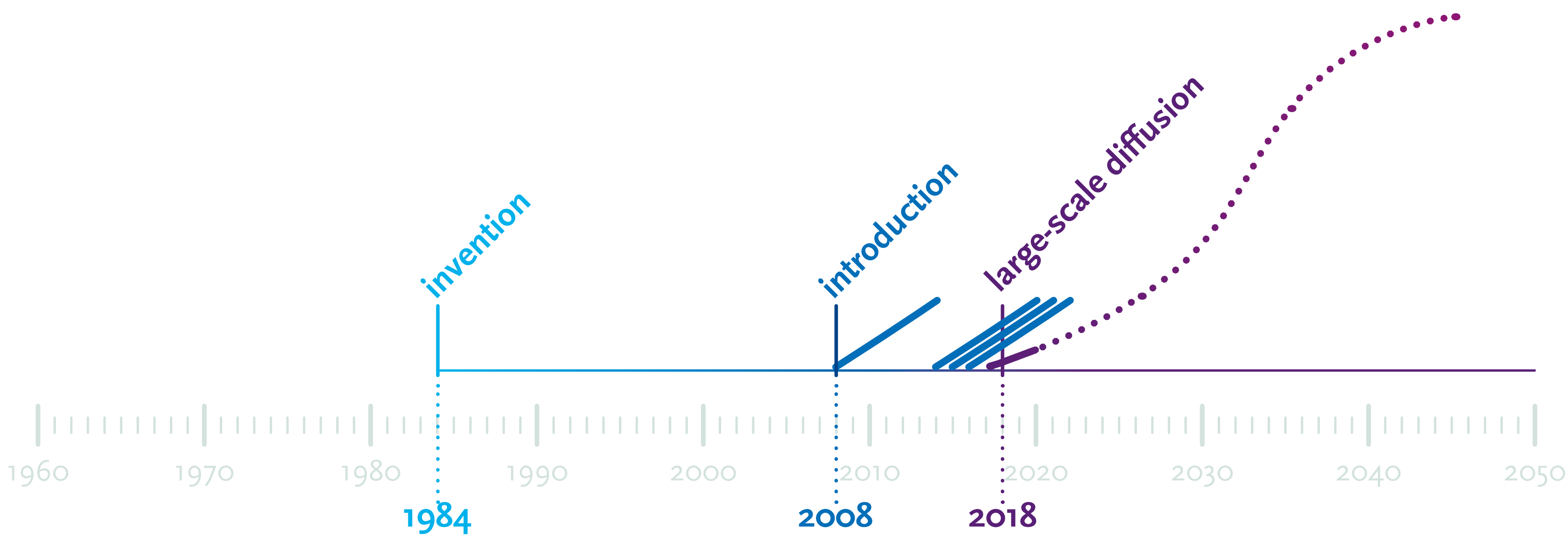
Table 5.1: Successive applications for self-driving cars

Year	Application	Explanation
2008 - 2011	Trucks in mining	Use in closed industrial areas and not on public roads.
2014	Shuttle for passenger transport	Navia shuttle by Induct Technology, a company outside the automotive sector, is sold for use in specific areas off the public road.
2016	Taxi service	In August of 2016, nuTonomy launches the first self-driving taxi in Singapore.
2016 - 2017	Tesla (potentially) self-driving car	From 2016 onwards, all Tesla's are prepared in their hardware for autonomous driving. The software operates in the background but is not yet active.
2017	Volvo leasing self-driving cars	In 2017, in Gothenburg, a large number of Volvo XC90's are leased that can drive autonomously in designated areas.
2017	Audi's first self-driving car in production	In 2017, the Audi A8 with AI is able to drive autonomously at speeds up to 60 km per hour.

If we examine all the information, we see the following pattern emerge: the invention was done around 1986, with the demonstration of the first self-driving vehicles. In 2008, the first self-driving car, a truck, is introduced on the market, followed by a number of other market introductions in specific market niches.

So where in the pattern do we find ourselves now? We are right before the start of large-scale diffusion, based on the announced market introductions of self-driving cars, for instance by Toyota and other manufacturers.

Figure 5.1: Pattern of development and diffusion of the self-driving car

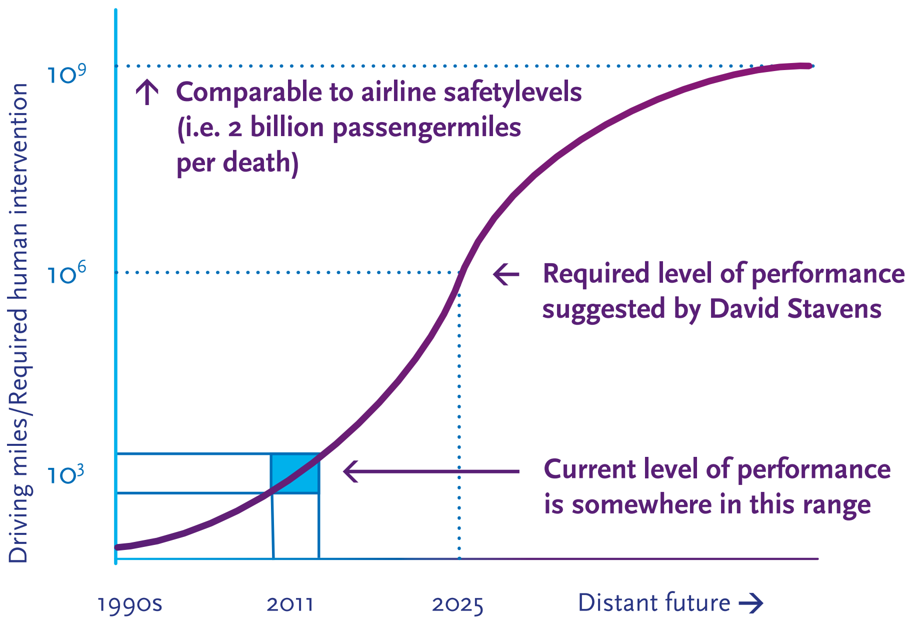


5.3 Conditions

Knowledge of technology

The basic knowledge for self-driving cars is available, but there are still many loose ends, for instance in terms of making the software error-free and hacker-proof.

Illustration 5.1: The increase in the performance of self-driving cars (More and Lu, 2011)



Knowledge of applications

By now, we know the most important applications of the self-driving car. However, the same technology also makes a whole range of other applications possible in industrial and logistical processes, which are not all known..

Employees and resources

The employees and resources are not a limitation.

Financial resources

Financial resources are not a limitation.

Macro-economic and strategic aspects

Self-driving cars can lead a considerable loss of jobs in the transport sector, taxi services, package delivery services, etc. However, self-driving cars can also have many positive economic effects, like people being able to work while driving and fewer employees losing their lives through accidents..

Socio-cultural aspects

There are various ethical issues: how do you let a computer algorithm decide on a given intervention to reduce the number of wounded? In addition, people have to get used to the loss of control. And finally, many people love driving, which means that a self-driving car can generate resistance.

Accidents and unexpected events

Although self-driving cars already cause fewer accidents than cars that are driven by people, there is a lot of attention when accidents do happen, which indicates a lack of knowledge. Cars are unable to find their way in the snow, paper bags and animals crossing the road are not recognized, which can lead to unnecessary dangerous situations. Software reliability is a challenge.

Product performance

The technology is not perfect yet. Sensors can be blocked, there are errors and deviations in the hardware and software, indicating that there is much that we do not know yet. Cars are unable to find their way in the snow, paper bags and animals crossing the road are not recognized, which can lead to unnecessary dangerous situations. Software reliability is a challenge.

Product price

Of course, self-driving cars are more expensive because of all the extra equipment, which can easily cost up to thousands of euros. On the other hand, there are many cost-saving opportunities, by preventing accidents, reducing insurance premiums and using roads more intensively.

