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Aim and Scope

The Journal of Business Chemistry (JoBC) focuses on current developments and insights at the intersection of management and chemistry, biotechnology or pharmacy.

The JoBC provides an international forum for researchers and practitioners in companies, research institutes, public authorities, consultancies or NGOs to present and discuss current challenges as well as potential solutions in an interdisciplinary manner. Thus, the JoBC aims to foster the dialog between science and business, to support management practice in the chemical and pharmaceutical industry and to indicate where further research from academia is needed. The JoBC offers high quality publications with academic standards, a fast publishing process and global reach. With this multidisciplinary and boundary-spanning approach, the Journal of Business Chemistry intends to become the leading journal for decision makers in the chemical and pharmaceutical industry.

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Letter from the Editors

Entering a new decade

The first Journal of Business Chemistry issue of the 2020s addresses the 'megatrends' that we will face throughout the next ten years - artificial intelligence, digitalisation, sustainable development and decarbonisation, to name a few. With developments in these fields, industry always faces the question of how to implement changes. The articles in this issue collect the perspectives of academia, industry and consulting as a guide through this process. We are also pleased to incorporate a new section to the journal - "Introductions to innovation management", which should be of particular interest to natural scientists in industry in the process of transitioning to a business or management role. In this section, literature concepts from the field of innovation management will be discussed.

The first article of this issue is titled „Can an Artificial Intelligence Model be the Inventor of a Molecule designed by the Model and how can Patentability be assessed?", a topic, which will become ever more important in the coming years and decades with the increasing presence of artificial intelligence in the pharmaceutical industry. Should new molecules generated by AI, but never made in the lab, be patented? If so, is the person who created the AI model the inventor of a conceived compound, the person who applied the model to find the new compound, or is the AI model itself the inventor? These questions are debated in Dr. Huhn's commentary, leaving much room for fruitful discussions.

In "Shaping Digital Sustainable Development in Chemical Companies", Dr. Keller and Dr. Bette share results of their survey on the topic of digitalisation and sustainable development conducted on 60 chemists in the chemical industry in Germany. What is the relationship between digitalisation and sustainability within chemical companies? How should digital sustainable development be carried out in the chemical industry and what are the factors impeding its implementation?

Continuing the topic of sustainability, we come to Dr. Falter et al.'s article on "Decarbonization Strategies in Converging Chemical and Energy Markets". The article reviews current energy usage in the chemical industry, along with governmental and industrial goals for carbon neutrality. Ways in which progress is being made to meet those goals, roadblocks to said goals and the possibilities for future improvement are described. If you are looking to develop a decarbonization strategy in your company, check out the four-step guide in the last chapter.

Mr. Smolnik's and Mr. Bergmann's article titled "Structuring and managing the new product development process – Review on the evolution of the Stage-Gate® process" provides a comprehensive literature review of the last four decades. The last chapter detailing the I2P3® process from Evonik Creavis GmbH may be of particular interest to chemical companies. This case study demonstrates how chemical companies can successfully adapt their new product development processes.

Lastly, Ms. Riesmeier introduces the concept of disruptive innovation in "Application of Kuhn's Theory of Scientific Revolution to the Theory Development of Disruptive Innovation". The development of disruptive innovation theory is assessed through Kuhn's four stages of scientific development: crisis, revolution, normal science and accumulation of anomalies. It is debated whether anomalies around the theory's definition and its predictive value will impact the theory's future.

Please enjoy reading the first issue of the seventeenth volume of the Journal of Business Chemistry. We are grateful for all the support from authors and reviewers for this issue. If you have any comments or suggestions, please do not hesitate to contact us at magdalena.kohut@businesschemistry.org.

Magdalena Kohut Bernd Winters

(Executive Editor) (Executive Editor)

Journal of Business Chemistry

Commentary

Can an artificial intelligence model be the inventor of a molecule designed by the model and how can patentability be assessed?

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1 Introduction

It appears not appropriate to refuse patentability of an invention on a new molecule designed by AI because the respective patent application does not have significant examples which were carried out in reality, but only generated by AI (usually a trained model/machine trained algorithm). However, to achieve patentability, certain requirements must be fulfilled, in particular relative to the estimation accuracy of the trained model and to successful repetition of the examples in view of known state of the art at the filing date.

It is more than questionable if an AI model can be the inventor of a molecule designed by the model, the first patent applications in this respect having been filed. Assessment of inventive step for new molecules generated by AI should remain subject of discussion. There are no clear positions by the patent offices for the time being.

It is a well-known fact that Artificial Intelligence (AI) has a vastly growing impact on our everyday life, for carrying out innovative and creative acts resulting in inventions, which could previously only be made by humans.

A rapid development in the use of computers in chemistry could be observed in the last 50 years. A further immense development, now in the design of new molecules, occurred when computers became powerful enough to process machine learning algorithms, discover patterns in data, and construct mathematical models using these discoveries. Algorithms can be provided with data to learn from (trained model). This is the principle of Artificial Intelligence. Patents can be issued on trained models themselves, or the trained model can be applied, e.g. in pattern or language recognition or the subject-matter of the present article – designing molecules (Chen et al., 2018; Engkvist et al., 2018; Sellwood et al, 2018).

Many questions relating to the protection of these inventions yet remain to be answered. The readers' attention is hereby drawn to the fact that the field "AI and patents" is still in a very early stage of development. Little is known. Only a limited number of publications related to this subject-matter exist, and it cannot be said that it is easy to get an overview on the actual state of art in the field. Some articles are very general, some treat the use of AI in drug discovery, some give general overviews of the various fields where AI can be applied, some disclose in which technical fields AI is used, and so forth.

The following publications are of considera-

ble interest in the present field:
“Artificial Intelligence and Drug Discovery” (Leanse, T., 2019)

“Artificial intelligence: the implications for patents” (Kuhnen, R. K., 2019)

“Artificial creativity—is the IP system ready for robot inventors?” (Inchley, T., 2019)

„Machine yearning: AI and patents” (various authors, 2019)

“Patenting Artificial Intelligence: Issues of Obviousness, Inventorship and Patent Eligibility“ (Tull, S. Y. and Miller, P. E., 2018),

“WIPO Technology Trends 2019 Artificial Intelligence” (WIPO, 2019).

A frequently encountered question concerns not the patentability of an AI method as such, but of molecules, materials, compositions and the like, designed (conceived) thereby. In these cases, the human (i.e. the „classical“ inventor) plays a lesser and lesser role. It is expected that this will have an impact on the assessment if results (examples) conceived by AI meet the requirements for sufficiency of disclosure.

It is assumed that AI is used frequently in chemical and pharmaceutical industry to design new molecules or related compositions of matter. However, it is not clear to which extent AI is used since industry is rather silent in this respect. Furthermore, the number of filed patent applications cannot be taken as an indicator. Due to uncertainty if protection of a molecule designed by AI (and not in the lab) is available at all, industry has not filed patent applications in this field. In surplus, the questions who is the inventor of the molecule and how the inventive step (i.e. if the new molecule is sufficiently distinct from the prior art) is assessed are not clear. As long as this is the case, patent applications will not be filed.

Hereinafter, it will be tried to give an answer to the question if it is or will be possible to patent molecules, materials, compositions and the like showing advantageous properties which are designed by AI and, in the affirmative, if the AI model is the inventor of the new compound. The author will furthermore address some crucial questions relating to the assessment of the inventive step.

2 Patentability of molecules designed by artificial intelligence

In the present context, molecules having pharmacological activity (interaction with targets, e.g. antigens, antibodies, enzymes) play a paramount role. However, the results provided below also apply for materials, compositions and the like not having a physiological, but other activity.

In the context of the present article, the term “molecule” refers not only to molecules, but also to materials, compositions and the like including DNA, enzymes, antibodies, (liquid) crystals, just to name a few.

The interaction of molecules with certain targets can be calculated very accurately today using AI. Even though this is nothing else, in principle, than well-known „*in silico chemistry*“, calculations supported by AI (“trained model”) now have a more accurate scientific basis, generating in many cases precise results in shorter time.

In consequence, an actual question in this respect is whether „AI-generated“ (“trained model generated”) molecules having certain (alleged) properties can be patented as such, even though they were not synthesized and tested in vitro at the priority date.

To answer this question, the two decisive questions criteria should be:

1) Does a patent application on a molecule generated by AI provide ample disclosure in the description and the (not real) examples for the person skilled in the art to enable

synthesis of the respective molecule in vitro?

2) Does the skilled person, at the priority date, assess the examples (and the respective parts of the description) as credible, because they do not contradict common teachings and/or the estimation accuracy of the trained AI model is sufficiently high?

It is held that application of the above two criteria could serve to avoid that the examples in the respective patent application are just an (uneducated) guess not having a sound scientific basis (meaning that even if the examples of the application could be successfully reproduced, this was purely accidental).

The above approach is supported, on the one hand side, by the **Japanese Patent Office JPO**, in "Examination Guidelines for Patent and Utility Model" (JPO, 2019a), „Case examples pertinent to AI-related technology" (JPO, 2019b) and „Newly Added Case Examples for AI-Related Technologies" (JPO, 2019c) (Presentation Material).

Example 51 in "Case examples pertinent to AI-related technology" and „Newly added case examples for AI-related technologies" is a fictive example for a patent application not providing enabling disclosure. The application is on a curable adhesive invented by a trained AI model. The adhesive has a certain composition to cure faster than state of the art adhesives. No real examples are found in the description, only an example created by the trained model. The estimation accuracy of the trained model has not been verified.

The facts that a) it was common technical knowledge at the priority date that it is difficult to control the curing reaction the way described in the patent application; and b) the example is a "trained model example" created without a verified estimation accuracy, are reasons that the application is assessed as not providing enabling disclosure (written support) in the description. This cannot be remedied by later filing data showing that the trained model result was correct, as the skilled person would not have believed that the claimed invention can be carried out at the priority date, for being a) contrary to common knowledge and b) based on speculation. However, this conversely should mean that the invention would have been patentable if the two above criteria had been met.

The actual „Guidelines for Examination" of the **European Patent Office EPO** answer almost exclusively questions related to assessment of inventive step and technicity of AI methods (Guidelines for Examination in the European Patent Office, November 2019, Section G-II, 3.3.1, Section G-II, 3.6, G-VII, 5.4) (EPO, 2019). Unfortunately, support for the correctness of the above assessment is not found there.

Such support, however, appears to exist in case law of the Boards of Appeal of the EPO. It is pointed to case law on so-called „prophetic examples", which are established as proof to show that an invention can be carried out at the priority date. Definite proof can then be filed at later points in time by "real" examples. However, in general such proof is only accepted if the teachings of the claims and the description is not contrary to the general teachings in the particular field at the priority date. Decisions have to be taken on a case-by-case basis.

In the present context, the decision T2220/14 (EPO Boards of Appeal, 2015) backed up by T1496/08 (EPO Boards of Appeal, 2012), is worthwhile mentioning.

T1496/08 states the following (p. 20, 1st paragraph): "*Post-published evidence may be taken into account, **but only to back-up the findings in the patent application** in relation to the use of the ingredient as a pharmaceutical, and not to establish sufficiency of disclosure on its own."* T2220/14 states the following in Point 63. of *"The Reasons for the Decision": The respondents have not presented convincing evidence that this would be the case, their main argument being that Example 3 is a "prophetic" example. However, **there is no requirement in the EPC that, either at the priority or filing date, the applicant must have carried out the*** **claimed**

invention. *The requirement of Article 83 EPC is that a person skilled in the art, following the* ***teachings in the application*** *as filed supplemented with his/her* ***common general knowledge*** *and with a reasonable amount of experimentation, including* ***some trial and error,*** *would be able to carry out the invention as claimed at the relevant date.* (emphasis added).

In summary, it appears not appropriate to refuse patentability of an invention on a new molecule because the respective patent application only has AI (trained model) generated examples. This would be the same as refusing an invention on a new molecule because all examples are prophetic. As shown by the Guidelines for Examination of the JPO and the above EPO case law, this is not appropriate – it has to be checked if the examples can be successfully carried out and – in the affirmative - if the success was not accidental. To this end, it has to be verified if the examples are not in line with common knowledge at the priority date and if the estimation accuracy of the trained model is sufficiently high.

3 Inventor questions

Another crucial question is: who is the inventor of molecules designed by AI? The person who has created the trained model and/or who has applied the trained model to find the new compounds? According to generally applied principles, an inventor must be a natural person (it should be noted, however, that this is not explicitly required by the European Patent Convention). However - what to do when an invention has been clearly made by a machine trained algorithm? Until now, for "serious" inventions having a potential commercial value, no one will name the trained model as an inventor, because it seems clear that the application will be rejected for not complying with inventor requirements.

However, recently two patent applications were filed in various countries by the same applicant (Dr. Stefan Thaler) which have in the meantime been published under the numbers EP 3 564 144 und EP 3 563 896 by the EPO . A machine trained algorithm was named as the inventor. The algorithm as such appears to be protected by a patent application (US 2015/0379394), naming Dr. Stephan Thaler as an inventor. The subject-matter of the patent applications are a food container and an electronic device.

More information is available on the website of the EPO (EPO, 2019), the magazines "The IPKat" (Hughes, 2019a, 2019b; Papadopoulou, 2019) and "iam" (Wild, 2019). This case should be a "trial balloon" challenging the Patent Offices to give an answer to the crucial question if a trained model can qualify as an inventor.

4 Inventive Step

A further, important topic, frequently also encountered when molecules are designed by AI is the inventive step. "Inventive Step" or also "Obviousness" refers to the patentability criterion if the new invention is sufficiently remote and different from what is known in the art (the pool of publications in the same field) is not considered "trivial".

Let's take the case that an individual helps to create a trained AI model/machine trained algorithm. The model reveals to give excellent results in designing molecules having certain desired properties, e.g. binding to certain targets (e.g. enzymes, receptors in the medical field) or lending themselves as perfuming ingredients, colorants or sweeteners, just to name a few. The person having conceived the trained model is the inventor, in the classical sense, of the model; but also (very probably, see below) of the new molecule. Until here, the story is still easy. But how about the assessment of the inventive step if the same model is used again to design further molecules? It appears that the threshold for patentability relative to inventive step becomes higher, or that the inventive step will be even denied. The design of a new molecule using the same model which has been already successfully applied in the design of the first molecule could be regarded as a simple routine act, even though the specific molecule provides advantageous properties and would be regarded as inventive under "classical" criteria.

It is not clear if one day the respective Patent Offices will take the above approach. In any case, applicants wishing to patent new molecules designed by AI may prefer not to disclose that the "method behind" the creation of the new compounds is a machine trained algorithm, in order not to "raise the bar" for the inventive step or, rather, to have the examiner apply the "classical" criteria. Applicants may even think of not disclosing the model in the first application (in which the trained model was used for the first time), i.e. not to mention the model. In this respect, however, the question arises if it does not become evident that the new molecules were the result of a trained model and the application gets rejected for lack of disclosure. The AI used to design new molecules should in principle be open to protection by patents. Such exclusivity for the best AI would clearly provide the company, often a drug company, with a competitive advantage. However, the protection for molecules, and in particular the important "crown jewels", might get lost, in a worst-case scenario.

5 Discussion

As more and more new molecules are designed by AI, without any examples having been carried out in vitro, the question arises if the design of the particular molecule results in a patentable invention. To answer this question, it appears appropriate to use argumentation based on patents having prophetical examples (the other type of examples which have not been carried out when the patent application was filed). Since patents having prophetical examples can be granted under certain conditions, this should also apply for patents having only examples for AI-designed molecules. A careful analysis of the Guidelines for Examination of the JPO and the above-cited EPO case law (EPO, Guidelines for Examiniation) reveals which criteria for patentability should be checked if the examples can be successfully carried out. It should be verified if the examples are in line with common knowledge at the priority date and if the estimation accuracy of the trained model is sufficiently high. Then the success was not accidental.

It seems that the bar for patentability of compounds designed by AI will inevitably be raised. Many questions cannot be answered for the time being, one of them being if AI programs can be inventors. Two cases are known to date in which patent applications naming an AI inventor have been rejected by the European Patent Office (decision can be appealed). As the reasoning for the decisions is not available yet, it is not clear what is behind the decision, but it is assumed that the EPO will base it on the reason that the inventor is not a human being.