Production system

Many car manufacturers are ready to produce self-driving cars: Infinity, Toyota, Mercedes, Audi, Google, Tesla. Many components (the sensors, the computer and control system, etc.) are available and production is not a problem.

Complementary products and services

All the systems in the self-driving car are available, but the adjustments in the infrastructure, the road system and traffic, to mark dangers and unclear locations better, can turn out to be costly.n.

Actors and network formation

Already, we can see alliances between various parties.

Customers

Many customers still do not trust self-driving cars (More and Lu, 2011).

Standards, regulation and legislation

A start has been made in modifying the system of rules and laws. However, the concept of liability will have to be examined carefully. In addition, the entire traffic regulation system will have to be revised, because in the case of accidents, there is not a driver who is responsible (Bimbraw, 2016).

Table 5.2: Overview of the conditions for the self-driving car

Influencing factors	Core factors
8 Knowledge technology	1 Product performance
9 Knowledge application	2 Product price
10 Natural and human resources	3 Production system
11 Financial resources	4 Complementary products and services
12 Macro-economic institutional strategic aspects	5 Actors, Network formation
13 Socio-cultural aspects	6 Customers
14 Accidents	7 Specific institutions

Augmented Reality

6. Augmented Reality

Augmented Reality, or AR, can be seen as adding information to reality so that people experience the combination of reality and the added information as one reality. Although AR seems very futuristic, people have been experimenting with it for more than half a century and it has been used for the last twenty years. Today, AR is applied on a large scale. In this chapter, we discuss the development and diffusion of AR.

6.1 Definition

Functionality

Augmented Reality includes multiple functionalities: (1) recording a scene (part of the actual environment); (2) identifying the contents of that environment so that some of it can either be filtered out or highlighted; (3) modifying the selected environment and adding extra information. The added information can be varied: it can be visual, sound, smells, tactile information or combinations of those. In practice, AR often contains sound and vision.

Operating principles

There are various principles for creating AR. The main principle, called 'video see-through', consists of the digitization of images from the environment, to which extra information is then added. We take that principle as the basis for our definition. But there are also other principles, like 'optical see-through', in which the actual environment is not altered or digitized, but another image information is instead added to that environment, as people see it. You could call that a projection and it is something that people experimented in stage performances even before video cameras were invented.

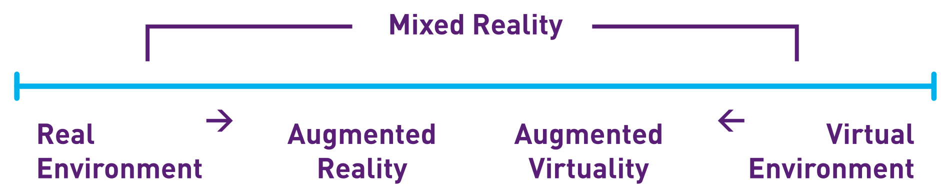
Components

You need a display for AR (to represent a combination of the actual and added reality) and sensors that indicate where the user is located and in what direction he or she is looking, because the virtual image depends on the position and orientation of the user. Finally, it takes a graphic computer and the associated software.

Augmented Reality (AR) and Virtual Reality (VR)

Augmented Reality and Virtual Reality pretty much developed side by side. Augmented Reality combines the existing environment with new information, while Virtual Reality creates an entirely new environment independent of the existing environment in which people are located. The first demonstration by Ivan Sutherland in 1968 is often viewed as the invention of AR and VR. Milgram also sees AR and VR as two options on a continuum that runs from a real to a completely virtual environment.

Illustration 6.1: Variants of mixed reality (Milgram and Kishino, 1994).



However, there is a fundamental difference between AR and VR: AR is a combination of reality and the added information, which means that that added information has to fit on or in that existing reality perfectly. When users move their head, the AR image has to copy their movements precisely. The same is true with regard to their eye movements. That synchronization of reality and added information is a technological challenge.

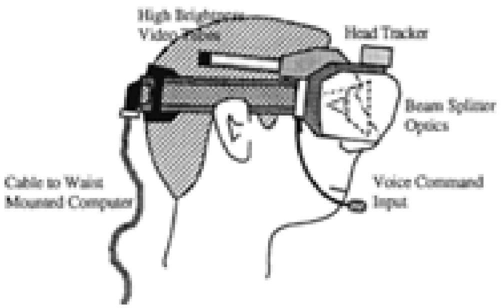
In this chapter, we speak of Augmented Reality when reality is digitized and processed, after which information is added, the so-called 'video see-through' principle.

6.2 Pattern and applications

People have been thinking about AR and VR since the 1950s and 1960s. In the 1950s, for instance, Morton Heilig, an American cameraman, believed in the idea of being able to involve movie audiences in the movie. In 1962, he created an installation in which people were surrounded by the movie's images, with vibrations, wind and smells being added to the sound and vision (Alkhamisi & Monowar, 2013). That was not AR because there was no mixture of sounds and images being added to reality. In 1968, Ivan Sutherland demonstrated his first AR set-up in which images are being added to reality. It is seen as the invention of AR, and also of

VR (Arth at al., 2015). It was still an optical 'see-through' system, but with a display that was placed on the head. The system allowed people to manipulate a simple figure. In the 1970s and 1980s, most research into AR was conducted at American universities and in military labs.

Illustration 6.2: An AR headset (Arth et al., 2015)



The first serious experimental systems were developed in the 1990s, for instance by Tom Caudell and David Mizell who, in 1994, created a system for Boeing that allows mechanics to see, while they are working on an airplane, how a part is (virtually) removed or installed (Bensch, 2015). Another application was the use of Augmented Reality in a theater show in 1994 (Williams, 2016). These were the first small-scale but realistic applications of what was until then a somewhat futuristic and experimental technology.

In the late 1990s, systems and technologies become available that are important to the application of AR (Van Krevelen and Poelman, 2010). Although the first mobile phones had been introduced in the 1980s, the technology did not start to really catch on until the 1990s. Later, mobile telephones would become important to large-scale AR applications. Computers became more powerful and were better able to process graphic information quickly. GPS became available for civilian applications. In scientific terms, AR developments also picked up, with the emergence of groups of scientists, conferences and workshops where information about AR is exchanged (Van Krevelen and Poelman, 2010), and user groups start programming applications themselves and work on AR technology, in what is after all a familiar phenomenon: something similar had happened at the start of the 20th century with radios, and later, from the 1970s onward, with computers as well. Such users and manufacturers are sometimes referred to as 'lead users' (Von Hippel, 2001).

In 1997, Sony marketed the first commercial 'head-mounted display'. Its adoption levels are low, however, and it is interesting to note that, although the device was meant for the general public, it was used primarily for research purposes (Arth at al., 2015). In 1999, a toolkit was marketed that allowed people to build AR applications, called ARToolKit (Arth et al., 2015). Also, the first location-based services for mobile telephones are marketed. Although a location-based service is not Augmented Reality, it is a service that provides things that are related to the user's location, for instance information about nearby restaurants. A similar thing had already been applied in museum audio systems, which of course were only available in museums or on a local network. All those services, products and technological developments at first appear to be unrelated, but they all contributed to the system of complementary products and services needed to AR applications.

Illustration 6.3: The Sony headset (Arth et al., 2015)

In 2000, the first AR game was introduced: AR Quake (Alkhamisis and Monowar, 2013). The game is produced at an International Symposium about Wearable Computers and can be used both indoors and outside. Meanwhile, the development of AR applications and equipment for military purposes continues. A wearable 'Battlefield Augmented Reality System' is presented in 2000 (Arth et al., 2015) and there is a growing number of applications: AR travel guides, where you can get information on certain locations about your environment (Joos2322, 2008) and more games, like Mozzies (Arth et al., 2015; Eden, 2010) and Human Pacman (Mixed Reality Lab, 2018). In addition to all the applications, work is also being done on technological improvements, for instance to improve the synchronization between reality and added information, or to allow several users at once to work together in an AR application.