It is not clear how the inventive step will be assessed in case an AI-designed compound was found patentable and the same trained model shall be used again to design a (further) compound. In such a case, the examiner may argue it was known that the trained model is capable of successfully designing new molecules with some desired properties. The design of another molecule will then just be the result of a routine act, namely providing the relevant data to the model. At present it is not clear how such an objection can be avoided or overcome. One solution might be not to disclose that the molecule was designed by a machine trained algorithm. This should avoid the objection that the new molecule was created in a routine act. However, shouldn't it immediately become obvious that the examples are only based on AI? Maybe this does not even trigger negative consequences as after all the situation appears very similar to a "classical" pharmaceutical patent application with prophetic examples (which would correspond to the AI-generated examples). Yet this would mean that the subject-matter of the application is patentable!

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Practitioner's Section

Shaping digital sustainable development in chemical companies

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Both, digitalization and sustainable development are two megatrends with significant impact on the chemical industry in Germany through to 2025, according to a recent survey among 60 chemists. Digitalization is as seen a driver for sustainable development, even though there is no quantitative correlation in the importance of the two megatrends. When implementing Corporate Digital Sustainable Responsibility (CDSR) chemical companies need to find the right balance between business, technology, society, responsibility and mindset-related facets that chemical practitioners refer to when arguing in favor of digitalization being a driver for sustainability or against it.

1 Introduction

Germany's chemical industry has taken a leading role in Responsible Care (VCI, 2011) – nowadays referred to as Sustainable Development (Sachs, 2015) – since about 25 years. Digitalization, a second, steeply evolving megatrend, is not new either. However, its breakthrough in the chemical industry has begun only recently, marking the beginning of Digital Sustainable Development (DSD) (RNE, 2018). An empirical survey among 60 chemists identifies some preconditions and obstacles for "Corporate Digital Sustainable Responsibility", the extended corporate governance (Werder, 2018), Digital Sustainable Development, the process to make it happen, and ultimately the desired Sustainable Development Goals (United Nations, 2015).

2 Progress of sustainable development in the chemical industry

The origin of sustainability is closely connected to major accidents, e.g. at Seveso (Kramer et al., 2019), Bhopal (Eckerman and Børsen, 2018), Houston Chemical Complex (U.S. Department of Labor, 1990) and Exxon Valdez (Cohen, 1995) in the 1970s and 1980s. In the mid -1980s, the global chemical industry took counter action in response to these disasters and to gain back its ruined trustworthiness. Today, sustainability is subject of numerous multi-stakeholder initiatives like Responsible Care (VCI, 2019, I, II; Delmas and Montiel, 2008; King and Lenox, 2000), Together for Sustainability (TfS, 2019), Chemie3 (Chemie3, 2019), Platform for Accelerating the Circular Economy (PACE, 2019) and Alliance to End Plastic Waste (AEPW, 2019), and an integral element of the strategy of many big chemical companies (BASF, 2019; Clariant, 2019; Evonik, 2019; Linde, 2019; Wacker, 2019, I). In this decade, chemists and chemical engineers have developed first technically and – at least partially - economically feasible industrial-scale approaches for product redesign, reuse, mechanical and chemical recycling (Werner and Mertz, 2016; Johnson, 2018; Stark, 2019; Stephan, 2019; Strathmann, 2019). The chemical industry is on a good way to achieve the desired Sustainable Development Goals and by 2050 will likely be able to be carbon neutral (VCI, 2019, III).

3 Progress of digitalization in the chemical industry

Unlike Sustainable Development, digitalization in the chemical industry is still in its early stages. Since about 5 to 10 years, bigger rather than mid-size chemical companies have begun to leverage information and communication technology, electronics, and the experience of automotive industries with digital technologies and applications (DECHEMA, 2016). Many of them have appointed Chief Digital Officer(s) whose primary task is to define and execute their company's digital transformation roadmap (Schmidt-Stein, 2018; Wacker, 2019, II; BusinessTech-Company, 2019, I to VI). Still, the emphasis of the digital transformation roadmap is often on technical aspects. True Corporate Digital Responsibility (CDR) needs to go far beyond, e.g. including compliance with legal obligations, digital ethics, interactions with society, chemical suppliers and customers, and the enablement of employees for chemical industry 4.0 with its modified jobs and competences (Keller, 2018; BAVC, 2018; Lade, 2019).

4 Corporate digital sustainable responsibility, a feasible composite?

Can CDSR facilitate chemical companies to exploit potential synergies between the two megatrends, sustainability and digitalization, while striving to fulfill their Sustainable Development Goals? In this context CDSR in the chemical industry can be defined "an embryonic concept aiming at seamlessly integrating the two time-shifted and often independently managed approaches of CSR and CDR in order to resolve de facto and potential conflicts of interest to achieve a company's SDGs". Here are some examples of these conflicts:

- A blockchain system negates the risk of trusting a single organization through distributed ledgers and reduces overall costs and fees of all kind of transactions by cutting out intermediaries and third parties. However, its required resources have significantly increased in the last few years. It currently consumes more energy than many countries, such as Denmark, Ireland, and Nigeria (Binance Academy, 2019).
- Super computers offer a quantum leap in computing power, e.g. 1 to 2 quadrillion floating-point operations or 1 to 2 petaflops per second. However, its electricity consumption at full capacity is approximately 600 kilowatts, and the water-cooling system requires up to 60,000 liters of water per hour (BASF, 2018).
- A simultaneous digital and sustainable transformation impacts a chemical company's future revenue and profit, but also public reputation, core values, culture, business model, technologies, products, services and employees, i.e. financial and non-financial dimensions. If mainly financial key performance indicators, e.g. the Return on Investment (ROI) for the transformation and the Return on Capital Employed (ROCE) for the ongoing business, remain the benchmark for investors and shareholders, business cases are instrumental, however rarely suitable to base not primarily financial decisions on.

The authors have undertaken an empirical survey among 60 chemists in the chemical industry in Germany to identify the relative importance of sustainability and digitalization by 2025. They look at mutual interdependencies and potentially missing competences required to pursue CDSR .

Participants represent different levels of education (Bachelor, Master, PhD), years on duty, company size (corporation, big, mid-size and small company) and management level (1 through to 4). The survey is hypotheses-based, with respondents indicating their degree of agreement with each proposed hypothesis, using a percentage scale.

The first hypothesis “By 2025 Digitalization will play a major role for chemists and engineers” achieves 83% level of agreement (sample size 56). The distribution of responses is surprisingly homogenous. There is no trend between the responses and the level of education, years on duty, company size, and management level.

78% level of agreement (sample size 56) is a clear indication that also “Sustainability will play a major role by 2025 for chemists and engineers”. The pattern of responses is almost identical with that of the role of digitalization by 2025.

The average level of agreement that “Digitalization is a driver for Sustainable Development” scores at 70% (sample size 53, Figure 1). This view is very consistent within each and across all clusters.

In addition, 53 data sets including values for each of the three hypotheses were sorted in declining order choosing “Digitalization is a driver of sustainability” as lead parameter, shown as solid line in Figure 2. The depending parameters “importance of digitalization” and “importance of sustainability” are displayed as radar charts underneath. The heterogeneity of the diagram corresponds well with poor correlation coefficients of -0.10 in case of digitalization and +0.07 regarding sustainability.

Figure 1 Degree of agreement to the hypothesis „Digitalization is a driver for Sustainable Development” depending on the level of education, management level and company size (source: own representation, 2019).

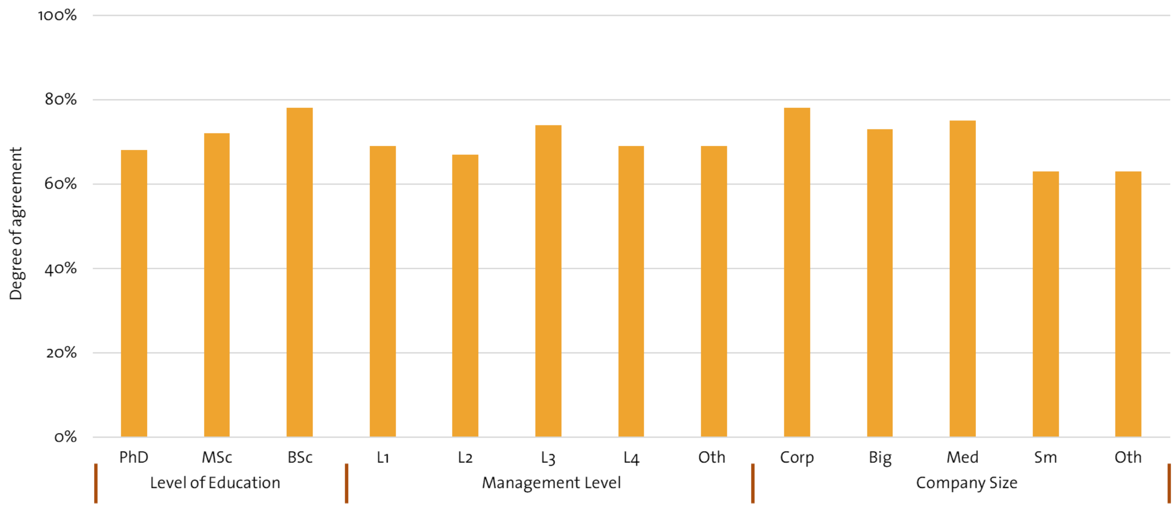
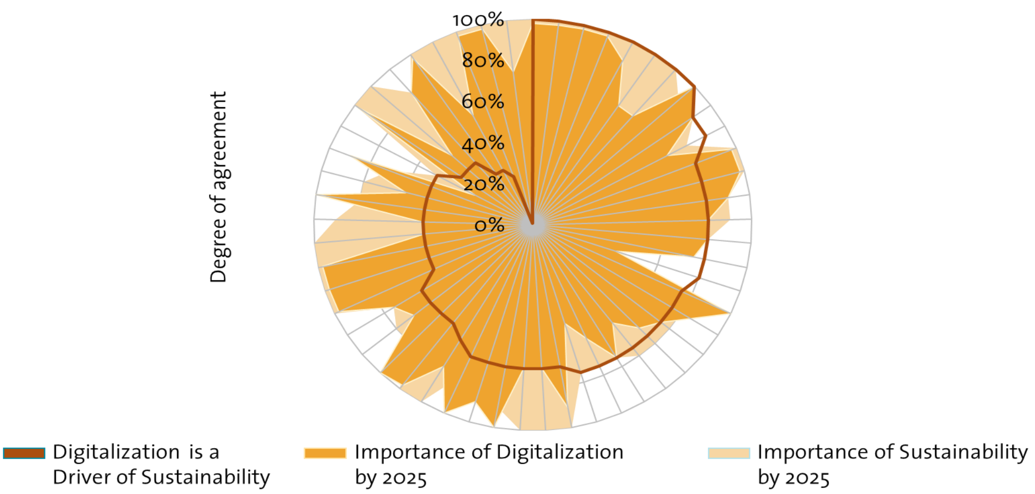


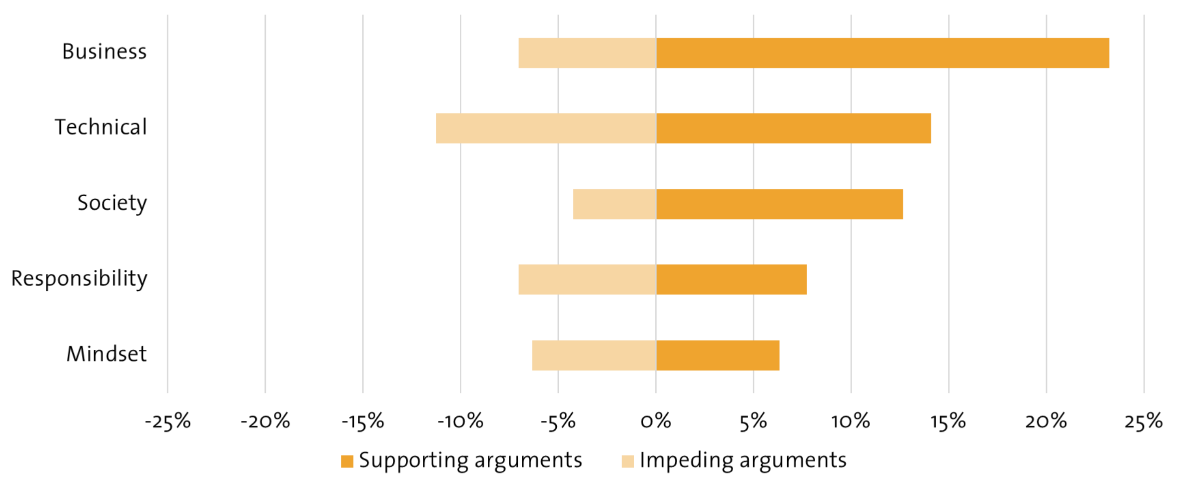
Figure 2 Lacking correlation between the importance of digitalization as a driver for sustainability . and the importance of digitalization and sustainability by 2025 (source: own representation, 2019).



To understand the full bandwidth of related comments from 100% euphoria to 100% skepticism, all comments made were classified in five clusters: business, technical, society, responsibility and mindset. Within each cluster responses were distinguished by supporting and impeding notions. The number of comments in each (sub-)cluster was divided by the total number to calculate comments' relative frequency. (Figure 3).

Business cluster: Key arguments that "Digitalization is a driver of sustainability" include the better control of sustainability-related technical and management processes and energy management, all leading to higher technical and human resource efficiency and bottom-line improvements. Major concerns address data availability, format, integrity, and security and management decision-making timeliness and effectiveness.

Figure 3 Hypothesis "Digitalization is a driver of sustainability" Distribution of supporting and impeding arguments by cluster and overall (source: own representation, 2019).



Technical cluster: On the positive side, benefits through big data and artificial intelligence to drive sustainable processes, products etc. dominate by far. Excessive energy consumption, high dependency on state-of-the-art IT infrastructure and the ability to handle giant quantities of data are the top concerns.

Society cluster: Respondents are – with few exceptions - aware of the driving role of politics, educational institutions and the chemical industry in defining and providing boundary conditions for DSD. There is considerable skepticism that educational institutions assume sufficient responsibility by not including digitalization and sustainability comprehensively enough in their curricula.

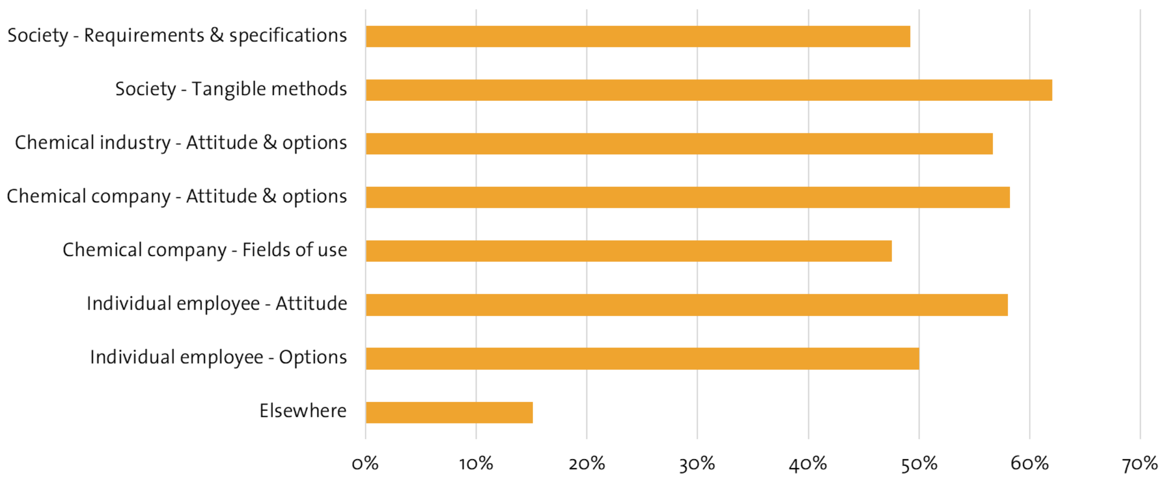
Responsibility cluster: Respondents consider clear responsibilities instrumental for DSD. Only 20% see their company in charge, not a clear vote for "corporate responsibility". The lack of commitment to digitally enabled sustainable chemical and management processes and management's hesitation to invest in required training are the two main concerns. 80% of respondents believe DSD responsibility is primarily with politics and educational organizations.