Around 2008, all kinds of major companies are waking up: small companies are taken over, Microsoft is collaborating with an Israeli manufacturer of 3D sensors, and together they develop Kinect, a motion game that is marketed in 2010. Around 2012, AR is a hit in the advertising world. Everyone with a mobile phone can see AR applications that promote certain products, Coca Cola launches an AR ad, in the Netherlands, supermarket chain Albert Heijn does the same, while IKEA also uses AR applications, for instance to show people what their room would look like with IKEA furniture.

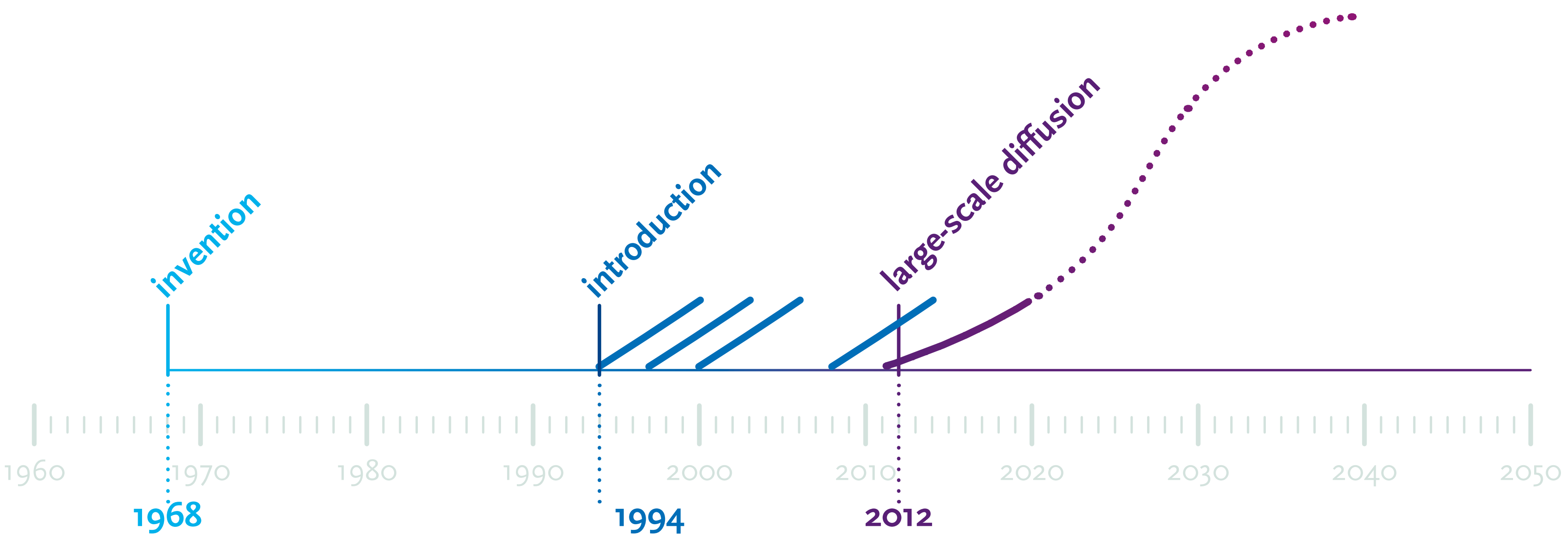
In 2012, Google markets Google Glass, and although that is not a great success, all the major companies enter the AR arena one by one: Facebook, Apple, etc. An overview of the main applications is listed in Table 6.1.

Table 6.1: Successive applications for Augmented Reality

Year	Application	Explanation
1994	Experimental application at Boeing (industrial)	At Boeing, AR was applied to support airplane mechanics. Initially, they had visual support in the form of images on a laptop indicating how they should install certain components. With AR, they could see the components projected and know how to install or remove them.
1994	Theater with AR	In 1994, a dance performance was created where dancers danced around virtual objects.
1997	Introduction of an AR headset designed for the consumer market	In 1997, Sony marketed an AR headset aimed at the consumer market, although in practice it was used primarily in experiments and research.
2000	Introduction of an AR game	In 2000, AR Quake is introduced. The game can be played indoors as well as outside. The system is equipped with a wearable computer in a backpack, an electronic compass (for orientation) and GPS (for positioning), a headset and an operating unit with two buttons.
2008	Travel guide with AR	In 2008, a travel guide is introduced that gives people information about buildings that exist now or existed in the past where they are.
2012	Advertising	In 2012, the large-scale use of AR for advertising purposes is introduced.
2016	Pokémon	The game Pokémon Go was played by large groups of people all over the world.

If we look at the developments over time, the following pattern emerges: the invention took place in 1968, the first application was probably in 1994 (although it is hard to say for sure because of the difficulty distinguishing between experimental and commercial applications). The first large-scale applications occurred after 2010, for example for advertising purposes (from 2012 on) or for the game Pokémon Go (from 2016 on). In practice, there have been numerous smaller applications next to the well-known applications with large groups of users. So where in the pattern are we now? We believe that we are at the start of large-scale diffusion, despite which we can note that a large number of applications of AR have not been used in practice yet. In short, large-scale diffusion has begun, but the technology's true potential has yet to be realized.

Figure 6.1: Pattern of development and diffusion of Augmented Reality



6.3 Conditions

In this paragraph, we look at the status of the conditions for large-scale diffusion.

Product performance

With regard to so-called 'head-mounted displays', there are a few problems (Bensch, 2015, p. 26; Buntinx, 2017):

- Synchronizing the actual and virtual images is difficult due to possible quick movements of head and eyes.
- Variation in light intensity can create problems, like differences in color as well as shapes.
- The camera is often positioned on top of the head, which gives a different orientation than that of a person's eyes. As a result, the image is distorted.

Product price

Although AR equipment is still fairly expensive, prices are dropping quickly. Developing an AR app is a costly affair, because it takes a lot of time: between 440-760 hours for the type of application IKEA uses, which can cost up to 100,000 euros. A good application is very valuable and it is expected that, over time, more and cheaper developers can be brought in outside the US (Morozova, 2018).

Production system

Various software packages are available for programming AR applications (Capterra, 2018).

Complementary products and services

Over time, since the 1990s, more and more complementary products, services, components and technological options have become available for using AR on a large scale (Wikitude, 2017).

Actors and network formation

From the 1990s onwards, there have been all kinds of takeovers, alliances and movements between companies, including big names like Google, Microsoft, Apple and Facebook (The Drum, 2018), and although, for now, the overall picture remains fragmented, each of those companies can set a global standard on its own.

Customers

Customers still know relatively little about what AR can do, both business clients wanting to create AR applications for their end-users, as well as those end-users themselves (See also: knowledge of the applications).

Standards, regulation and legislation

By and large, there are no specific laws or rules for AR or, if they do, they have not been updated to accommodate the special situation that is created when AR is used. Injuries and offenses are poorly regulated in the part-real/part-virtual world (Volokh, 2017). Some of those problems relate to unwanted sexual behavior or expressions, which was already a problem in a completely virtual world, think for instance of the negative experiences some participants of the imaginary world Second Life were subjected to. AR is even more intrusive than a completely imaginary or virtual world (Keidar et al., 2017).

Knowledge of technology

Knowledge of applications

Although at a global level, there is knowledge about the technology, so far it is limited to potential users and developers, and the same is true about the applications. The technology has to be further improved, and a large collection of sample applications is needed to illustrate all the possibilities (Buntinx, 2017).

Employees and resources

There are not enough AR programmers, which makes developments more costly and slows down the development of new AR applications.

Financial resources

Financial resources are not a restriction.

Macro-economic and strategic aspects

Also military applications have been examined from the start, for instance in airplanes (head-up displays) and other systems, AR is strategically important to any country. It may be that the strategic importance is underrated until we understand all the applications.

Socio-cultural aspects

There are serious concerns about privacy. Reality is recorded and then all kinds of things are added. If all of that becomes available in public, that can violate user privacy. However, this element is prevalent in the use of so many media that it does not appear to be a limitation to AR.

Accidents and unexpected events

Accidents can happen easily in a half-real world. All over the world, thousands of people were injured and there were even some people killed playing Pokémon Go with people running around in traffic after a Pokémon (Beall, 2016). On the other hand, AR can also be used for security and to train people to increase security (Sybenga, 2010).

Table 6.2: Overview of the conditions for Augmented Reality

Influencing factors	Core factors
8 Knowledge technology	1 Product performance
9 Knowledge application	2 Product price
10 Natural and human resources	3 Production system
11 Financial resources	4 Complementary products and services
12 Macro-economic institutional strategic aspects	5 Actors, Network formation
13 Socio-cultural aspects	6 Customers
14 Accidents	7 Specific institutions

7. Conclusions

In this chapter, we compare the results for the four technological breakthroughs we examined in this report (3D printing, blockchain, self-driving cars and Augmented Reality). It is important to go back to the three research questions: 1. What technological breakthroughs are expected to lead to fundamental changes in society? 2. What is the current status of the development and diffusion of those potential technological breakthroughs? 3. What are the conditions that determine whether or not a technology is a success? In addition, the successive applications of the technologies in question are mapped.

In the second paragraph, we look at the practical implications of the results of this report. What are the management implications, what do the findings regarding the four breakthrough technologies mean for businesses? What are the social implications of the results, what can the findings mean for various groups of stakeholders and what do they mean for governments?

In the third paragraph, we look at the models and ways to answer the research questions. What are the assumptions of the models? What are the possible improvements? In practical terms: can these models provide a basis for an exploration tool that STT can use regularly, as a 'Technology Monitor'? What can be done with such a tool, how can the results be used within STT in other explorations? What can members or customers of STT do with the results?

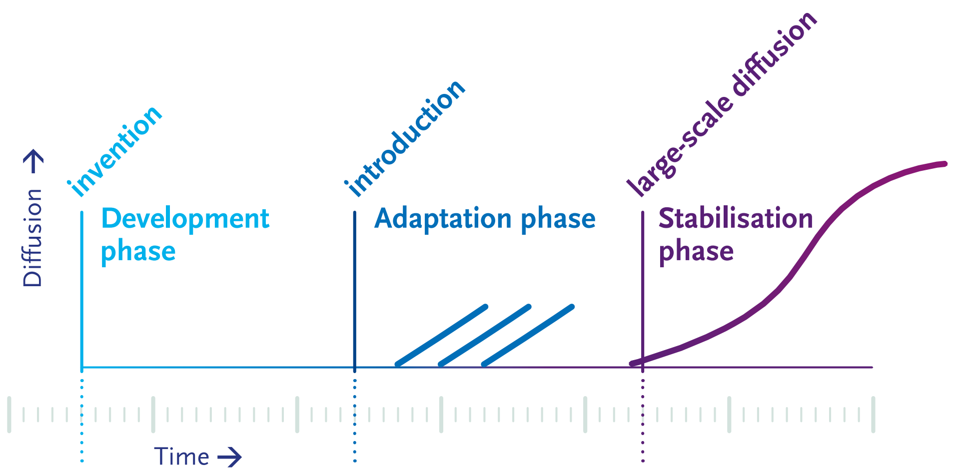
7.1 Comparing the technologies

The research questions

The definition of a technological breakthrough is important to avoid talking about different technologies in the analysis. Each of the technologies we selected can be seen in a different way. Blockchain, for instance, is more than just a platform for cryptocurrencies. We chose a definition in which, for each technology, the technological principle, the functionality and the main components are included.

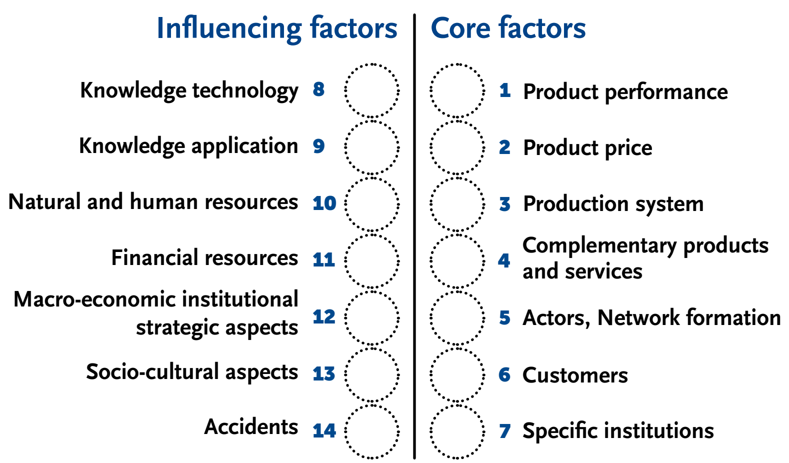
How did the technologies develop and diffuse? That development is shown in a model that divides the pattern of development and diffusion into three phases. The first phase (development) goes from invention to the first introduction of the technological breakthrough in a specific application. The second phase (adaptation) goes from the first introduction to the start of large-scale diffusion, and the third phase (stabilization) goes from the start of large-scale diffusion until the technology is hardly or no longer being used at all.

Figure 7.1: Model of the development and diffusion of technological breakthroughs



What are the conditions that determine whether a technology will really break through and how does that apply to the technologies we examined? The factors have been divided into fourteen groups, seven of which make up the socio-technological and economic system surrounding a technology, we call them the core factors. The remaining seven factors influence that system, and we call them influencing factors. The fourteen groups together form a dashboard that is used to indicate the current status of the technology.

Figuur 7.2: Dashboard of the factors that can prevent large-scale diffusion



The definitions

In this chapter, the four breakthrough technologies are carefully defined. A number of aspects of those definitions are briefly discussed below.

3D printing is actually a family of different technologies that slowly build components, not by grinding, cutting, sawing or burning, but incrementally by adding the material layer by layer. It is a breakthrough technology because it is now possible to produce locally and in small batches. Initially, it was a cheaper and quicker way to produce prototypes of complex products or systems. As the costs of 3D printing are being reduced, it also becomes a serious alternative to traditional mass production technology, like injection molding, leading to a structural change in the production industry.

Blockchain is a platform on which transactions of many different types of information can be stored securely in a permanent and verifiable way, which is convenient for registering transactions, identities, property and also for money. This is also a breakthrough technology: no authority or government is needed to safeguard everything, like a central bank guaranteeing the value of money or a government-appointed notary registering a testament or relationship contract, so it is hardly surprising that blockchain has made those same authorities very nervous.