Mindset cluster: Only 12% of all comments address the attitude of managers and employees. Leadership by example and individual freedom to act are seen instrumental for DSD. The biggest concern addresses low willingness and readiness across all levels of the company, from shop floor to C-level, to cope with change associated with DSD.

In summary, regardless which role digitalization and sustainability will play by 2025, 58% of the participants (degree of agreement ≥ 67%) are strong believers that digitalization is a key enabler for DSD, 32% (agreement between 34% and 66%) have mixed feelings, and 9% (agreement ≤ 33%) see no or a limited driving role of digitalization.

DSD is significantly affecting chemists' job profiles, required skill sets and training needs. Training needs in the context of digitalization (Keller, 2018; Gruß, 2018; Lade, 2019) and those addressing sustainability (Keller and Knoll, 2020; ILO 2019; Graf and Reuter, 2017; ILO and CEDEFOP, 2011) have been defined. Contrary to digitalization skills, respondents consistently claim (degree of agreement between 48% and 62%, Figure 4) that there is no single highest priority for sustainability-related training. Instead, training covering requirements, specifi-

Figure 4 Hypothesis *"This specific Sustainable Development area represents the highest training need"*. Degree of agreement in % for each individual answer, not additive (source: own representation, 2019).



cations, methods, applications, attitude and options to act for each area - society, company and individual chemists, is required. 68% of the participants request their company to take primary responsibility for subject specific training in the context of Sustainable Development, which stands in conflict with the low overall responsibility (20%).

5 Conclusions

By 2025 digitalization (83% agreement) and sustainability (78% agreement) will be even more instrumental elements of Sustainable Development in Germany's chemical industry than today, as the results from the empirical survey among 60 chemists suggest. 70% agreement to the hypothesis "Digitalization is a driver of sustainability" and the in-depth evaluation of respondents' comments reveal key input for Corporate Digital Sustainable Responsibility.

Firstly, there is no quantitative correlation between the importance of digitalization and sustainability by 2025 and the ability of digitalization to drive sustainability. Secondly, chemists already have an extensive repertoire of ideas supporting Corporate Digital Sustainable Responsibility and counter arguments impeding it. Thirdly, there are major concerns regarding scope and maturity of digital and social responsibility competences required for Sustainable Development.

A balanced technology-, people-, and society-oriented Corporate Digital Sustainable Responsibility is required to drive the process of Digital Sustainable Development, which, in turn, helps to achieve Digital Sustainable Development Goals.

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Appendix

Table A1 Digitization and Sustainability questionnaire (source: own representation, 2019).

How do Digitalization and Sustainability match in the Chemical Industry? CHEM4CHEM

1	**Digitalization is a driver for sustainable development** *(degree of agreement, %)*									
2	**The following approaches are *suitable or required* for 1)** *(examples, comments):*									
3	**The following obstacles are *working against* 1)** *(examples, comments):*									
4	**Indicate who is *responsible for the objectives and scope* of digital and sustainable development** *(degree of agreement in % for each option, not additive)*									
	Politics (government, parties)		**NGO** (consumer organizations, MoreThanDigital.info, Greenpeace)		**Education** (university, university of applied sciences), professional education company)		**Employer organizations** (association of chemical employers)		**Employee organizations** (trade unions)	
	Associations with corporate members (VCI, VFA, CEFIC)		**Associations with personal members** (GDCh, VDI, DECHEMA)		**Enterprise** (management, training department)		**Functions within enterprises** (departments, staff positions)		**Individual employees** (blue collar, white collar)	
5	**Indicate who is *responsible for the education/ training* of digital and sustainable development** *(degree of agreement in % for each option, not additive)*									
	Politics (government, parties)		**NGO** (consumer organizations, MoreThanDigital.info, Greenpeace)		**Education** (university, university of applied sciences), professional education company)		**Employer organizations** (association of chemical employers)		**Employee organizations** (trade unions)	
	Company associations (VCI, VFA, CEFIC)		**Associations with personal members** (GDCh, VDI, DECHEMA)		**Company as such** (management, training department)		**Individual functions within a company** (departments, staff positions)		**Individual employees** (blue collar, white collar)	
6	***Digitalization* will play an important role for chemists by 2025** *(degree of agreement, %)*									
7	***Sustainability* will play an important role for chemists by 2025** *(degree of agreement, %)*									
8	**Indicate *sustainable development training needs* by subject** *(degree of agreement in % for each option, not additive)*									
	Politics		**Chemical industry**		**Enterprise**		**Individuals**		**Attitude**	
	Areas/ departments within a company		**Methodology and approaches**		**Elsewhere** *a) (%)*		**Elsewhere** *b) examples, comments*			
A	**Indicate, whether your company/ university is a …:**									
	Corporation		Large company		Medium-sized company		Small-sized company		University/ University of applied sciences	
B	**Indicate your highest academic degree:**									
	Professor		Ph.D.		Master/ Diploma/ 2nd degree		Bachelor/ First degree		Non academic qualification	
C	**Indicate your hierarchical/ leadership position:**									
	1: Board, Managing Director, Executive VP		2: Functional head, Senior VP		3: Department Manager, Program manager		4: Team leader, Lab manager, Project leader		None	
D	**Inidcate the years of professional experience** (after latest graduation):									
E	**Comments:**									

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Practitioner's Section

Decarbonization strategies in converging chemical and energy markets

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Transforming the chemical industry to carbon neutrality requires abundant and cheap renewable energy as well as synergies and flexibilities from a convergence of the chemical and energy markets. Decarbonization strategies need to manage technical, financial and stakeholder requirements in an uncertain, volatile and ambiguous regulatory and socio-political environment.

1 Introduction

Today's chemical industry is built on fossil hydrocarbons, which are used as feedstock and a source of energy. The industry is a significant contributor to human made greenhouse gas (GHG) and carbon dioxide (CO_2) emissions. Via national and European associations, the chemical industry has communicated the goal to become carbon neutral by 2050 at the latest (Stoy, 2019). Higher energy and resource efficiencies, using bio- or waste-based feedstocks and circulating materials are activities currently being undertaken. However, all of this covers only about 40% of the emission reduction goal. The remaining 60% requires abundant, cheap renewable energy and a convergence of the chemical and energy markets. The higher the synergy and flexibility of this convergence, the less carbon-capture utilization (CCU) and sequestration (CCS) is needed to achieve emission targets. A smart utilization of synergies between chemical and energy markets could go well beyond the implementation of new climate standards and beyond the borders of the chemical industry. The chemical industry is the critical linking pin between natural resources and energy and the downstream industrial and consumer applications. Rather than being part of the emission problem it could become the engine to build decarbonized supply chains from natural resources to consumers and the creator of a new, differentiating, green and intersectoral "Verbund" in Europe.

2 Current situation — almost 10% of GHG/CO_2 emissions created by the chemical industry

In 2018, 85% of the global energy supply was based on fossil hydrocarbons, especially crude oil, natural gas and coal (IEA WEO and Statista, 2019). Those fossil hydrocarbons contain high concentrations of carbon - 75% of natural gas, 86% of crude oil and 96% of coal (IPCC, 2006). By combustion, utilization and potentially second use of fossil hy-drocarbons, practically all carbon will ultimately end up as carbon dioxide (CO_2) in the atmosphere. There is a widely accepted consensus (COP 21, UNFCCC, 2015) that human-made CO_2 emissions from fossil hydrocarbons are the major source of greenhouse gas emissions and thus global warming and climate change. Until 1971 oceans and vegetation could completely compensate for the human made emissions. In 1990 the earth overshoot day was December 7th and in 2019 it was already on July 29th. This discussion is not new, but started more than two decades ago, when 192 parties signed the Kyoto Protocol (Kyoto Protocol, 1997).

However, reality is very different from those agreements and ambitions (IEEJ, 2018; IEA 2018; Jacob 2019; OPEC 2018). Predictions forecasted much more energy and resource efficiency activities and a global energy demand growth below 1% per annum. In 2018 and 2019 energy demand has grown more than 2% per annum, which is almost in line with the growth rate of global gross domestic product. Even more concerning is the fact that more than two thirds of the new energy supply additions are based on fossil hydrocarbons (Deloitte 2019a; IEA 2019; CNPC 2018; Equinor 2018, Shell 2019).

This does not at all match the COP21 climate targets. The latest congress in December 2019 in Madrid (COP25) has shown that countries that have strong oil, gas or coal industries, such as the United States, Brazil, China, India, Saudi Arabia or Australia, are resisting change.

In order to achieve the 2030 greenhouse gas (GHG) emission targets and to limit global warming to 1.5°C, energy consumption would need to be reduced drastically. We are talking about an order of magnitude of the energy consumption of the whole of Europe and the United States together. This is unlikely to happen in the next decade. Just the opposite: decarbonization activities in many sectors will demand much more renewable energy. However, we are often too optimistic about what we can achieve in the shorter term, but are too pessimistic about what we can change longer term (Amara, 1978). Those changes typically come exponentially. Just think about the lengthy discussions and ultimately very effective ban of fluorocarbons to fight ozone layer depletion.

Almost three quarters of the 2018 energy demand growth and global greenhouse gas emissions come from China (33%), the United States (29%) and India (11%) (IEA, 2019). Forty percent of the energy is used for power generation (electricity and heat), followed by transportation (23%, planes, vehicles, ships) and industry (21%, especially iron and steel, cement, chemicals and fertilizers, refineries, non-ferrous metals, ferroalloys and silicon, pulp and paper, ceramics, lime and glass). Statistics show a sector view within the four walls of each industry, neglecting the interlinkages. In order to cover the full carbon footprint, it is more advisable to have a usage or application view that reaches back all the way to the natural resources being used. This would mean that we look at the carbon footprint of housing including heating or cooling, mobility of people and goods, food chains from farm to plate, healthcare, communications, clothing, leisure and sports, etc. Individual carbon footprint calculators, like those offered by WWF, TerraPass, ICAO, EPA, Climate Care or CarbonTrust, do exactly that. They all have different scopes of which categories and emissions are included and which are not. There is no commonly agreed upon emission data set, but the carbon footprint calculators directionally point at the most relevant emissions and ask for appropriate actions.

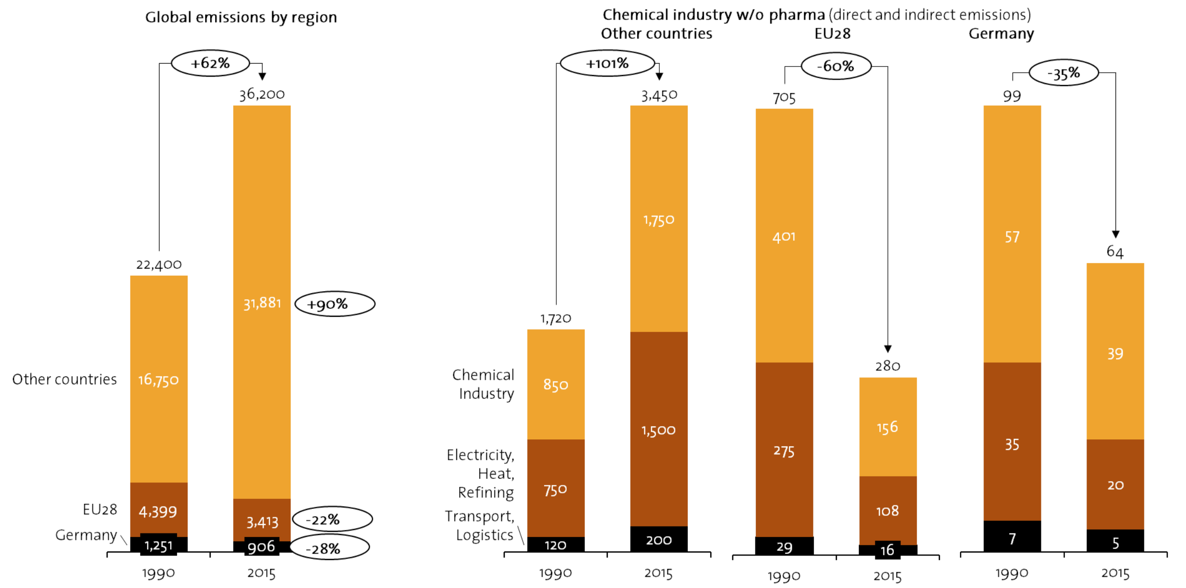
When looking at the climate impact of the chemical industry, we suggest to do the same and look at the application of chemicals and materials from natural resources to consumption. This means to not only look at scope 1 emissions (WIR/ WBCSD, 2019) from chemical operations, but also scope 2 emissions from imported energy and scope 3 emissions from purchased products, transportation and application and usage of chemicals and materials. This broader view helps to identify sustainable, climate-friendly applications and those, where other solutions are preferable. However, it is not always easy for a producer of chemicals or materials to know enough about all relevant applications or to be able to steer demand into certain application areas and avoid others. Thus often the producer and product perspective is taken as a pragmatic shortcut. By doing that, the chemical industry is often seen as part of the emission problem rather than an obvious part of the solution, i.e. any decarbonization strategy or abatement of emissions needs the chemical industry to succeed. The chemical industry is the crucial linking pin to carbon neutrality. It transforms natural resources and energy into industrial and consumer products and solutions. It is appropriate to show the avoided GHG/CO_2 emissions through precision applications, insulation, electrification, renewable power generation and distribution, lightweight materials and chemicals rather than other material alternatives. In any case, we recommend to consider the GHG/CO_2 emissions within four walls plus indirect emissions from transport, third-party energy and feedstock supply. By doing that, the chemical industry's GHG/CO_2 emissions are almost 10%, which is nearly double the numbers found in most statistics.

Between 1990 and 2015, those emissions more than doubled globally (Figure 1) and with the chemical industry growing at 1.5 times the rate of global GDP (CEFIC, 2020), the sector's CO_2 emission share is likely to further increase in the future. More than 85% of current investment decisions in the chemical industry are in favor of fossil hydrocarbons, while less than 15% of global investments are currently in favor of renewables (bio- or waste-based), recycling (mechanical and chemical) or energy and resource efficiency improvements. Boards are currently struggling to dedicate more money to green investments, as they typically have lower returns than fossil hydrocarbon-based ones.

When looking to Europe/ EU27 or, more specifically, Germany, we see different dynamics (Wachsmut 2018; Wyns 2018). In Germany, the chemical industry´s share of CO2 emissions has decreased significantly over the past few decades despite more output and value creation (VCI, 2019c).

Germany has a much higher share of rene-

Figure 1 CO2 emissions 1990 and 2015, globally and for the chemical industry [in million metric tons] (source: VUB - IES, CEFIC, Statista, VCI, Deloitte, 2019c).



wable electricity sources, in 2018 at 38% compared to 4% globally (UBA, 2019). Until 2025 the renewables share is expected to be 40-45% (Bmwi, 2019). However, this reflects electricity, not heat, which is an important energy source for the chemical industry. The European and German chemical industries have accelerated energy and resource efficiency actions, moved selectively to bio- and wastebased materials, and are exploring opportunities related to mechanical and chemical recycling of materials (VCI, 2019). However, the bulk of the impact is due to the fact that the European and German chemical industry is becoming less and less competitive in producing organic and inorganic building blocks. These building blocks account for more than three quarters of the energy and CO_2 intensity and also emissions of the industry, but cover only 40% of revenue (Figure 2).