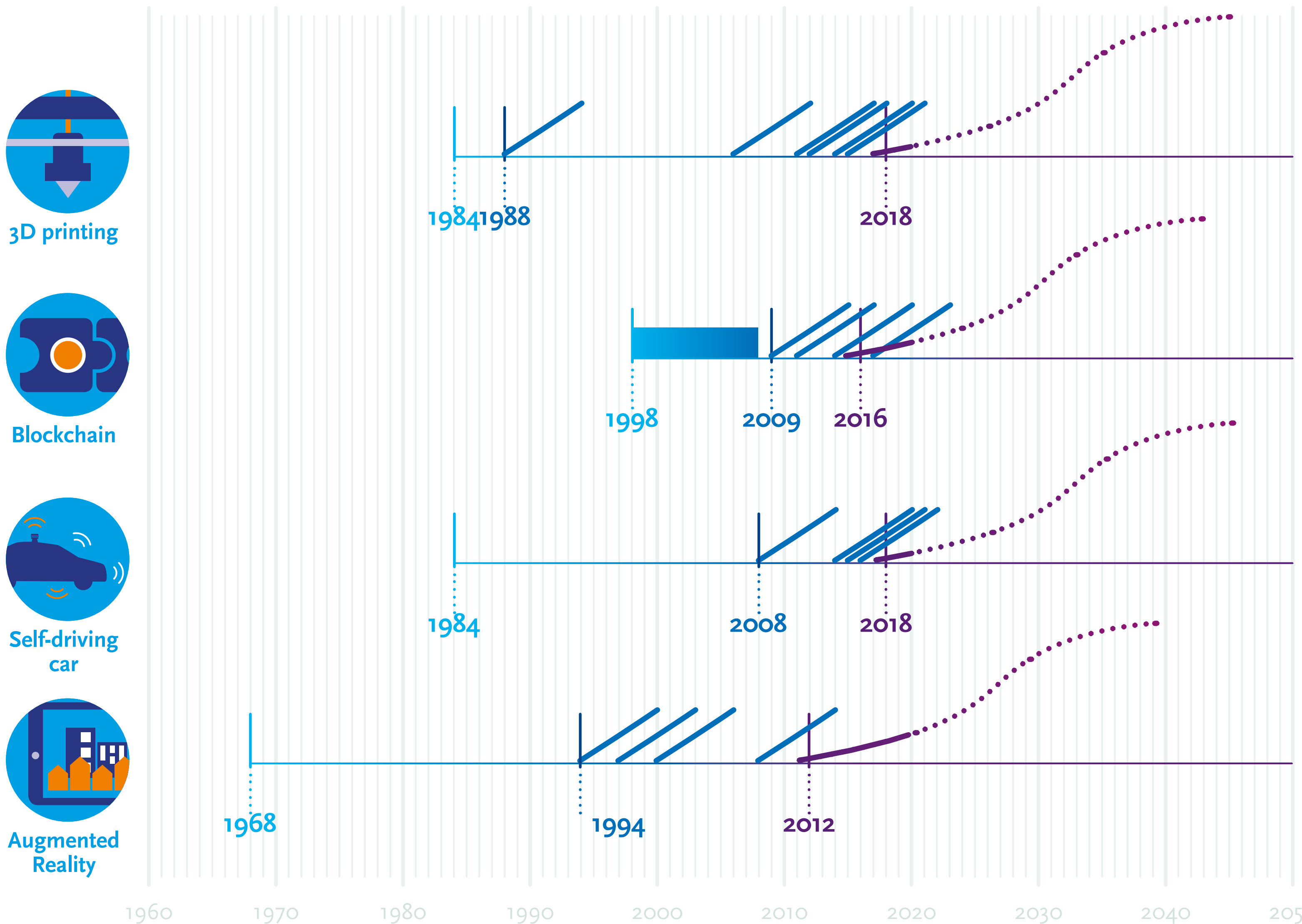
The self-driving car is a complex machine that is made up of many different technologies. Each of those technologies has already been marketed individually: lane assist, park assist, automatic breaking, they have all been implemented in different models by well-known car brands. However, the self-driving car is still a breakthrough technology, because the driver is no longer fully responsible and it is that very responsibility that is a core element of our traffic legislation.

Augmented Reality is a collection of different ways to complement reality with extra information. It is a breakthrough technology that can be used in many applications, and like with blockchain, 3D printing and the self-driving car, the consequences have not yet become fully clear.

The patterns of development and diffusion

Figure 7.3: Pattern of development and diffusion for four breakthrough technologies

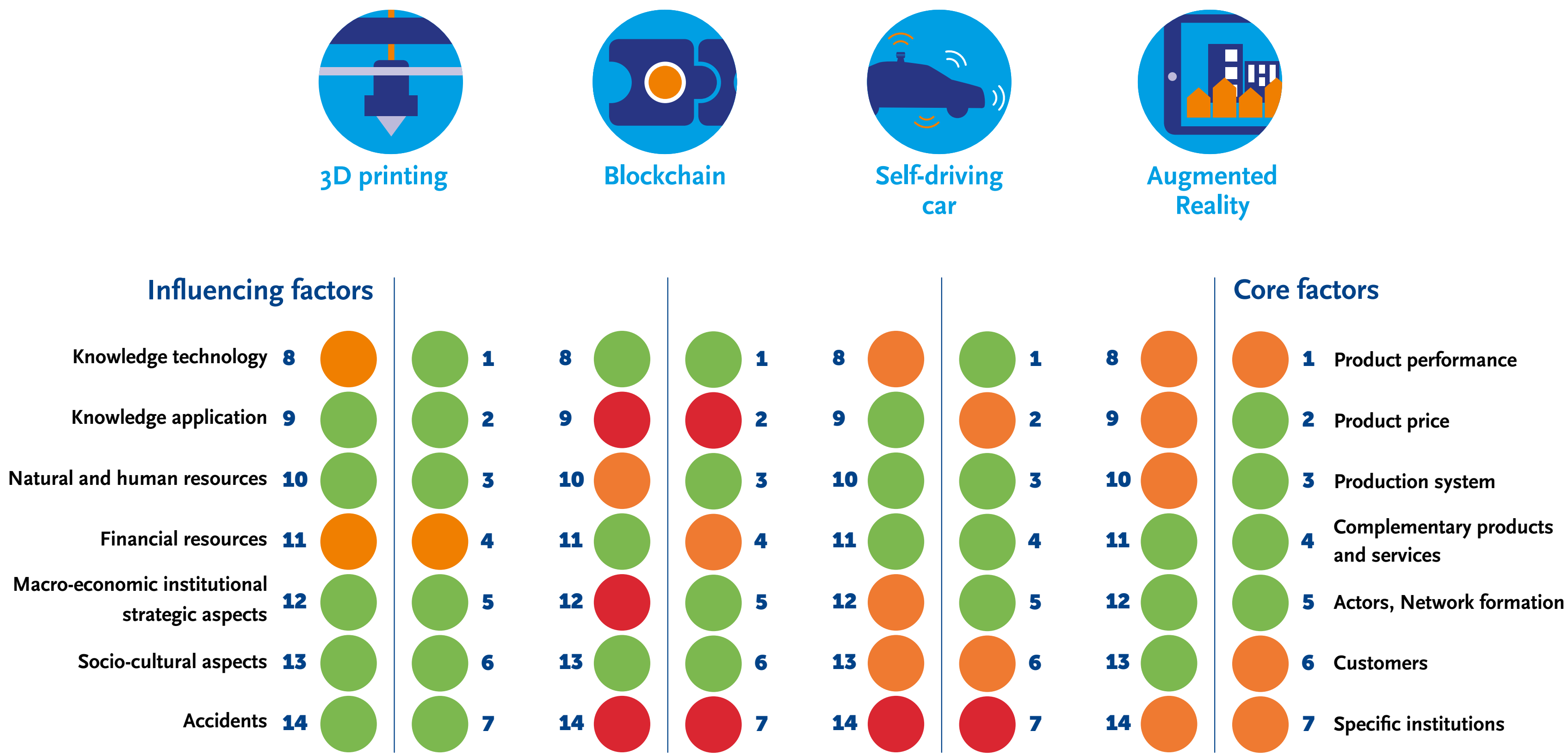
All four technologies go through the two phases prior to the start of large-scale distribution, but the length of those phases vary. At the moment, Augmented Reality has come the farthest, with large-scale diffusion having started in 2012, but the initial phase took the longest, from 1968 to 2012. Blockchain experienced the quickest development and, although both the self-driving car and 3D printing were invented in 1984, they vary considerably in the remaining course of the phases.



The conditions for large-scale diffusion

Figure 7.4: Dashboard of four breakthrough technologies

The dashboard for the four technologies vary greatly. There are some similarities. First of all: standards, rules and laws are an important limiting factor for multiple technologies. Secondly: in three cases, there is still limited knowledge of the technologies involved. Otherwise, the dashboards vary considerably.



7.2 A list of the applications

Table 7.2: Successive niche applications of four breakthrough technologies

Technology	3D printing	Blockchain	Self-driving car	Augmented Reality
1st application	*1988* Rapid Prototyping	*2009* Cryptocurrency	*2008/11* Trucks in mining	*1994* Experimental application at Boeing
2nd application	*2006* Printing at home	*2011* Illegal activities, laundering	*2014* Shuttle for passenger transport	*1994* Theater with AR
3rd application	*2010* Printing car body	*2014* Designing and registering contracts (Blockchain 2.0)	*2016* Taxi service	*1997* Introduction of an AR headset aimed at the consumer market
4th application	*2013* Printing clothes	*2015* National cryptocurrency (in Tunisia)	*2016/17* Tesla (potentially) self-driving car	*2000* Introduction of an AR game
5th application	*2013* Printing in construction	*2017* Selling real estate	*2017* Volvo pilot with leasing self-driving cars	*2008* Travel guide with AR
6th application	*2013* Medical applications		*2017* Audi's first self-driving ca in production	
7th application	*2014* Printing food			
8sth application	*2014* Printing cultural heritage			
9th application	*2015* Printing airplane parts			

Each technology was applied in several niche markets prior to large-scale diffusion. 3D was initially used especially to generate prototypes and the technology was used a lot by consumers wanting to be their own manufacturers, the so-called lead users. Blockchain became known especially by the application of cryptocurrencies, which was how the technology was able to realize large-scale diffusion relatively quickly. The self-driving car consists of many sub-technologies that were each introduced incrementally in the car industry and elsewhere in industrial and logistical processes. Augmented Reality has already been used on a large scale in advertising as an eye-catching gadget. At the same time, the technology was used from the start in research into military applications.

7.3 Practical implications of the results

Implications of the nature of the breakthrough technologies

Each of the breakthrough technologies consists of a family of related technologies. In addition, they are all complex systems with many components and subsystems that can be viewed as technologies in their own right. In this report, we decided to provide an unambiguous definition of the technologies, although in practice, the development and diffusion does not adhere to pre-formulated definitions. The complexity and diversity of breakthrough technologies have far-reaching implications for companies operating in the market. In addition to competition between the new technologies and existing (old) technologies, there is also competition between the different versions of the new technology and alternative technologies. That also applies to the technologies we have examined, as well as to their various components. At the start of the pattern, there is a great deal of uncertainty. It is in particular in the beginning, when standards and agreements between different market parties could limit uncertainty, that it is very hard to agree on those standards, because it is unclear what the development of different technological variants will be. The uncertainty also has far-reaching implications for government, which wants to encourage technology development without wanting to interfere in the market process and, in doing so, benefit certain parties and their particular technological variants. The government often chooses to play a role whereby different parties can further develop a technology in a pre-competitive stage with government subsidies, often inadvertently interfering in the competition between technologies.

Implications of the pattern of development and diffusion

The pattern of development and diffusion of the four breakthrough technologies clearly shows how much time passes between the invention of a technology and the start of large-scale diffusion: on average, about 20 years or more (Ortt, 2010). That has far-reaching implications for companies. Patents expire within such a time-frame, which means they have become meaningless when they are needed the most: at the start of large-scale diffusion. Protecting technology in such a prolonged pattern is a problem. The prolonged first phase means that it will take a long time to earn back early investments and that uncertainty is relatively high, which explains the wait-and-see attitude of many companies.

It is noteworthy that a lot more is happening between invention and initial introduction besides a single development project. The period is also longer than that of individual projects. Often, multiple parties are working side by side on separate projects and activities. Even within individual companies, activities surrounding a breakthrough technology are often fragmented. In addition, it appears that the adaptation phases, after initial introduction, consists of more than just a small-scale start of the a technology that then quickly enters large-scale diffusion. There is a period of up to ten years or more in which the technology is applied in different variations in a large number of different niche applications. Because the entire socio-economic system of actors and factors that is needed for large-scale applications of a technology does not yet exist at the start of the adaptation phase, the initial niche applications are often completely different from the later large-scale applications, which is not caused by the technology itself (the technological principle, the functionality and the main components stay the same), but especially by the design of product versions on the basis of the technology and the consumer groups in the market niches. The different first niche applications have implications for companies: they spend a long time experimenting on a small scale with different versions of the product. It is often difficult for large companies to adjust to the quickly changing small-scale applications with different product versions and consumers. They often decide instead to invest in start-ups and spin-offs or enter into large alliances to limit the risks. In that situation, government can play an important role by encouraging alliances and supporting start-ups, which will not immediately lead to new inventions or a large-scale application of new technologies, but it does help market parties to utilize and bridge the adaptation phase.

The pattern of development and diffusion of breakthrough technologies shoes a prolonged period of developing and experimenting with different technological versions, improvements and small-scale applications. In that period, some things go wrong: accidents happen. The first self-driving cars caused accidents through software limitations, blockchain is used for illegal purposes, 3D-printed components turn out the be less sturdy than expected, etc. The history of technology shows us that it is impossible to develop a breakthrough technology without accidents, misuse or unforeseen side-effects, the implication of which is that both governments and market parties have to work together to limit or control those effects in a responsible way.

Implications of the conditions for large-scale diffusion

The dashboard with actors and factors that are important to large-scale diffusion has far-reaching implications with companies and for the government. The model provides an explanation for the lengthy run-up to large-scale diffusion and indicates which conditions have to be met to realize a large-scale diffusion.

The model provides an analytical basis for the formulation of (government) policy aimed at creating those conditions. Standards, regulation and legislation often pose restrictions on experiments with and the development of new technologies. That can be very useful to prevent accidents, but when a new technology reduces risks and improves practical processes, restrictive regulations present a social problem. The dashboard indicates how government can create conditions for large-scale diffusion of new technology.

That model also serves as an analytical basis for the formulation of business strategies during the pattern. Those strategies can take the conditions into account, by avoiding or even breaking down barriers or by utilizing stimulating factors.

7.4 The Technology Monitor of STT

In addition to the careful domain explorations, it is important for STT to also gave a vision on technological developments that may affect multiple societal domains. In the past, STT has also examined major technological changes. The advantage of the Technology Monitor is that it is a study that is carried out and published regularly and that is available not only to STT, but also to its members. STT can use technology studies to comment on the effect of a technology in a given domain, while the members can look at the effect of that technology on their organization.

In order to be used, the monitor has to steer a sensible course between dangerous simplification and unnecessary complexity. It is like a medication: it is effective if you make sure you read the instructions first. The instructions of the Technology Monitor are expressed in its assumptions and limitations (see the appendix). So are we ready to prescribe the medication?

References

3D Print Canal House. (2016). Frequently Asked Questions. Available [online] at: http://3dprintcanalhouse.com/frequently-asked-questions-2.

Accenture. (2017). Using Distributed Ledgers: Blockchain moves to Early Adoption.

Alkhamisi, A. O. en M. M. Monowar (2013). "Rise of augmented reality: Current and future application areas." International journal of internet and distributed systems 1(04): 25.

AngelList. (2018). Blockchains Startups. Available [online] at: https://angel.co/blockchains.

Architect Magazine. (2015). China's WinSun Unveils Two New 3D Printed Buildings. Available [online] at: http://www.architectmagazine.com/technology/chinas-winsun-unveils-two-new-3d-printed-buildings_o.

Arth, C., et al. (2015). "The history of mobile augmented reality." arXiv preprint arXiv:1505.01319.

Arthur, W. B. (2009). The nature of technology: What it is and how it evolves, Simon and Schuster.

ASTM. (2015). Additive manufacturing — General principles — Terminology. Available [online] at: https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-1:v1:en.

Bayer, D., Haber, S., & Stornetta, W. S. (1992). Improving the efficiency and reliability of digital time-stamping Sequences II (pp. 329-334): Springer.

Beall, A. (2016). Could Pokémon Go kill you? Experts warn the augmented reality game is increasing distraction-related deaths. Available [online] at: http://www.dailymail.co.uk/sciencetech/article-3823318/Could-Pok-mon-kill-Experts-warn-augmented-reality-game-increasing-distraction-related-deaths.html. Geraadpleegd op: 20 februari 2018.