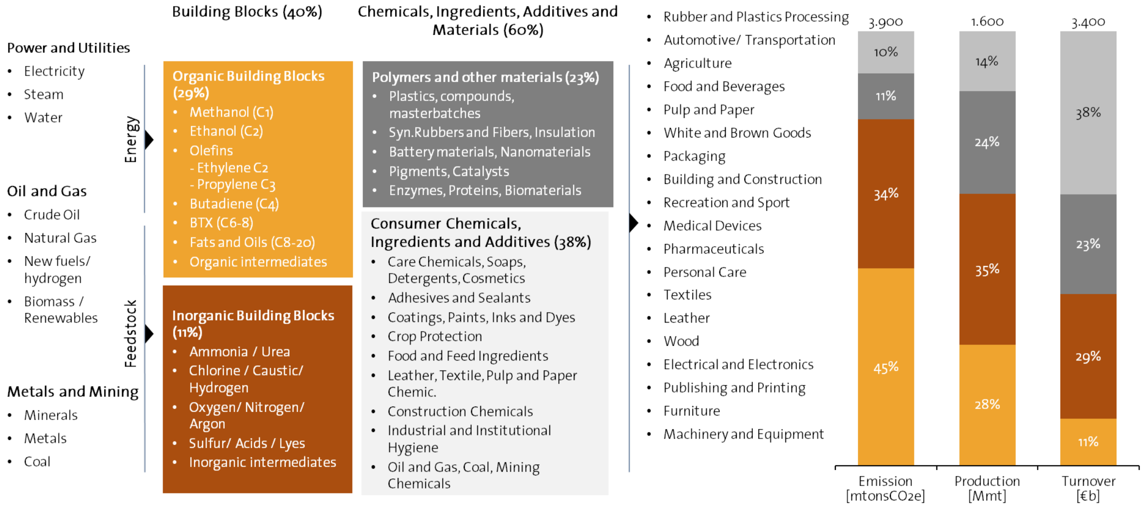
By shortening the value chain, we have become greener in Europe and Germany. However, the climate does not care if GHG and CO_2 emissions are generated inside or outside the EU or Germany. And thus, the question is: How long can we sustain a high-value-creating European and German chemical industry without being backward integrated into feedstocks? There is a widely shared view that further cutting the roots of the European and German chemical industry by importing energy- and CO_2-intense building blocks cannot be the solution. Doing so would not contribute to meeting global climate targets and would further endanger the sustainability of the integrated downstream structures of specialty, fine and consumer chemicals as well as materials, whether plastics, rubbers, fibers, catalysts, batteries, packaging or others.

It is a fact that the chemical industry in Europe is losing global competitiveness (CEFIC, 2019) especially in the backend of basic building blocks and petrochemicals, despite its absolute revenue, value and export growth. In 2007, EU28 accounted for more than 27% of the global chemical industry. In 2018, it accounted for less than 17% in spite of 0.7% p.a. absolute growth.

3 Climate protection — a societal challenge

The perception of sustainability as a costly luxury has changed irrevocably, especially in

Figure 2 CO2 emissions, production and turnover global chemical industry (w/o pharmaceuticals) (source: CEFIC, VCI, IHS, Statista, Deloitte 2019).



the past 12-18 months. With the energy transition well underway, the financial risks and opportunities of de-carbonization are now an imperative for consideration at the board level. The political and societal discussions around climate protection and carbon neutrality are captured in the form of climate and emission targets, especially in Europe and Germany.

The energy intense industries, which include base chemicals and fertilizers, are currently more defensive and see short-term cost increases and much higher energy consumption with higher carbon dioxide, raw material and energy prices that are able to destroy the competitiveness of the European energy-intensive industries (VCI, 2019d). At the same time the direct and indirect customers of the chemical industry are already taking action on decarbonization and signed up for initiatives such as the RE100 (https://there.100.org) or the B Team (https://bteam.org). Specialty chemicals and consumer chemicals companies like Akzo, BASF, Bayer, Corbion, DSM, Givaudan, IFF and LANXESS are starting to follow the trend. This may have more stability and longevity than any political trend.

At the same time investor pressure is being exerted on chemical companies to disclose their climate risks with respect to transition risk (winning or losing product portfolio, carbon pricing, stranded assets, etc.), regulatory risks (regulations, license to operate, etc.) and physical risks (damaging weather events, low or high water levels influencing logistics, etc.). Under a range of future scenarios, the impacts on companies´ earnings over the next 10 to 20 years can flag material potential writedowns. While this pressure is currently mostly being felt by the global companies, from the investor pressure combined with the increasing community expectations, chemical companies at the national level are likely to experience the same within the next year or two.

The change is rapid and the biggest risk for organizations is to be blindsided. There are however also significant opportunities for those that are innovative. There is a nascent demand for "green" or carbon neutral products and solutions across the economy and in export markets.

On December 11, 2019 the European Union presented a "Green Deal" that will enable the EU to become the first climate neutral continent by 2050 (EU, 2019). It foresees the supply of clean, affordable and secure energy and a mobilization of several industries for a clean and circular economy. The focus is on cities that account for two thirds of energy consumption and more than 70% of greenhouse gas emissions.

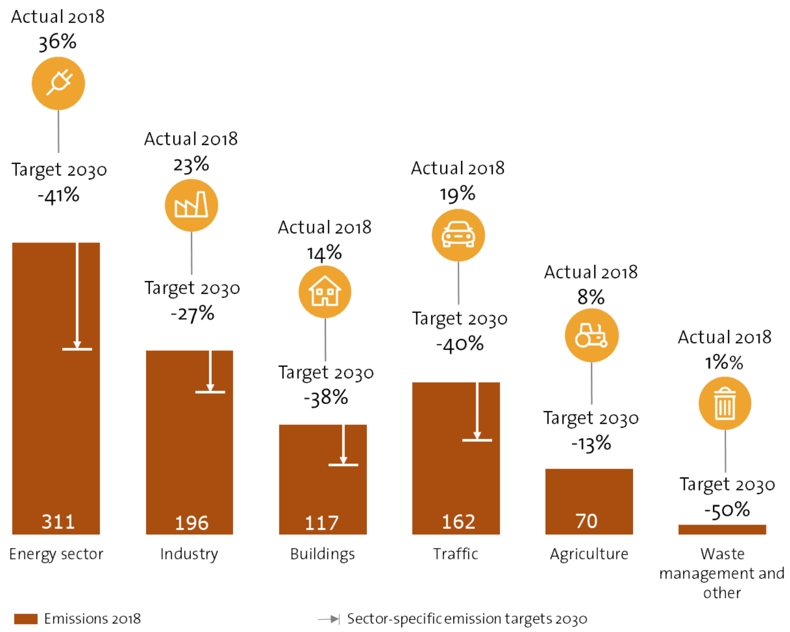
Some countries are starting to define sector-specific emission targets based on the European emission framework (Figure 3). They will be achieved by 2030 and are based on 2018 actuals.

In Germany, for instance, the energy sector contributed 36% of CO_2 emissions in 2018. Industry (23%), traffic (19%), buildings (14%), agriculture (8%) followed. Specific reduction targets of 41% for the energy sector and 23% for the industry sectors have been defined. Note that those politically determined, sector-specific emission reduction targets neither facilitate cross-sector synergies nor do they reflect the convergence of the energy sector with other industries.

Moving from fossil hydrocarbon to renewable energy generation has the biggest emission reduction impact in absolute terms. This might be easily overcompensated by a much higher demand for renewable energy. Wind and solar are the typical renewable energies in Germany that substitute nuclear and fossil hydrocarbon energies. However, smart grids, buffers and storage technologies are needed to secure reliable power generation. An integration with mobility (power-to-fuels), heating (power-to-heat) and industrial sectors (power-to-products) can help to achieve the set targets.

Industry is the second biggest user of energy in the form of electricity and heat in Germany. Unlike other energy-intensive industries, the

Figure 3 Sector-specific CO2 emissions 2018 and 2030 emission targets in Germany [in million metric tons] (source: Bundesregierung, 2019; UBA, 2019).



chemical industry has a dual challenge. It is faced with the substitution of fossil hydrocarbon-based generation of electricity and steam and fossil hydrocarbon feedstocks. Crude oil and to a lesser extent natural gas and coal are by far the largest feedstock suppliers of the chemical industry. While demand for crude oil for heating and mobility applications is starting to decline, demand for chemical applications is growing strongly. Direct Crude Oil-to-Chemicals (COTC) technologies have the potential to merge refining and petrochemicals and more than double the value that can be unlocked from a barrel of crude oil (IHS, 2019; Dickson, 2019). However, Asia, the Middle East and the US Gulf Coast are the primary regions to build and use these technologies.

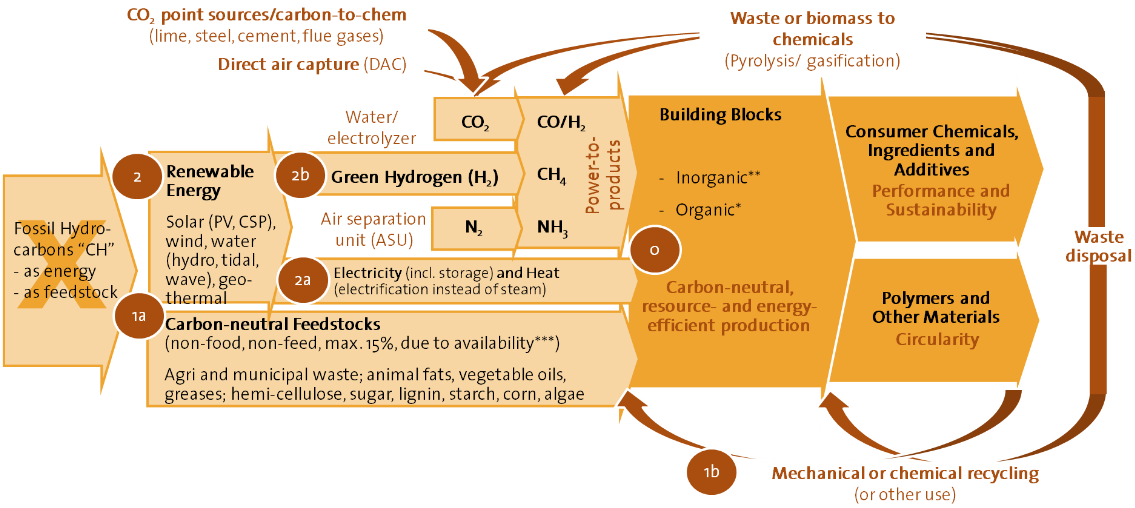
4 Decarbonization options — efficiency, carbon-neutral feedstocks and circular flows are insufficient to meet emission targets

In spite of the achievements already made by the chemical industry in Europe and Germany, more work is required to meet the European and German climate targets (Simon 2019). In order to achieve those targets, the industry has to avoid the use of fossil hydrocarbons, both as a feedstock and as a source of energy (Figure 4). Although it is not fully clear which activities will ultimately lead to achieving the climate targets (Günther, 2019), there are some obvious decarbonization options and pathways to consider.

Improvement of resource and energy efficiency (Figure 4, 0) in producing chemicals and materials has always been a key activity of the industry, but further improvements are possible by using digital tools.

The net effect of energy and resource efficiency activities is about 4% (Figure 5, 0). The gross effect is potentially much larger, but digitalization leads also to a dematerialization. This means that chemicals and materials can be used much more effectively, which reduces the specific chemical or material consumption. Pre-

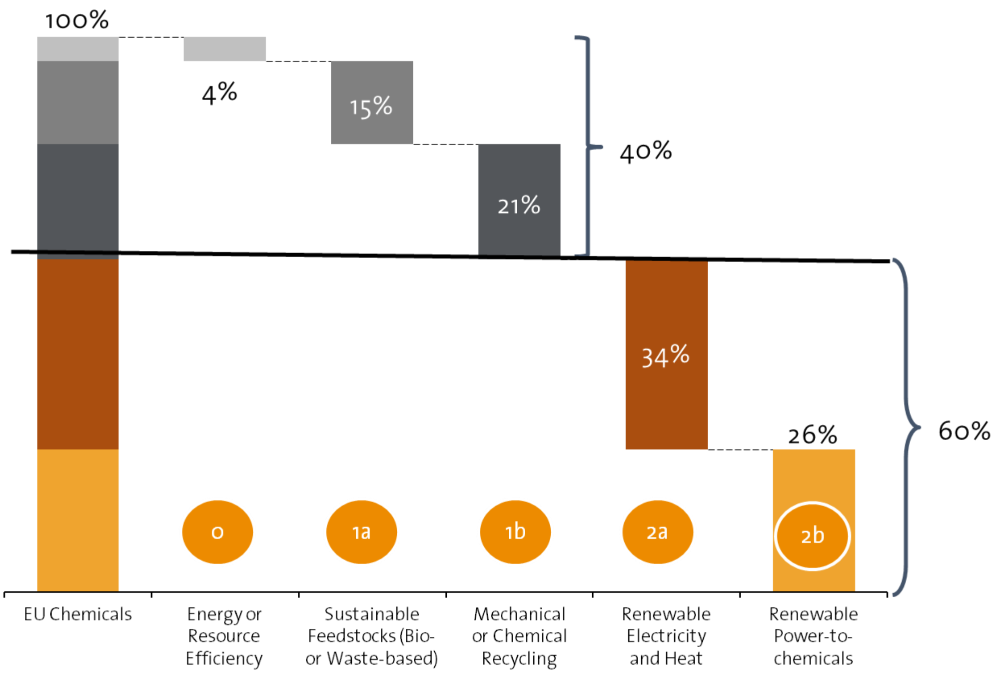
Figure 4 Options for the chemical industry to reduce CO2 emissions in the production of building blocks* (source: Deloitte, 2019c).



* Organic building blocks contain olefins (ethylene/propylene), butadiene, BTX (benzene, toluene, xylenes), fats and oils, methanol, ethanol
** Inorganic building blocks contain ammonia, urea, sulfur, hydrogen, industrial gases, acids, lyes, chlorine, caustic, soda
*** Chemical feedstocks compete with biofuels, but are also limited due to soil erosion, water shortage, land use, biodiversity, transport/logistics and pesticide and fertilizer usage

Note: Sector coupling CO2-relevant, but not shown here

Figure 5 Emission reduction opportunities towards a climate-neutral, fossil hydrocarbon-free chemical industry [CO2 emissions in % of CO2e reduction potential] (source: Deloitte, 2019).



cision farming, personalized food or medicine or 3D/4D printing of materials are examples where up to 40% less material or chemicals are needed to fulfill the same purpose. This comes with a significant emission reduction, at least before rebound effects. However, specific efficiency gains are easily overcompensated by much higher absolute energy demand. Additionally, the reduction is taking place in the application and not the production of chemicals and materials. Thus the effect is included in a lower demand growth and is not calculated a second time as an efficiency driver and contributor to emission reduction.

A much bigger effect of up to 15% emission reduction can be expected using sustainable feed-stocks (Figure 5, 1a). Sustainable feedstocks are either waste- or bio-based and can include plant or animal fats, sugar, lignin, hemicellulose, starch, corn and algae. It is likely that sustainable feedstocks will play an increasingly important role in the production of bio-based chemicals like alcohols, organic acids and polyesters. However, the use of sustainable feedstocks is also limited due to competition with food, feed, biofuels and bioenergy applications as well as physical limits imposed by soil erosion, water shortage, land use, reduced biodiversity and the use of agrochemicals. Another limiting factor is the typically low resource and logistics efficiency. For instance, to produce 1 ton of methanol, it takes 2.5 tons of lignocellulose or 8 tons of sugar and transportation of the raw materials over long distances.

Another pathway to avoid the production of virgin materials (e.g., polymers, rubbers, fibers, catalysts, batteries, packaging materials, solvents, heat transfer fluids and lubricants) is the closure of material loops (Figure 5, 1b). This can happen through reuse, mechanical or chemical recycling or alternative uses in other applications. An additional positive effect is the avoidance of uncontrolled littering (e.g., of single-use plastics).

If circular logistics, material separation and recovery are feasible, this is often the best solution to support climate neutrality. Note that circularity does not necessarily mean producing the same product for the same application again. Often, it is more effective and efficient to make other products or use the original product in other applications, such as employing wind blades as additives for construction materials or giving lithium-ion batteries of electric vehicles a second life in stationary applications before recycling them. However, all those materials make up only a bit more than 20% of the chemical industry. Thus, the impact is also limited to that order of magnitude, even if almost all materials would be reused or recycled.

Overall, we can probably achieve 40% of the chemical industry´s long-term emission target by maximizing energy and resource efficiency (Figures 4 and 5, 0), using sustainable bio- or waste-based feedstocks (Figures 4 and 5, 1a) and running materials in circles (Figures 4 and 5, 1b) to prevent them from leaking into the environment. So far so good, but what about the remaining 60% (Figures 4 and 5, 2) of the emission reduction target?