Bensch, A. M. (2015). Toward Real-Time Video-Enhanced Augmented Reality for Medical Visualization and Simulation, Rochester Institute of Technology.

Bijker, W. E. (1995). Of Bicycles, Bakelites, and Bulbs; Toward a Theory of Sociotechnical Change. Cambridge, The MIT Press.

Bimbraw, K. (2015). Autonomous cars: Past, present and future a review of the developments in the last century, the present scenario and the expected future of autonomous vehicle technology. Informatics in Control, Automation and Robotics (ICINCO), 2015 12th International Conference on, IEEE.

Biss, K., Chien, R.T., Stahl, F.A., Weissman, S. (1976). "Semantic Modeling for Deductive Question-Answering Systems", IEEE TRANSACTIONS ON COMPUTERS, C-25(4):358 – 366.

Bourell, D. L. (2016) Perspectives on Additive Manufacturing. Vol. 46. Annual Review of Materials Research (pp. 1-18).

Buntinx, J.P. (2017). Top 4 Challenges for Augmented Reality Right Now. Available [online] at: https://themerkle.com/top-4-challenges-for-augmented-reality-right-now/. Geraadpleegd op: 20 februari 2018.

Cannucciari, C. (2016). Banking on Bitcoin.

Capterra (2018). Augmented Reality Software. Available [online] at: https://www.capterra.com/augmented-reality-software/. Geraadpleegd op: 13 april 2018.

CoinMarketCap. (2018). All Cryptocurrencies. Available [online] at: https://coinmarketcap.com/all/views/all/.

Cooper, R. G. (1990). Stage-Gate Systems: A New Tool for Managing New Products. Business Horizons (May-June): 44-54.

Eden, T. (2010). Augmented Reality Games - How Far Have We Come In 7 Years? Available [online] at: https://shkspr.mobi/blog/2010/11/augmented-reality-games-how-far-have-we-come-in-7-years/. Geraadpleegd op: 17 april 2018.

Friedlmaier, M., Tumasjan, A., & Welpe, I. M. (2016). Disrupting industries with blockchain: The industry, venture capital funding, and regional distribution of blockchain ventures.

Gautham. (2017). Three Million Active Cryptocurrency Users Says Cambridge Center for Alternative Finance. Available [online] at: https://www.newsbtc.com/2017/05/07/three-million-cryptocurrency-users/.

Guadamuz, A., & Marsden, C. (2015). Blockchains and Bitcoin: Regulatory responses to cryptocurrencies. First Monday, 20(12).

Gupta, V. (2017). A brief history of blockchain. Harvard Business Review. Available [online] at: https://hbr.org/2017/02/a-brief-history-of-blockchain.

Haber, S., & Stornetta, W. S. (1991). How to time-stamp a digital document. Journal of Cryptology, 3(2), 99-111. doi:10.1007/BF00196791.

Hu, C., & Yin, G. (2014). 3D printing, a new digital manufacturing mode. Paper presented at the Advances in Transdisciplinary Engineering.

Keidar, R., Vromen, N. en Goldstand, A. (2017). Enhanced Legality With Augmented and Virtual Reality. Available [online] at: http://www.lawtechnologytoday.org/2017/02/augmented-and-virtual-reality/. Geraadpleegd op: 20 februari 2018.

iAfrikan News. (2016). Senegal To Introduce A New Blockchain-Based National Digital Currency, The Second Such Currency In The World. Available [online] at: https://www.iafrikan.com/2016/11/24/senegal-to-introduce-a-new-blockchain-based-national-digital-currency-making-it-only-the-second-country-to-have-a-national-digital-currency/.

Iansiti, M., & Lakhani, K. R. (2017). The truth about blockchain. Harvard Business Review, 2017 (January-February).

Joos2322 (2008). Wikitude AR Travel Guide (Part 1). Available [online] at: https://www.youtube.com/watch?v=8EA8xlicmT8. Geraadpleegd op: 12 april 2018.

Kodama, H. (1981). Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer. Review of Scientific Instruments, 52(11), 1770-1773. doi:10.1063/1.1136492.

Lu, B. L., Dichen; Tian, Xiaoyong. (2015). Development Trends in Additive Manufacturing and 3D Printing. Engineering, 1(1), 85-89. doi:10.15302/j-eng-2015012.

MakerBot Industries. (2018). About Thingiverse. Available [online] at: https://www.thingivse.com/about/.

Milgram, P. en F. Kishino (1994). "A taxonomy of mixed reality visual displays." IEICE TRANS ACTIONS on Information and Systems 77(12): 1321-1329.

Mixed Reality Lab (2018). Human Pacman. Available [online] at: http://mixedrealitylab.org/projects/all-projects/human-pacman/. Geraadpleegd op: 17 april 2018.

Moore, M. M., & Lu, B. (2011). Autonomous vehicles for personal transport: A technology assessment. Available [online] at: http://www.pickar.caltech.edu/e103/Final%20Exams/Autonomous%20Vehicles%20for%20Personal%20Transport.pdf. Geraadpleegd op: 5 juni 2018.

Morozova, A. (2018). How much does it cost to build an Augmented Reality app like IKEA Place?. Available [online] at: https://jasoren.com/how-much-does-it-cost-to-build-an-augmented-reality-app-like-ikea-place/. Geraadpleegd op: 20 februari 2018.

Ortt, J. R. (2010). Understanding the Pre-diffusion Phases. Gaining Momentum Managing the Diffusion of Innovations. J. Tidd. London, Imperial College Press: 47-80.

Ortt, J. R. (2017). Guest editorial. Journal of Manufacturing Technology Management, 28(1), 2-9. doi:10.1108/JMTM-01-2017-0010.

Pisa, M., & Juden, M. (2017). Blockchain and Economic Development: Hype vs. Reality. Center for Global Development Policy Paper, 107.

Resins Online. (2013). 3D Printed Clothing Becoming a Reality. Available [online] at: http://www.resins-online.com/blog/3d-printed-clothing/.

Reynolds, J. (26 May 2001). "Cruising into the future". London: telegraph.co.uk.

Sandner, P. (2017). Identifying Leading Blockchain Startups on a Worldwide Level. Available [online] at: https://medium.com/@philippsandner/analysis-of-leading-blockchain-startups-worldwide-8ecee1a7d670.

Sedgwick, K. (2017). Bitcoin by Numbers: 21 Statistics That Reveal Growing Demand for the Cryptocurrency. Available [online] at: https://news.bitcoin.com/bitcoin-numbers-21-statistics-reveal-growing-demand-cryptocurrency/.

Steenhuis, H. J., & Pretorius, L. (2015). Additive manufacturing or 3D printing and its adoption. Paper presented at the IAMOT 2015 - 24th International Association for Management of Technology Conference: Technology, Innovation and Management for Sustainable Growth, Proceedings.

Stratasys. (2010). Stratasys is Development Partner on Urbee Hybrid - the First Car to Have Entire Body 3D Printed. Available [online] at: http://investors.stratasys.com/news-releases/news-release-details/stratasys-development-partner-urbee-hybrid-first-car-have-entire.

Sybenga, S. (2010). How augmented reality can help safety. dalam Study Tour Pixel, 4. Available [online] at: http://www.vudream.com/wayray-can-augmented-reality-ar-prevent-car-accidents-safety/. Geraadpleegd op: 20 februari 2018.

Szabo, N. (2011). Bitcoin, what took ye so long? Available [online] at: http://unenumerated.blogspot.nl/2011/05/bitcoin-what-took-ye-so-long.html

TechRepublic (2016). Updated: Autonomous driving levels 0 to 5: Understanding the differences. [online] available at: https://www.techrepublic.com/article/autonomous-driving-levels-0-to-5-understanding-the-differences/.

The Drum (2018). TOP 30 Augmented Reality Companies for 2018. Available [online] at: http://www.thedrum.com/profile/news/284263/top-30-augmented-reality-companies-2018. Geraadpleegd op: 13 april 2018.

Van Krevelen, D. en R. Poelman (2010). "A survey of augmented reality technologies, applications and limitations." International Journal of Virtual Reality 9(2): 1.

Vincent, J. (2014). British Museum releases scans of artefacts to let you 3D print your own museum at home. Available [online] at: https://www.independent.co.uk/life-style/gadgets-and-tech/british-museum-releases-scans-of-artefacts-to-let-you-3d-print-your-own-museum-at-home-9837654.html.

Volokh, E. (2017). Law, virtual reality, and augmented reality. Available [online] at: https://www.washingtonpost.com/news/volokh-conspiracy/wp/2017/03/17/law-virtual-reality-and-augmented-reality/?noredirect=on&utm_term=.c5d4d43f9d3e. Geraadpleegd op: 20 februari 2018.

Von Hippel, E. (2001). "PERSPECTIVE: User toolkits for innovation." Journal of Product Innovation Management 18(4, July): 247-257.

Wikitude (2017). Augmented Reality 101: all about the technology behind ARCore and ARKit. Available [online] at: https://www.wikitude.com/blog-augmented-reality-google-arcore-arkit-apple/. Geraadpleegd op: 13 april 2018.

Wilkinson, S., & Cope, N. (2015). 3D Printing and Sustainable Product Development. Green Information Technology: A Sustainable Approach (pp. 161-183).

Williams, D. (2016). The History of Augmented Reality (Infographic). Available [online] at: https://www.huffingtonpost.com/dennis-williams-ii/the-history-of-augmented-_b_9955048.html. Geraadpleegd op 14 februari 2018.

Wong, V. (2014). A Guide to All the Food That's Fit to 3D Print (So Far). Bloomberg Business week. Available [online] at: https://www.bloomberg.com/news/articles/2014-01-28/all-the-food-thats-fit-to-3d-print-from-chocolates-to-pizza.

Appendix

Discussion: the Technology Monitor for STT

The methods: assumptions and limitations

In this report, we described three methods that together form the basis for the Technology Monitor, which is a tool designed to examine (each year) what the status is of technologies that appear to be on the verge of a breakthrough. In addition, the number of technologies being analyzed can gradually be expanded, making it important to clearly define the technology, how the development and diffusion can be mapped (model 1) and how we can identity the conditions that determine the further development of (large-scale) diffusion (model 2). Finally, it is important for domain studies by STT to have an idea of how a certain technology will be applied in successive domains over time.

The definition

The way to define technological breakthroughs consists of two parts. The first part indicates what it is that turns the technology into a technological breakthrough: that is the case when a technology can be applied broadly (and so potentially in multiple domains) and has the potential to lead to structural change there. The other parts are specified by the technology itself by indicating exactly what the operating principle is, what the functionality is and what the main components are. This method worked well for the technologies we examined in this report, with some provisos.

First of all, the definition limits the scope of a technology. That is careful, because technology is often defined in narrow or broad terms, often referring to completely different things. In practice, that definition is necessary, but also restrictive. After all, 3D printing is a family of different technologies, and so is Augmented Reality, of which there are also fundamentally different versions. Blockchain is a platform that can be used in a broad way for multiple functionalities, namely the registration of transactions that are secure and that have been checked and verified by many. That is useful for a wide range of applications: recording identities of people and things, recording transactions and defining currencies (cryptocurrencies). The self-driving car is a complex combination of many very different technologies. Our proposal is to use the definition used in this report for the monitor, because otherwise it will not be possible to list pattern, conditions and applications.

Table 7.3: Assumptions and limitations of the definition (principle, functionality and components)

Definition	Comment
Limitation	The scope of the technology (the unit) is determined and therefore limited.
Assumption	Despite many changes, the unit of analysis (the technology) at heart stays the same during the pattern of development and diffusion.
Possible expansion	Multi-level analysis, for instance at a higher level, the level of a family of technologies, each with their own pattern and conditions. Or at a lower level, the level of a certain version of a technology.

Model 1: the pattern of development and diffusion

The pattern of development and diffusion is a model that is a considerable improvement, in terms of its realism, on by far the most commonly used model, the innovation-diffusion model. It is a step from a very simple ‘life cycle’ model towards a slightly more realistic ‘evolutionary’ model.

The level of realism further increases when we realize that the length of each phase can vary, generating scenarios, like a scenario with a prolonged phase from innovation to first introduction, followed by a short adaptation phase from first introduction to large-scale diffusion (typical for medications) or a scenario that is the opposite (typical for electronic components). The technologies discussed in this report varied considerably in terms of the length of the successive phases.

The assumption in our model, the pattern, is that the phase transitions (invention, first introduction and start of the large-scale production and diffusion) can be identified clearly and unequivocally, which is not always the case: sometimes, the steps are so incremental and gradual that it is hard to pinpoint the moment of invention. Sometimes the phase transitions are so uncertain that the uncertainty is higher than the periods between the phase transitions, in which case the entire model becomes unstable and cannot be used.

In this report, we noticed that the pattern for blockchain is similar to that of software or materials: the first applications do not take place separately but are cumulative, so that the transition between the adaptation phase and the later phase of large-scale production and diffusion cannot be identified. This appears to occur with technologies that can be used in many applications, or with technologies that serve as a platform on which many other applications can be used.

Table 7.4: Assumptions and limitations of the pattern (development, adaptation and stabilization)

Pattern	Comment
Limitation	Hindsight bias
Assumption	It is possible to clearly identify the phases
Expansion	Update the analysis of a technology over time and thus limit hindsight bias. Possibly add variations of the pattern.

Method 3: the conditions

The conditions indicate which factors are important to further development and diffusion. The factors can obstruct or stimulate, depending on their value. The list of conditions provides a simplified overview of the mutual complex way these factors influence each other. The dashboard model assumes that the influencing factors affect the core factors when, in practice, they also affect each other, while core factors can also affect the influencing factors in a feedback loop.

Table 7.5: Assumptions and limitations of the dashboard (factors for large-scale diffusion)

Conditie	Commentaar
Limitation	Mutual influencing of factors
Assumption	Influencing factors primarily affect core factors
Expansion	Dynamic model

About STT

The Netherlands Study Centre for Technology Trends (STT) is an independent non-profit knowledge institute. Its board consists of over 60 members from the highest levels of Dutch government, the business community, the research community and social organizations. Since 1968, the STT's core activity has been to organize long-term futures explorations at the crossroads of technology and society. The explorations help generate vision, agendas for the future, research programs, networks, institutes and projects. The explorations are always interdisciplinary in nature and try to contribute to solutions for grand societal challenges.

In addition, STT Academy is involved in method development and sponsors teaching chairs, organizes master classes and maintains the Network Futures Explorations (NTV) and the youth network Young STT.

For more information about STT, its activities and its publications, visit our website at www.stt.nl.

Publicaties

Some recent STT explorations:

STT 84 **National Future Monitor 2016.**
Dhoya Snijders, 2016

STT 85 **Who we become. Future visions of people in 2050.**
Ellen Willemse, 2016

STT 86 **Data is power. About Big Data and the Future.**
Dhoya Snijders, 2017

STT 87 **And then the light went on. Transitions towards an emission-free energy system.**
Soledad van Eijk, 2017

STT 88 **Long Life Learing. About Learning, Technology and the Future.**
Dhoya Snijders, 2018

Colofon

Authors
Roland Ortt, Bram Dees (TU Delft)

With the collaboration of
Patrick van der Duin, Dhoya Snijders, Silke den Hartog, Carlijn Naber (STT)

Text and language editing
Gert Stronkhorst

Design and illustrations
IM VormCommunicatie

NUR 950

Keywords: future, monitor, breakthrough technologies, blockchain, virtual reality, 3D printing, self-driving car, Netherlands