5 Abundant and cheap renewable energies are a prerequisite for full decarbonization

Abundant and cheap renewable energy is a prerequisite (Figures 4 and 5, 2) for achieving the remaining CO_2 reduction target. The cost of many renewable technologies are plummeting. Solar photovoltaics (PV) have decreased in price by 80% since 2008 (Lazard, 2019), more than wind power or other renewables. Renewable energy is already today the cheapest way to generate a unit of electricity and its advantage against fossil fuels, nuclear and other energy sources is likely to further increase in the future. Low unit cost is a good starting point, but it needs to be complemented by a secure supply also in cases when the sun does not shine and the electricity has to be transmitted from where it is generated to where it is consumed.

A total of 34% of current fossil hydrocarbon-based emissions result from energy generation (electricity and heat) (Figure 5, 2a), either by third party energy providers or within the chemical industry, and a smaller part from the transportation of feedstocks, chemicals or materials. A full substitution of fossil hydrocarbons with renewable energies like solar (PV – photovoltaic or CSP – concentrated solar power/ solar thermocycle), wind power, bioenergy, waste-to-energy, heat pumps, energy storage, hydro power (tidal, wave) or geothermal energy is needed in order to become climate neutral. Nuclear power might also fall into that category, but not in Germany, where there has been a political consensus to move away from that technology.

An electrification of transportation and chemical processes is needed. On the transport side, electrification becomes less attractive the longer the distance, the heavier the load and the faster the means of transportation. Biofuels for trucks, ships and especially planes are an alternative route towards carbon-neutral transportation. Longer-term hydrogen might serve as a direct fuel for planes. For chemical processes, electrification is technically feasible, but it becomes increasingly inefficient and energy-intensive to electrify processes that operate above 400°C or below -150°C. Furthermore, electric heating of a gas or naphtha cracker requires about three times more energy than using natural gas, liquefied petroleum gases or naphtha. It is also much more difficult to create energetic synergies between endothermic and exothermic processes ("heat Verbund") with electricity than with steam. Currently, chemical processes are often heated via natural gas-based cogeneration of power and heat. This is a very efficient process, but creates climate-relevant CO_2 emissions.

The share of renewable energy generation in Germany, Austria and the Nordic and Baltic countries currently exceeds 38% (Bmwi, 2019), but this is not true for most of the rest of Europe and certainly not for most regions outside of Europe (Motyka 2019). Buffering renewable energy both short- and long-term, as well as distributing the energy to areas where it is really needed, are still inefficiencies that people are currently trying to overcome. Chemicals like chlorine, ammonia, hydrogen and methanol are potential chemical buffers that could be used to store abundant renewable energy.

The remaining 26% (Figure 5, 2b) of emissions is the toughest to reduce, because this requires the substitution of fossil hydrocarbon-based feedstocks with climate-neutral feedstocks that do not result from waste, biomass or circularity. The carbon part is relatively easy to solve. There are currently enough point sources of CO_2 available from the lime, steel and cement industries and other flue gases. In the future, direct air capture will potentially become an option, if prices come down from the current high point of 500 €/ton of CO_2. Carbon Engineering, Climeworks, Global Thermostat and other pioneers in Direct Air Capture technologies are optimistic to get costs down to 100-250 €/ton of CO2.

The primary issue is climate neutral hydrogen. Currently, hydrogen is produced from natural gas via steam reforming (48%), crude oil in refineries (30%), coal gasification (18%) and as a by-product in the production of chlorine via electrolysis of salt (4%) (GVR, 2018). Thus, 96% of hydrogen is currently made from fossil hydrocarbons ("grey hydrogen").

If climate neutral hydrogen was available, we could produce syngas/ methanol and ammonia and ultimately the nine key chemical building blocks (chlorine, ammonia/urea, methanol, ethylene/propylene and benzene/ toluene/xylenes) that make up more than half of the chemical industry's overall CO_2 emissions (power-to-products) (Figure 6).

There are three major routes to climate-neutral hydrogen (Figure 7): via steam reforming plus CCU/CCS („blue hydrogen"), via methane pyrolysis (or pyrolysis of other hydrocarbons or waste) - ("turquoise hydrogen"), or via water electrolysis (solar thermocycle and other

Figure 6 CO2 footprint of major products/ product groups in the chemical industry 2015 [million tons of CO2e] (source: Bazzanella, 2017; Deloitte, 2019a).

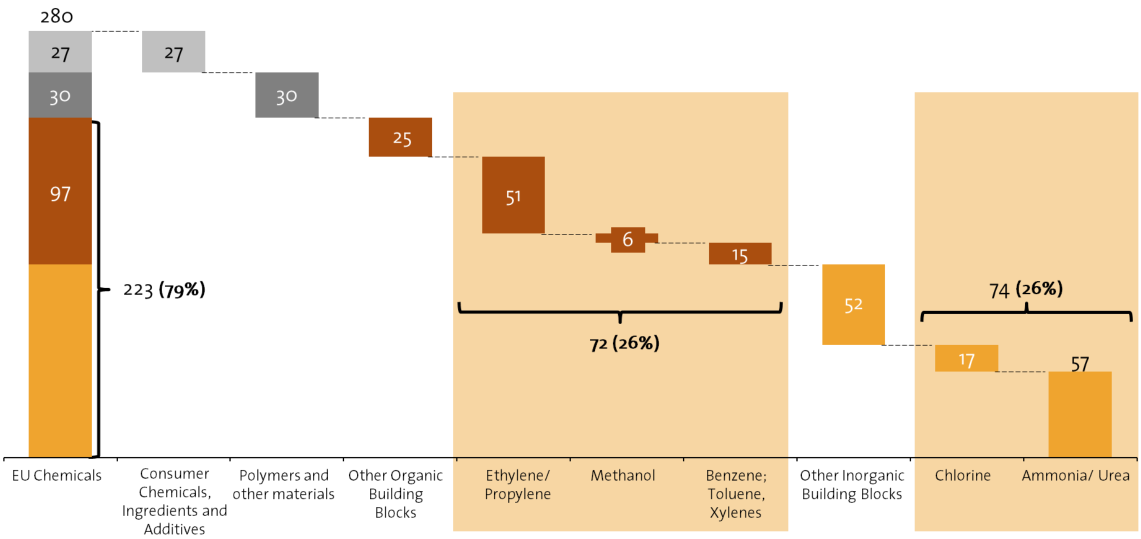
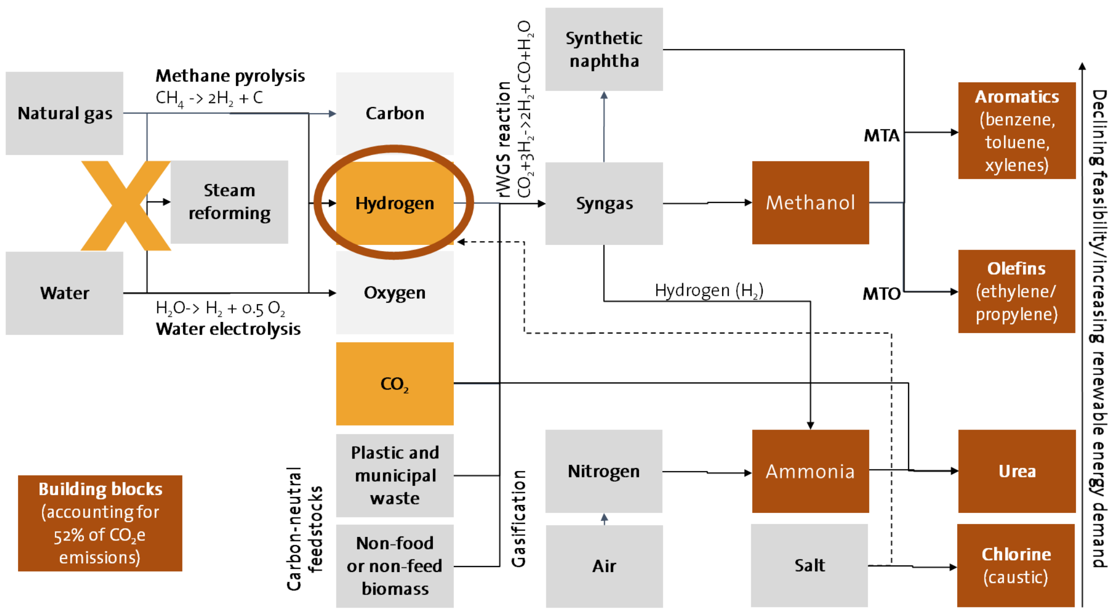


Figure 7: Climate-neutral, fossil hydrocarbon-free building block production (source: Deloitte, 2019c).



experimental routes excluded) - “green hydrogen”.

Steam reforming is energetically and thermodynamically the best option to produce hydrogen. However, it generates CO_2 which needs to be stored or used. This makes the whole process not really carbon neutral and there is already a lot of criticism about calling „blue hydrogen“ a climate or carbon neutral synthesis route.

The issue with methane pyrolysis is that it produces only half as much hydrogen per molecule of natural gas as the current process of steam reforming. Further, and importantly, it produces three times as much carbon black as hydrogen. What to do with all the carbon black?

(BFI, 2019)

Thus, the environmentally preferred route is the electrolysis of water to produce hydrogen and oxygen. End-to-end efficiency is only around 30% currently and reliability is relatively poor, but the process is being worked on and technological progress can be expected.

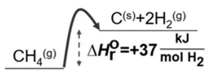
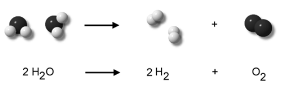
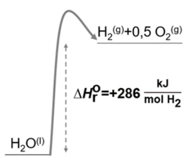
Unfortunately, this environmentally preferred route towards carbon neutral hydrogen is the thermodynamically poorest pathway since more than 10 times as much energy is needed to produce hydrogen from water compared to steam reforming, where hydrogen is made from natural gas (Figure 8).

This is not surprising since water as well as air or carbon dioxide are very stable molecules with a very low energy level. However, fossil hydrocarbons already bring a high level of energy with them intrinsically. As it is about thermodynamic stability and energy differences, there is not much that technological progress could change about that thermodynamic fact. Thus, only if renewable energy is abundantly and cheaply available, the water electrolysis route towards "green hydrogen" can become economically feasible.

Currently, it is hard to imagine how to make those green routes that consume enormous amounts of renewable energy, cost competitively in comparison to existing routes. We are not looking at 10-20% cost increases, but 4-6 times the current costs of producing chemicals from fossil hydrocarbons. This also means that we would need much more renewable energy. We are talking about 60% of the current European and 100% of the German energy demand today to cover only the energy needs of the chemical industry in Europe or Germany respectively to become carbon neutral.

In the past 20 years about 253 megawatts of "green hydrogen" capacity were built globally. Wood Mackenzie projects an almost 13 times as high growth in the coming five years until 2025. We share the long-term optimism about "green hydrogen", but currently, at the beginning of 2020, we do not see the needed return on capex logic of those investments (Wood-Mackenzie, 2019).

Figure 8 Energy demand for different hydrogen synthesis routes [kJ per mol hydrogen] (source: Konoplyanik, Deloitte, 2019c).

	Reactions	Minimum energy demand	
Steam reforming of natural gas (Grey hydrogen); Steam reforming + CCU/ CCS (Blue hydrogen)	$CH_4 + H_2O \leftrightarrow CO + 3H_2$ $\Delta H_{295} = -206$ kJ/mol $CO + H_2O \leftrightarrow CO_2 + H_2$ $\Delta H_{298} = -41$ kJ/mol $CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$ $\Delta H_{298} = 165$ kJ/mol	$\Delta H_r^o = +27 \frac{kJ}{mol\ H_2}$	Steam reforming generates hydrogen from methane and from water (8 hydrogen per carbon)
Methane* pyrolysis (Turquoise hydrogen)	$CH_4 \rightarrow C + 2H_2$		Methane pyrolysis cleaves methane (4 hydrogen per carbon)
Water electrolysis (Green hydrogen)			Water electrolysis cleaves water (4 hydrogen, no carbon)

* Chosen as preferred pyrolysis feedstock with the highest hydrogen/carbon ratio (4/1) against biomass or even coal gasification, but even methane process produces three times more carbon black than hydrogenPEM = polymer electrolyte membrane, SOEC = solid oxide electrolyzer cell, AEM = anion exchange membrane Electrolyzer—esp. reliability needs further improvements

A good starting point for „green hydrogen“ applications are energy intense inorganics, like urea, chlorine or oxygen, before trying to make larger hydrocarbons, like aromatics, from „green hydrogen“. For the latter one should probably think about other CO_2-abatement options.

Depending on the future costs for carbon-capture sequestration (CCS) and utilization (CCU), it might be much more economical to apply those decarbonisation routes at the end of the life cycle rather than producing chemicals and materials from “green hydrogen”. CCS technology can reduce carbon dioxide emissions by up to 90%. This would increase hydrogen costs by about a third compared to current cost levels. Thus “grey hydrogen plus CCS” and “blue hydrogen” seem to be reasonable „bridge“ technologies mid-term, but probably not longterm, due to upscaling and supply logistics issues and the fact that they are not fully carbon free.

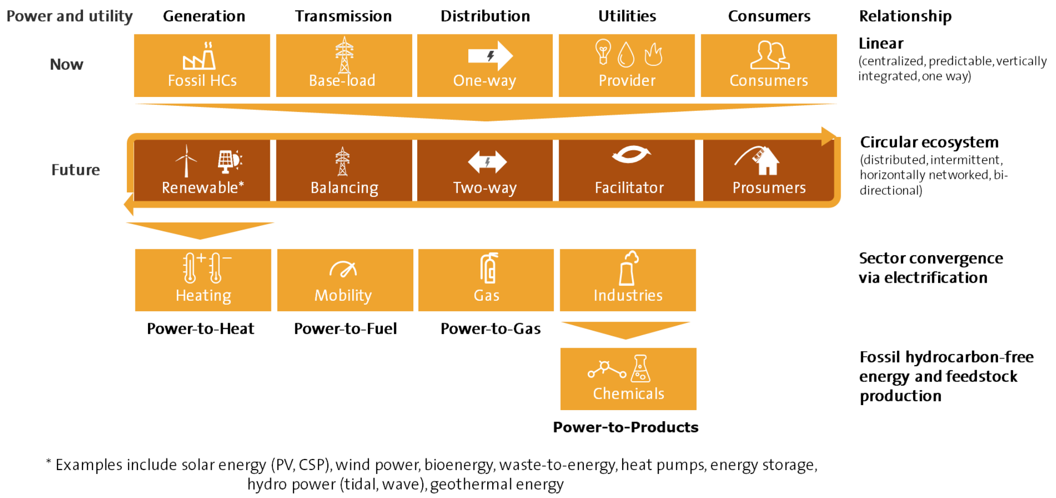
In the case of “green hydrogen” we are talking about the longer-term preferred route, but also multiple times the current hydrogen costs and huge energy demand. Additionally, we must evaluate whether it makes sense to use “green hydrogen” to produce chemicals and materials, or if the production of fuels or heat or storing electricity might be a better use.

The thermodynamic and cost discussion shows the social dimension and equality discussion around decarbonization. If costs of individual transportation and heating or cooling double, meat and milk prices quadruple and air plane tickets cost five to ten times as much as today, we will find ourselves in the midst of a socio-political equality discussion. The tension between those who can afford decarbonization costs and those who cannot will become much larger than the digital divide discussion about those who participate and benefit from digitalization and those who do not. This social divide will most likely spread across all societal groups and needs careful political management to avoid unrest or other unwanted side effects.

6 Cross-sector synergies and flexibilities can support renewable power-to-products

The mere substitution of fossil hydrocarbons to produce energy or feedstocks for the chemical industry is likely to stay uneconomical, even if fossil hydrocarbons are heavily

Figure 9 Transformation of the power and utilities sector, and integration with other industries (source: Schlaak, 2019).



taxed and if there is a high price for CO_2. It will be hard to find convincing and sustainable business models for this substitution. However, renewable energy is more than a supply chain change. It is a transformation of the whole industrial sector, which opens further opportunities.

Currently, power producers first burn fossil hydrocarbons, then transmit a base load to the utility provider and ultimately to the industrial customer or consumer (Figure 9).

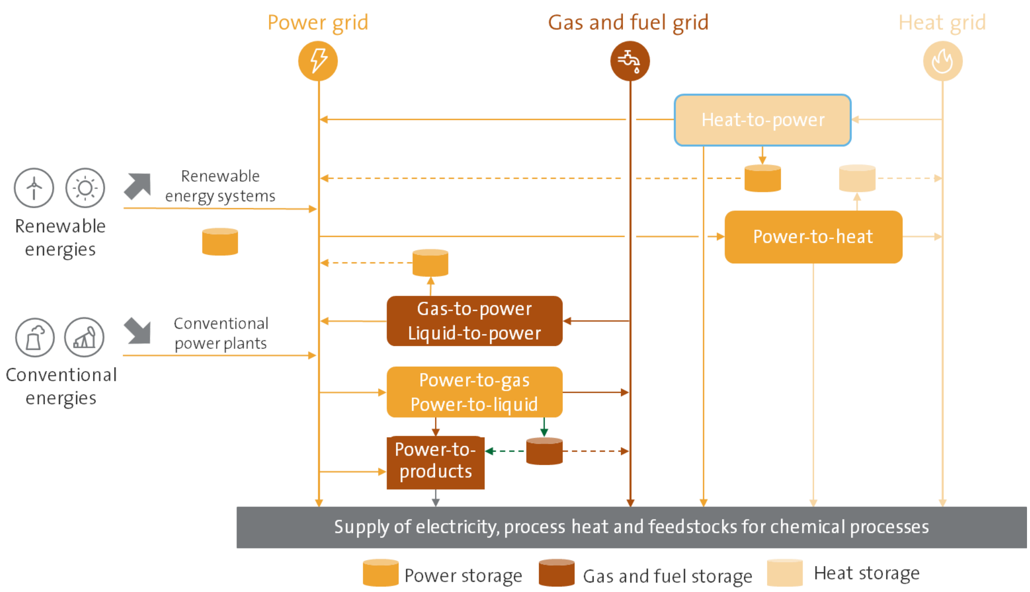
In the future, renewable energies will be balanced in a two-way fashion. Utilities are becoming facilitators to industrial or private prosumers. A centralized, predictable, vertically-integrated, one-way, linear business model becomes a distributed, intermittent, horizontally-networked, bidirectional and circular ecosystem. Via the electrification and, in the case of the chemical industry, renewable power-to-products routes, the industrial sectors from power and utilities via heating, mobility, gas and energy-intensive industries converge (Figure 10).

This enables cross-sector synergies and flexibilities, but also requires a multitude of renewable energy at affordable prices. The chemical industry, for instance, can help to buffer, store and optimize the fluctuating renewable electricity supply and demand by adjusting production levels in real time and/or using less power for the same production volumes and thermic or chemical storage. Optimizing this circular ecosystem by coupling the electricity, gas, fuel, heat and chemical grid can optimize production and reduce investment needs.

7 Control reserve market participation, interruptible loads and redispatch

The increasing share of renewable energies will lead to an increasing volatility of energy generation, which will be increasingly difficult to match with a fluctuating energy demand. Here, network operators need the support of other sectors to buffer, capture peak loads and avoid shortages. The chemical industry is the biggest single energy user and is earmarked to be a natural partner for the energy and utility sector. The starting point could be the supply of control reserve by transmission system opera-

Figure 10 Coupling of energy generation with electricity, gas, fuel and heat grids and power-to-products (source: Deloitte, 2019; Graf 2019).



tors (TSOs) to balance power fluctuations. Primary control reserve has to be available within 30 seconds, secondary control reserve within five minutes and minute reserves within 15 minutes (SMARD, 2019). This can be either positive (more supply, less demand) or negative (less supply, more demand) control reserve. Traditionally, this has been done by power plants. However, since July 2018, the minimum performance for secondary control reserve and minute reserve was reduced to 1 MW (megawatt), which allows energy-intensive industries to participate in the control reserve market, whether individually or pooled together with other participants. Like power plants, they are reimbursed for their readiness (capacity price) as well as for their contribution (energy price). From January to October 2019, 3.6 GW (gigawatt) of secondary control reserve and 2.4 GW of minute reserve power have been available in Germany, of which 2% and 8%, respectively, were actually retrieved (SMARD, 2019).

Fluctuating auction prices, available infrastructure and the type of chemical process determine on a case-by-case basis if participation in those control reserve markets is financially attractive or not. With increasing subsidies of up to 55% capex for climate-friendly investments and other direct and indirect support for energy efficiency and carbon neutrality, more and more co-investments are becoming economically attractive. Chlorine and hydrogen through electrolysis, air separation and industrial heat pumps/ thermal storage are products under investigation and pilot realization.

As an alternative to participating in the control reserve markets, the chemical industry can also participate directly in the grid by integrating large, energy-intensive assets (electrolysis, air separation, large heat pumps, cogeneration plants, etc.). Since 2017, market entry barriers for industrial power users have been lowered to a minimum supply performance of 5 MW (Kratzsch, 2018). Currently, 750 MW of immediately interruptible loads 'off' (automatically frequency-controlled within 350 minutes) and an equal volume of quickly interruptible loads 'off' (remotely controlled within 15 minutes) are tendered each week, but only 57% of the immediately and 98% of the quickly interruptible loads are being served.

Due to this unserved demand, capacity and energy prices have been 500 €/MW and 400 €/MW respectively. Interruptible loads are thus an interesting playing field for the chemical industry. As with the control reserve market, players need to be prequalified by TSOs. This is typically free of charge, but takes two to three months and internal efforts, like organization, planning and providing the necessary control and reporting technology.

The opposite interruptible loads 'on' are another area for feeding collaboration. In the first quarter of 2019, 3.3 TWH (terawatt hours) of power from EEG (Gesetz für den Vorrang Erneuerbarer Energien) and cogeneration plants had to be abolished in order to prevent bottlenecks in the distribution and transmission network. This primarily affected wind parks (77% on-shore, 22% off-shore). Their power supply control rate was 7% for on-shore and 11% for off-shore wind parks. The forced shutdown of EEG plants led to 364 € million in compensation payments to the operators. This loss of electricity production could also have been used to contribute to decarbonization and climate targets. 3.3 TWH of power could have produced 870 million Nm^3 of "green hydrogen" via high-temperature electrolysis.

This back-of-the-envelope calculation shows the potential for decarbonization. Instead of shutting down renewable power generation or over-investing in network bottlenecks, excess energy can be used to produce heat via cogeneration (power-to-heat) or "green hydrogen" (power-to-gas, potentially to-liquids or to-products).

The energy industry act (Energiewirtschaftsgesetz, EnWG § 13 Abs. 1 No. 2 EnWG and Ordinance on flexible loads, AbLaV) provides an existing regulatory and legal framework for flexible loads contracts between transmission network operators and chemical companies. Although the 2016 amendments (EnWG § 13 Abs. 6a) focus explicitly on power cogeneration technology, other technologies are not excluded.

Redispatching is another bottleneck activity of transmission operators, where power plants before the bottleneck have to reduce and those behind the bottleneck have to increase their power. This primarily affects hard coal power plants. In the first quarter of 2019, this equaled 5 TWH, with redispatch costs of almost 110 € million. Although here we do not ‘lose’ renewable energy, we generate high network costs, which are avoidable through intelligent sector coupling.

8 Decarbonization strategy

Why do chemical companies need to have a decarbonization strategy? It is essential for them to understand the climate risk embedded in their operations in terms of physical risk (extreme weather events, low or high water levels, etc.), regulatory risk (new legislation, license to operate, etc.) and transitional risk (portfolio changes, market trends, etc.). In parallel there is an increasing pressure from shareholders and other stakeholders to become more transparent on the climate risks and opportunities companies are facing. There are currently no generally accepted accounting standards on decarbonization and climate change. Michael Bloomberg´s Task Force on Climate-Related Financial Disclosures (TCFD) is one attempt among others to establish those standards. Chemical associations and large chemical companies are currently trying to define and agree upon those standards.

But companies should not wait for those standards. Until they exist and are agreed upon companies should leverage scientific information from leading bodies and methodologies, including the Intergovernmental Panel on Climate Change (IPCC), Representative Concentration Pathways (RCP), the International Institute for Applied Systems Analysis (IIASA), Shared Socioeconomic Pathways (SSP) and Science Based Targets (SBT) methodologies among others (Figure 11).

It is important to include at least the suppliers and customers, but ultimately we are looking at the decarbonization of the whole supply chain. This becomes a very interesting area, as not only energy and chemical sectors are converging, but there is also a new view to select and support decarbonization projects along the whole supply chain to ensure that they are meeting market demand. A project at a downstream user or a supplier of the chemical industry might have a much larger decarbonization impact per Euro invested than a project at the value step of the chemical production. This involves a new collaboration along the supply chain with suppliers, partners and customers. The chemical industry knows how to play and perform in „Verbund“ structures and has a crucial role in this supply chain perspective, as it is the linking pin between the natural resources and energy industries on the one hand side and connecting them with 96% of the downstream industries and users on the demand end, which cover almost all sectors one can think of.

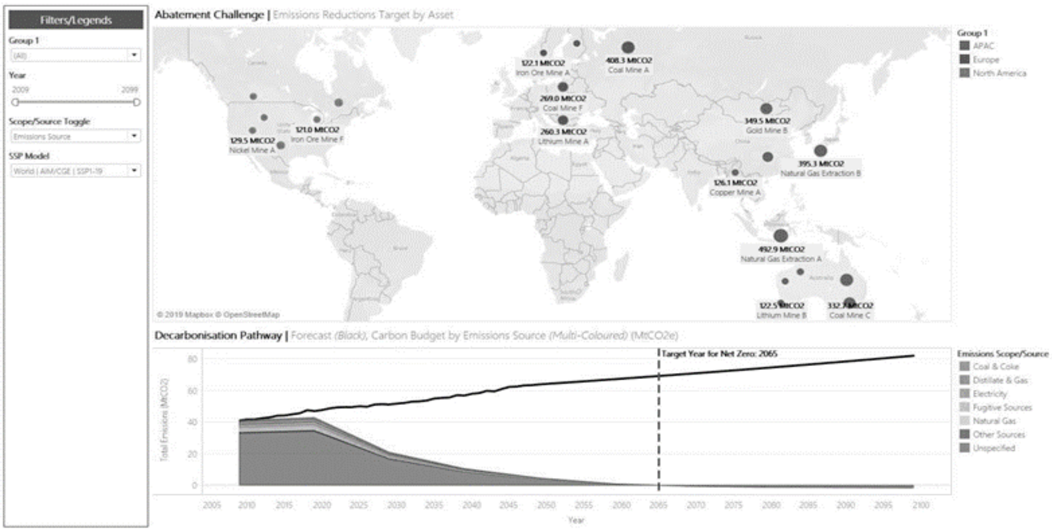
A decarbonization strategy and net zero emission plan can be developed in four steps:

Step 1: Understand the **abatement challenge** in the value chain **and** quantify your **emission gap**

- Understand climate risk under a range of future scenarios, how markets, revenues, profits and the asset values could be impacted.
- Define your current greenhouse gas/ carbon dioxide emission footprint, including external material and energy suppliers and transportation of chemicals and materials per product/ product group and asset/ site/ region.
- Understand the carbon footprint challenge of your customers and the role of your che-

Figure 11 Decarbonization Strategy: Abatement challenge, decarbonization pathways, scenarios and selection (source: Deloitte, 2019b; Liggins 2019).

Step 1: Abatement challenge and emission gap



Step 2: Decarbonization projects and pathway

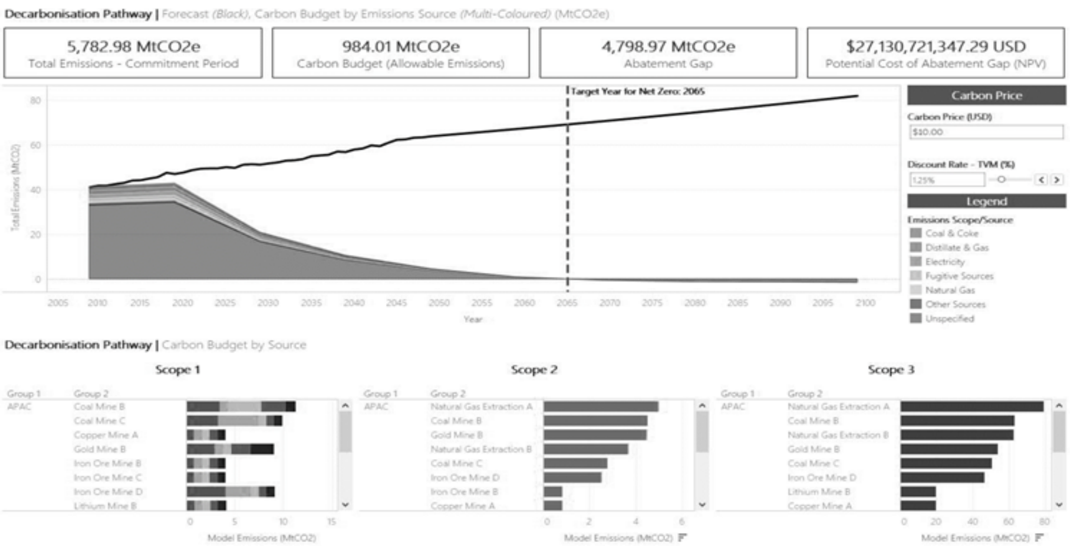
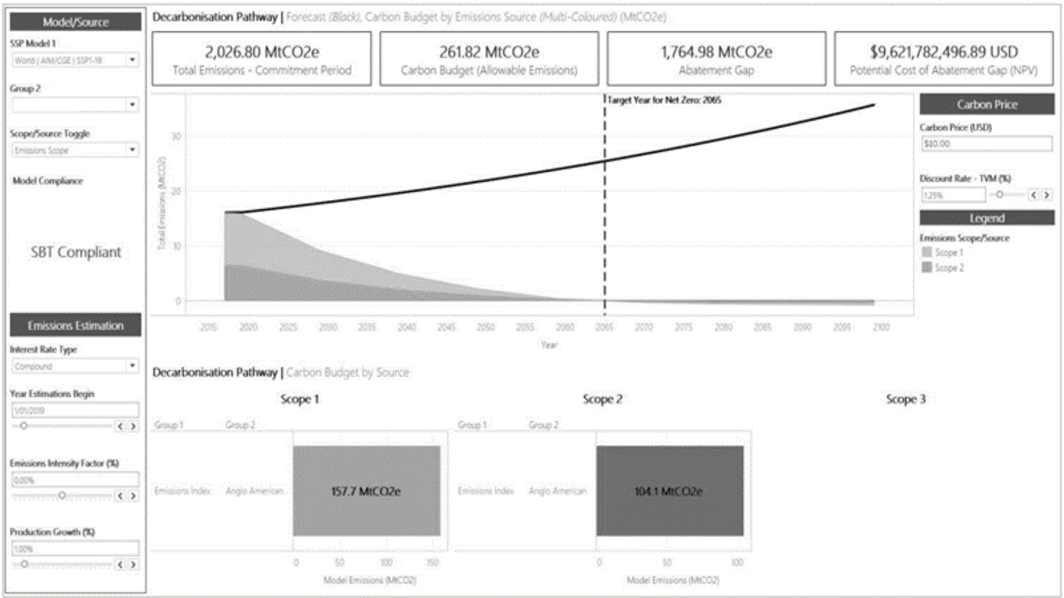
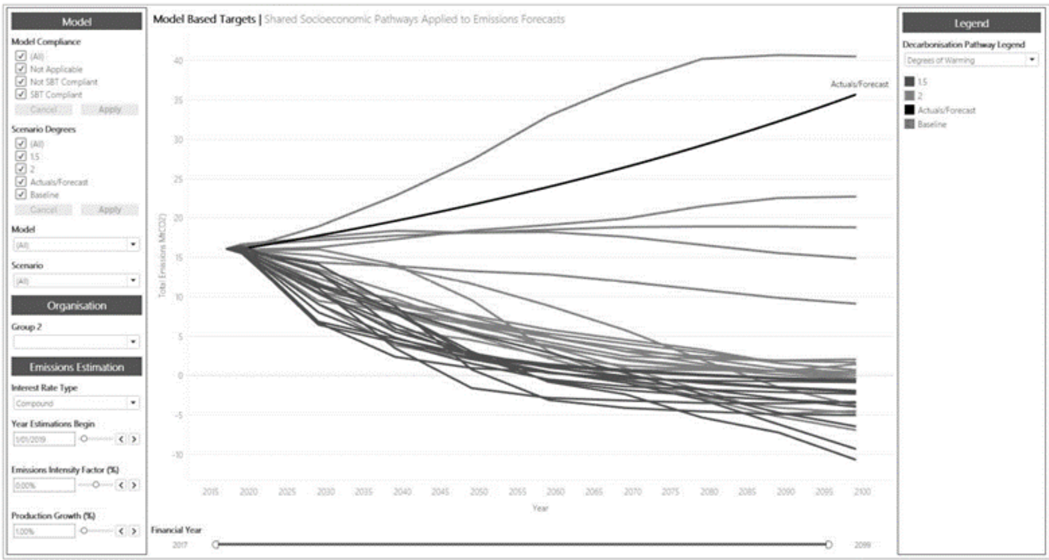


Figure 11 (continued) Decarbonization Strategy: Abatement challenge, decarbonization pathways, scenarios and selection (source: Deloitte, 2019b; Liggins 2019).

Step 3: Robustness of abatement pathway



Step 4: Execute and integrate into strategy and communications



micals or materials relative to alternative applications customers might have for all major product applications. This includes also potential new applications and customers.

- Review the specific product/ sector value chain to identify upstream or downstream linkages and abatement challenges. Evaluate players/ competitors, their likely strategies and corresponding opportunities and threats for your products and company.
- Quantify the abatement gap for the next 30 years, primarily for your individual position, but also with a view on your suppliers and customers as well as the relevant product group/ sector as a whole.

Step 2: Identify and prioritize **decarbonization projects and pathway ("base case")**

- Reference IPCC scenarios and consider a range of abatement pathways for your company and the potential costs, liabilities and opportunities inherent in each.
- Undertake thorough technical and commercial analysis of potential decarbonization pathways. Be as concrete and tangible as possible per project, which could be an asset/ site/ region or product/ product group.
- Carry out financial modelling to identify and prioritize profitable business opportunities. Quantify the impact of abatement projects and determine least cost projects.
- Use actual prices and costs, especially for fossil hydrocarbons, energy and carbon dioxide.
- Summarize all ranked projects into best return of capital employed abatement pathway ("realistic scenario" or "base case").

Step 3: Identify and quantify opportunities and risks to define **robustness of abatement pathway**

- Quantify the abatement challenge and financial impacts with an agreed pathway and define short- and long-term abatement emission targets.
- Define possible future scenarios for fossil hydrocarbon, energy, product and CO_2-prices and combine in optimistic and pessimistic scenarios.
- Evaluate potential future regulatory or political actions (per country/ region or product/ product group and assumed timing) and calculate impact on emission pathways, financial model and potentially license to operate.
- Explore opportunities to obtain funding and include into optimistic scenario.
- Calculate sensitivities and determine overall robustness of abatement strategy. Define "no regret" activities, which are valid and recommended in all scenarios.
- Summarize in actionable and communicable Decarbonization Strategy, including portfolio risks, abatement delivery schedule and financial exposure.

Step 4: Execute and integrate decarbonization **into strategy and communications**

- Develop least cost abatement projects in order to achieve emission targets and maximum competitive differentiation.
- Define decarbonization communications strategy towards all stakeholders.
- Integrate decarbonization projects and pathway into overall corporate strategy and business/ regional strategies.
- Define responsible decarbonization project managers and overall leader, including program management office.
- Define milestones for activities, set quantitative abatement targets and restrict financial exposure.

Chemical companies need to understand that climate risk has the potential to have a material impact on finances. Whilst this is obvious if you happen to work in an emissions-intensive sector, all sectors of the economy will be impacted over the next few years.

It will be critical to understand how these risks could play out for your company and how they can best be mitigated. At the same time, significant opportunities provide material upside for those who act. Decarbonization will have financial impacts across the economy and only the informed decision makers will be able to successfully navigate their companies through the risks and realize the significant opportunities.

9 Summary

Energy and resource efficiency activities, mechanical and chemical recycling and renewable bio- or waste-based feedstocks can contribute to about 40% of the decarbonization target of the chemical industry. The remaining 60% must come from the use of renewable energy and power-to-X technologies if we want to avoid CCS/CCU as much as possible.

Power-to-heat and power-to-gas (including to-liquids and to-products) require close sectoral cooperation. The existing opportunities of control power markets as well as switchable loads (on and off) need to be utilized by the chemical industry. At the same time, chemical processes should be electrified. This is only possible if renewable energy is reliably available at affordable costs. Much more renewable energy is needed at much lower costs. Governments, regulators and energy players have to provide an attractive playing field to attract more carbon neutral investments and improve both the planet and their prospects for the future.

Chemical companies should develop decarbonization strategies in four steps:

1. Evaluate the abatement challenge and quantify the emission gap
2. Identify decarbonization projects and summarize in an abatement pathway
3. Test the robustness of the abatement pathway and define no-regret actions
4. Execute all “no-regret” projects and integrate into strategy and communications

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Research Paper

Structuring and managing the new product development process – review on the evolution of the Stage-Gate® process

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Cooper introduced the *Stage-Gate®* process to structure the new product development (NPD) process in the late 1980s. Empirical evidence showed that successfully managing the NPD process helps firms to outperform their competitors over long periods of time. This indicates that appropriately managing the NPD process has become an imperative for firms. While some firms possess these capabilities succeed, many other firms lack the knowledge how to appropriately design and implement NPD processes. The NPD process must be flexible and adapted to changing market and customer requirements. Consequently, an efficient, less complex, and adaptive NPD process ensures not only a firm´s continuance but differentiates between winners and losers. For this reason, best performing firms are reinventing their NPD processes by adding elements of adaptivity, agility and acceleration to the original *Stage-Gate®* process, which represents a rather rigid framework. Novel approaches for the NPD process adaption have mainly emerged from literature and thus, still lack empirical evidence. However, some firms have already incorporated these elements in their NPD process. Therefore, the example of the *I2P3®* process is used to illustrate how a *Stage-Gate®* process can be adapted to the changing environment of the chemical industry. This article uniquely provides an overview of the evolution and advancements of different *Stage-Gate®* models and future research areas. In addition, it gives assistance for practitioners to select the right approach for their NPD process.

1 Introduction

Daubenfeld et al. (2014) showed in a survey that especially larger chemical companies use a *Stage-Gate®* process in new product development (NPD). The adaption and acceleration of the NPD process plays a crucial role for the chemical industry, since the chemical industry is currently facing ever-increasing competitive pressure. This increasing competitive pressure is driven by the globalization of value chains, shorter product life cycles, faster commoditization of products, and shareholder's expectations of publicly listed companies (CHEMonitor, 2014; Roland Berger, 2014; Daubenfeld et al., 2014). Thus, the NPD process must be custom-tailored for the respective industrial sector. Additionally, the high customer diversity, especially in the B2B sector, enforces high pressure on the innovativeness of chemical firms.

Therefore, the present article focuses on NPD processes, which are defined as actions, activities, and well-founded decisions which culminate in succeeding with the development of new products (Krishnan and Ulrich, 2001). Thus, NPD processes are described in literature as development processes comprising a linear system and as a lock-step process full of mandatory activities and actions (Cooper, 2008; Jespersen, 2012). Additionally, the goal of each NPD process is to separate high-potential inventions from losing ideas, reducing managerial uncertainty, and identifying areas where additional attention and resources are necessary to succeed in NPD (Hart et al., 2003). Concurrently, NPD processes ensure a strong strategic decision-making process of the firm by supporting management to develop and deploy the accurate competencies and resources across the NPD exertion (Bossink, 2002; Hart et al., 2003; Schilling and Hill, 1998). The most common way to organize and steer NPD processes is implementing stages and gates (Cooper, 2008). Therefore, Cooper (1990) introduced the concept of *Stage-Gate*® processes, which has become the basis of the majority of current NPD processes used in industry (Acur et al., 2012; Lewis, 2001). In the following sections, the original *Stage-Gate*® process from Cooper will be explained firstly. Subsequently, its evolution and advancements will be presented and discussed. At the end of the article, implications for practitioners and future research areas will be given.

Besides, the example of the *I2P3*® process from the Evonik Creavis GmbH, which is the central innovation unit of Evonik - a specialty chemicals company - will be presented to demonstrate how chemical companies can adapt their NPD processes to successfully develop new products to encounter changing market conditions and increasing competitive pressure.

2 Structuring the NPD process: The *Stage-Gate*® system

The ongoing management´s desire to reorganize the NPD process, to increase the product success rate, and to minimize the product development time culminates in an unending endeavor (Cooper and Kleinschmidt, 1995). Moreover, the continuous development of new products is a crucial success factor ensuring a sustained firm performance (Blundell et al., 1999). For instance, new products should balance expiring patents. However, while the development of new products is fundamental to guarantee a firm´s successful future, many empirical studies emphasize the high failure rate in NPD (Crawford, 1987). Cooper et al. (2004) benchmarked this difficult ambidexterity by opposing the immense benefits and the high risks in NPD. Thus, a significant difference between top performers and bottom players has been identified (cf. Table 1).

While companies being successful at new NPD belong to the 20% of the top businesses, companies failing with their NPD process stagnate within the bottom 20%. Although the average success rate for commercially successful projects values respectable 60.2%, the significant disparity of the top and bottom 20% of businesses poses the question: *What distinguishes winners and losers?* In addition to the lower success rate, the bottom 20% of businesses exhibit more than around 3.5 times the failure rate than the winning 20% according to Cooper et al. (2004). Furthermore, this also directly corresponds to the percentage of NPD projects, which are on time and budget (cf. Table 2). This emphasizes the importance of a successful and tough NPD process management.

For this reason, firms all over the world implemented *Stage-Gate*® processes as blueprints to overcome the *chaos* that comes along with the development of new products (Cooper, 1990). Thus, implementing a structured innovation process improves not merely structure of

Table 1 Percentage of businesses revenues and profits resulting from new products (NP) and percentage of businesses' new products failure, success and killed by type of business (source: In allusion to Cooper et al., 2004b).

Businesses	Revenues resulting from NP	Profits resulting from NP	Commercially successful projects	Commercially failing projects	Projects killed prior to launch
Top 20%	38.0	42.4	79.5	8.1	4.3
Bottom 20%	9.0	9.1	37.6	28.4	25.7
Average	27.5	28.4	60.2	20.8	19.0

Table 2 Percentage of businesses´ new products (NP) on time and budget (source: In allusion to Cooper et al., 2004b).

Businesses	NP projects launched on schedule in %	NP projects late in time as % of schedule	NP projects on budget in %
Top 20%	79.4	17.2	79.0
Bottom 20%	20.5	44.3	15.5
Average	51.1	35.4	57.1

the process but also increases the success rate of the NPD process (Cooper, 2008). In general, NPD processes combine a conceptual and an operational perspective to bring a new product from idea to launch (Cooper, 2008). Cooper (1990) states that managing NPD processes comprises the improvement of effectiveness and efficiency by integrating discipline into an ad-hoc and seriously deficient process (Grönlund et al., 2011). Based on this, Cooper (2001) emphasizes the importance of a well-structured NPD process by defining the world´s marketplaces as highly competitive *battlefields*. Cooper (2001) additionally highlights more recent combatants, which gained prominence due to fast and numerous new product victories, such as *Apple*, *Glaxo* and *Nortel* (Cooper, 2011; Cooper, 2008; Cooper, 2001). The weapons to win this *fight* are the thousands of new product launches, which should enable the firms to invade the chosen marketplaces. Although all *troops* are important to win this *fight*, the *battle* is often already won within the cradle of innovation, the R&D departments (Cooper, 2011; Cooper, 2008; Cooper, 2001). Cooper (2001) reduces the high failure rate in NPD process to the following circumstance:

"The combatants have their generals - the senior executives who plan and chart direction and attempt to define a business and technology strategy for their firm. The generals speak in terms of strategic thrusts, strategic arenas, and the need for strategic alignment. Sadly, many generals haven't really grasped the art of new product or technology strategy very well. So, as is often the case with ill-defined strategy, the battle is won or lost tactically in the trenches by the shock troops and infantry".

Since most of new product developments fail, the desire to generate *weapon* superiority by adapting the NPD process to the changing market environment rises (Cooper, 2001). Hence, firms recognized the necessity of adjusting their NPD process. Griffin (1997) has identified that 60% of all investigated NPD functions implemented a form of *Stage-Gate®* process to improve product innovation (Griffin, 1997). Today, the positive influence of *Stage-Gate®* processes on being successful at new product conception, development, and launch has been shown to a great extent (Cooper, 2019). The most crucial *weapons* are speed, strategy, and tactics in NPD processes due to decreasing product lifecycles and increasing competition (Cooper, 1990). Speed to market ensures competitive advantage by recognizing costumer´s demand faster than competition, it also yields higher profitability by realizing revenues earlier, and minimizes surprises by evading the threat of fast changing market environments (Cooper, 2001). Strategy focuses on the determination of the strategic direction of the NPD process, products, and technologies to invest in, while tactics describe a set of *maneuvers* designed to bring a new product from idea stage to launch (Cooper, 2001).

To put it in a nutshell, it seems that only some firms possess the knowledge on how to successfully adjust the NPD process on a regular basis with the goal to outperform their competition in the long-term. In contrast, many firms still fail with their NPD process. These failures have been empirically traced back to missing order, poor organization, inadequate quality of execution, and missed timelines (Cooper, 2008). Therefore, the firms need to set up NPD processes matching their market and competitive position (Cooper, 2008). An overview on the evolution of NPD processes over the last decades is displayed in Figure 1. Literature utilizes the terms system and model as synonyms for the term process. The different NPD processes will be presented in the subsequent chapters.

2.1 Introducing the *Stage-Gate®* process: the original *Stage-Gate®* process by Cooper

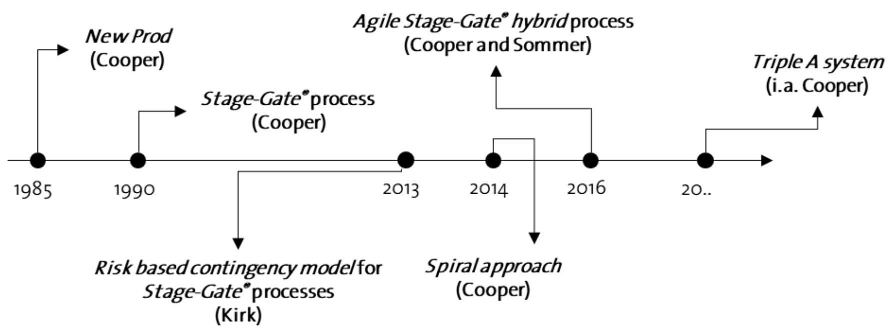
Cooper (1985) introduced *New Prod* to increase effectivity, efficiency, commercial success, and reduce development times (cf. Figure 1) (Cooper, 1985). The New Prod process was the first precursor of the *Stage-Gate®* model.

The original *Stage-Gate®* process was created by Cooper in the late 1980s based on in-depth studies of both, firms being successful with passing new products from idea stage to market, and firms failing at NPD (Cooper, 2014). The most rudimentary form of a *Stage-Gate®* process has been presented by Cooper in 2008. Within this simplest concept, a series of stages containing the collection of information, data integration, and analysis is followed by gates, where Go-/Kill-decisions adjudicate on the project's resource investment (cf. Figure 2).

Cooper (2008) compares the simplest form of a *Stage-Gate®* process with buying options on an investment, where initially inexpensive options were purchased and afterwards a decision regarding the investment´s perpetuation has to be made. Today's most commonly used representation of the original *Stage-Gate®* process is shown in Figure 3.

In general, the whole innovation process can be seen as a series of stages. Individually for

Figure 1 The evolution of NPD processes over the past decades (source: Own representation, 2020).



each stage a set of required or recommended best-practice activities are defined, which must be fulfilled that the product idea can pass to the next decision point (Cooper, 2008).

The original *Stage-Gate®* process starts with the ideation stage, namely *Discovery*, and culminates in the *Post-Launch review* (Cooper, 2014). The intermediate stages can be classified in homework phases to conduct required activities. While the initial stages do not require large financial expenditures, phases after *Go to Development* require serious financial commitments (Cooper, 2008). Following each stage, a Go-/Kill-decision (*Gate*) is made which decides on the project´s progress. Thereby, every gate has a similar structure comprising defined deliverables as visible results which are the output of the preceding gate´s discussion. These gates also contain criteria against which the project is judged. Thus, the criteria are subdivided into *should meet and must meet criteria* (Cooper, 2008). These categories of criteria are utilized to prioritize projects and to decide on its progress (Cooper, 2008). Moreover, the discussion at each gate results in outputs representing the go/kill-decision and a concrete action plan for the following stage, such as new deliverables (Cooper, 2008). Furthermore, the *Stage-Gate®* process consists of a series of stages which contain a set of required best practice activities leading to the process´s progress (Cooper, 2008). These activities contain market-oriented idea generation activities, such as focus groups and Voice of Customer (VoC) research in order to determine unmet customer needs (Cooper, 2019).

The activity and actions of each stage and gate of the original *Stage-Gate®* process from Cooper (1990) are summarized in Table 3.

Cooper (2008) describes this process as

Figure 2 Most rudimentary form of a *Stage-Gate®* process (source: In allusion to Cooper, 2008).

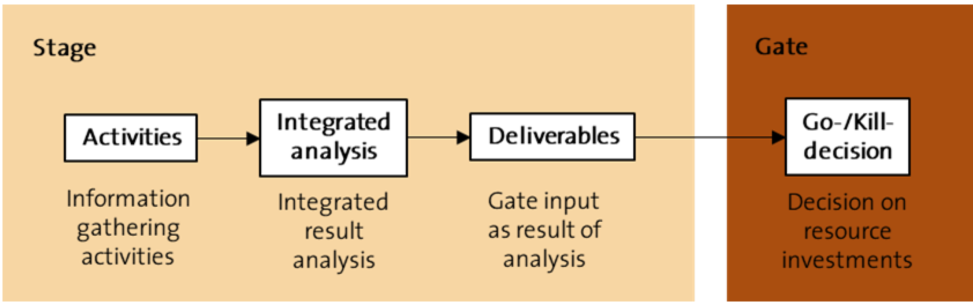
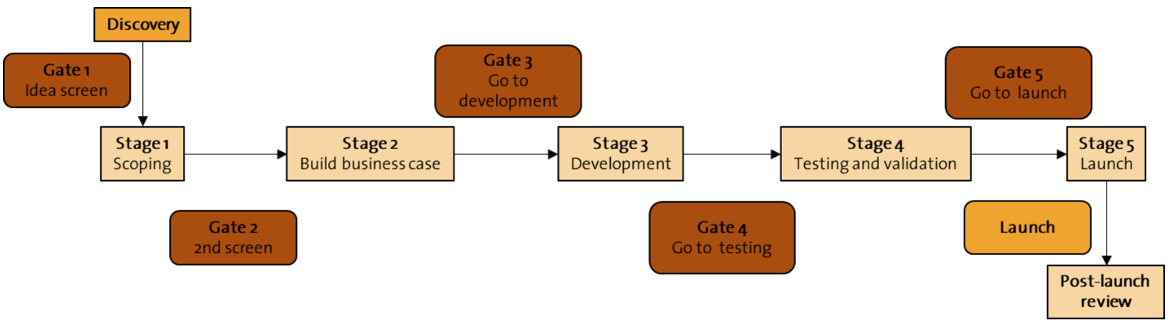


Figure 3 Standard *Stage-Gate®* model in NPD (source: In allusion to Cooper, 2014).



games of football including well-defined strategies, clear purposes, and proficient execution. Hence, the stages are designed to decrease risks and uncertainties by gathering required information, which may be adapted to the purpose of the different stages. Since the stages build on each other, each stage is costlier than the preceding one because of additional approved resources. However, the initial risk is managed by constantly decreasing uncertainties and unknowns.

2.2 Extending the *Stage-Gate®* processes

The *Stage-Gate®* process has been enhanced and adapted to changing corporate environments over the last 30 years. However, most firms maintain the basic concept from Cooper (Cooper, 2014). The advanced next generation processes should be more agile, flexible, dynamic, accelerated, and simultaneously leaner, faster, more adaptive, and risk-oriented (Cooper, 2014). Though, the criticism on sprawling bureaucracy and extended development periods was seized and implemented in the next generation of *Stage-Gate®* systems. The execution and implementation of these processes are quite different compared to the primary model from Cooper, although the framework of gates and stages remains the same (Cooper, 2014; Ettlie and Elsenbach, 2007). The new idea-to-launch processes comprise several novel aspects which are elucidated in detail below. The *Triple A system* represents the coalition of all these new approaches, which will be presented in chapter 2.2.5.

Table 3 Activity and underlying actions of each stage and gate within the original Stage-Gate® process (source: In allusion to Cooper, 2011, 2001, 1997, 1990).

Stage/Gate	Activity	Actions
Start	Discovery	Generation and collection of promising new product ideas.
Gate 1	Idea screen	Selection and prioritisation of product ideas for NPD project within a dynamic process with high uncertainty.
Stage 1	Scoping	Rough market and technology analysis such as assessment of basic financial values.
Gate 2	2nd screen	Decision on project´s progress based on profound conditioned information collection and analysis.
Stage 2	Build business case	Conceptualization of business case including detailed development and market launch plan.
Gate 3	Go to development	Decision on project´s profitability and release of exalted resources.
Stage 3	Development	Technological development and evaluation of marketing and fabrication activities.
Gate 4	Go to testing	Assessment of project's technical feasibility and control of R&D spending.
Stage 4	Testing and validation	Evaluation of customer acceptance, validation of financial planning and technological achievements.
Gate 5	Go to launch	Approval of market launch.
Stage 5	Launch	Market launch and product commercialization.
Post-launch review	Monitoring	Evaluation of launch process.

2.2.1 The spiral approach

An early, sharp, and fact-based product definition has always been one of the major requirements of the primary *Stage-Gate*® model (Cooper, 2011). In former times, the general tonus has always been that customers do not know what they want or need (Isaacson and Jobs, 2011). However, nowadays a fast-changing market environment as well as fluctuating customer requirements avoid a stable product definition in early stages of the NPD process (Isaacson and Jobs, 2011). Therefore, the primary product definition may be rendered invalid due to changing requirements during the process based on competitive developments or new market trends. Hence, the new *Stage-Gate*® processes must be orientated to fluid requirements and information, which on the other hand must be integrated into the process to decrease response time and increase efficiency (Cooper and Sommer, 2016). The integration can be achieved by the incorporation of spiral development cycles designed to directly integrate the customer´s feedback (Cooper, 2017a). Additionally, such an iterative process supports the appropriate product development and steers the development progress. This gains importance in rapidly changing markets, when some information is unsolidified and partially unreliable at the beginning of product development (Cooper, 2019). In pre-development stages, firms should avoid the usage of rigid and linear NPD processes comprising only the market assessment since a market might not exist yet. (Potential) customers should be rather involved (Cooper, 1988). As a consequence, the rigid process may culminate in the failure of new product launches due to today's fast-paced world. These failures can be avoided by stepping a cycle back in the NPD process to rethink the product's properties (Cooper, 2019). These iterative steps include the demonstration of preliminary versions of the product to the customer and the verification and integration of the customer´s feedback (Cooper, 2017a).

In general, each iteration stage consists of the following phases (Cooper, 2014):

1) **Build**: Start with building something what can be shown to the customer, this may be a rapid prototype, a protocept, a crude working model, or an early beta version.
2) **Test**: Test each version of the product with customers. Let them tell you what they like and what value they see.
3) **Feedback**: Gather feedback on the respective version of the product from the potential customer or user.
4) **Revise**: Reset your thinking about the value proposition, benefit and the product's design based on the feedback. Then, start again, and may go back to step 1) build.

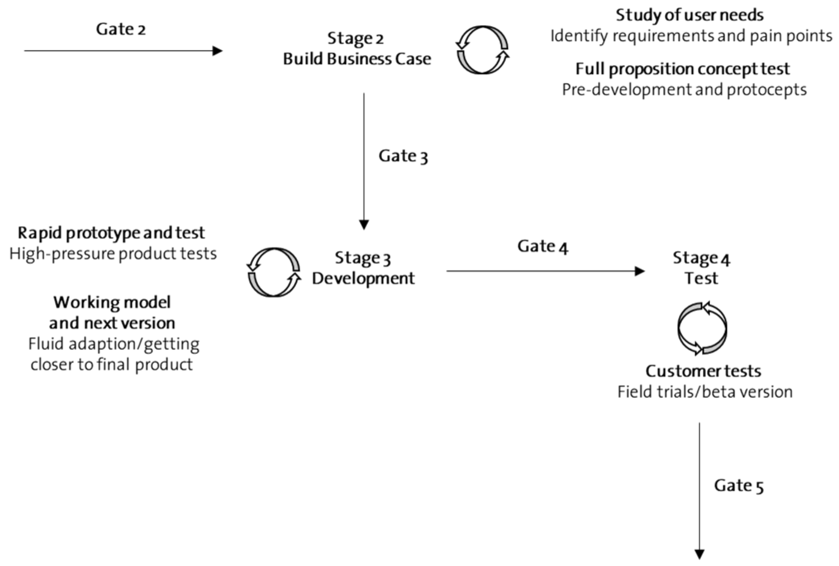
Each iteration enforces an adaption step that brings the product closer to its final design. Furthermore, this spiral development approach allows and encourages to fail often, fast, and cheaply (Cooper, 2014).

Figure 4 illustrates the spiral development phases as a novel aspect of the next generation *Stage-Gate*® processes. The spiral approach has no impact on stage 1 and 5, and thus both remain the same as in the original *Stage-Gate*® process. For this reason, they are not shown in Figure 4.

A regular alignment of the product´s design with the customer´s feedback does not merely decrease the market uncertainties but also strengthens the technical development. This is based on the customer´s high-pressure tests, in which the technical knowledge of customers is used.

Currently, statistical studies have rarely proven the advantages of the integration of spiral phases into the *Stage-Gate*® process. However, first evidence exists that this integration results in higher and better output, as 44.8% of best-performing firms practice these "build - test - feedback - and - revise" iterations, whereas only 26.3% of average-performing

Figure 4 Integration of spiral development phases in *Stage-Gate*® process. Note: Stage 1 and 5 remain the same as in the original *Stage-Gate*® process (source: In allusion to Cooper, 2014).



firms do (Cooper, 2012).

The spiral approach is congruent with the two core doctrines of the *Agile Manifesto* for software development - focus on quick response to change and continuous customer or stakeholder involvement in the development of the product – and thus, has a direct linkage to the subsequent aspect of next generation *Stage-Gate*® systems (Cooper, 2014).

2.2.2 *Agile-Stage-Gate*® processes

Agile development methods have been primarily created for software projects. However, within the last years agile methods have been also integrated into traditional stage-gating approaches resulting in an *Agile–Stage-Gate*® hybrid process in 2016 (Conforto and Amaral, 2016; Cooper and Sommer, 2016). The agile methodologies are based on the *Agile Manifesto* crafted by IT industry leaders in 2001 and incorporate a set of rules how to efficiently develop new software codes (Beck et al., 2001; Highsmith et al., 2001). The *Agile Manifesto* comprises the four following joint values (Beck et al., 2001):

- Individuals/Interactions more important than processes and tools
- Working software more important than comprehensive documentation
- Customer collaboration more important than contract negotiation
- Adaption instead of following a rigid plan

These four core values are antithetic to the initial purpose of the original *Stage-Gate*® process, since they omit a strict documentation and are geared to the customer instead of the process (Highsmith et al., 2001).

For the development of physical products, skepticism proliferates among industrial representatives and researchers whether the incorporation of agile methods into traditional NPD processes can be beneficial. Currently, only limited evidence in literature exists, which proves that the integration of agile methods into existing *Stage-Gate*® systems has beneficial effects (Conforto and Amaral, 2016; Cooper and

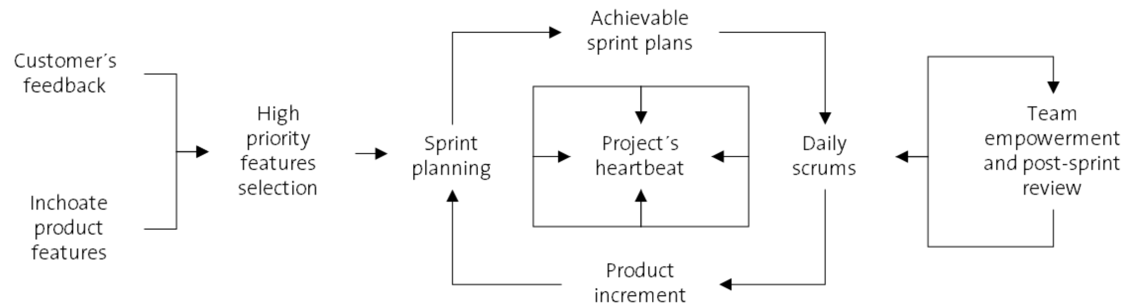
Sommer, 2016). However, after first trials and the implementation of hybrid processes in the manufacturing industry, positive effects have been shown by a few studies (Cooper, 2014; Cooper and Sommer, 2016; Sommer et al., 2014). These positive effects cover a wide field of benefits which are (Cooper, 2017a; Cooper and Sommer, 2016):

- Improved focus and prioritization
- Higher team morale
- Increased intersection between process and methods
- Improved productivity
- Improved communication and coordination
- Faster response to change

In addition, the benefits of *Agile–Stage-Gate®* hybrid processes contain the advanced focus on customer needs, the integration of the VoC, avoiding the problems of resource allocation, and the reduction of development cycle times (Conforto and Amaral, 2016; Cooper and Sommer, 2016).

The *Scrum* method of the *Agile Manifesto* represents the most popular version of the *Agile principle* and is mostly chosen for the integration into *Stage-Gate®* processes (Cooper and Sommer, 2016; Sommer et al., 2014). Therefore, the *Agile–Stage-Gate®* hybrid process incorporates the sprints of the *Scrum* method. These *sprints* are executed in very short time frames, characteristically one to four weeks. In doing so, the whole NPD process is separated into various small working packages. Each working package represents one *sprint*. *Sprints* in combination with a set of other activities form the framework and *heartbeat* of the agile project management according to Wells (2009) The framework is illustrated in Figure 5. For each iteration, customer´s feedback and an inchoate product is required to generate a valuable input for the process. The input and therefore the features must be prioritized before this information will be utilized within the agile process. Following the collection of valuable data and information, the agile development starts with the sprint planning to define realistic goals, which can be achieved within a given timeframe (Wells, 2009). Thus, *sprint planning* yields a *sprint-plan* containing all actions that are necessary for the accomplishment of the previously defined goals (Cooper, 2017a). Moreover, daily *Scrums* are executed, in which the team reviews what has been accomplished and which new problems and challenges occurred. In addition, a discussion takes place how these problems or new challenges can be solved (Abrahamsson et al., 2002). The preponderant goal of each *sprint section* is to deliver an improved prototype or protocepts that can be tested by the customers and other relevant

Figure 5 Process and framework of *Agile–Stage-Gate®* hybrid processes (source: In allusion to Wells, 2009).



stakeholders (Cooper, 2017a). Since the manufacturing industry requires longer development times than the software industry, the deadline for *sprints* can be more flexible. Additionally, the finished prototype must not be a physical product but can be a completed design drawing, a computer simulation, or even the reworking of the VoC results (Cooper, 2017a). Building on the feedback, the project team decides on the improvements that have to be completed within the next iteration step (Abrahamsson et al., 2002). Simultaneously, the incorporation of senior management via *post-sprint reviews* is crucial for these *Agile–Stage-Gate®* hybrid processes because physical product development is generally resource intensive and thus, senior management needs to approve necessary resources (Cooper, 2017a).

Agile–Stage-Gate® hybrid processes become particularly relevant in the development and testing stages of new physical products, since customer feedback shows the highest impact at these development phases (Conforto and Amaral, 2016; Cooper, 2017a). However, it should not be withheld that *Agile–Stage-Gate®* hybrid processes rather prove their most promising results at riskier projects (Cooper, 2017a). Indeed, customer integration bears the danger of know-how loss and may limit the development of disruptive innovations. The integration of short-sighted customer feedback could additionally rather result in the development of incremental innovations (Cooper, 2017a).

2.2.3 The risk-based contingency model for *Stage-Gate®* processes

The risk-based contingency model for *Stage-Gate®* processes based on the Corning´s approach was introduced in 2013 by Kirk (2013) and the most significant characteristic is custom-tailoring the process to every project uniquely (Cooper, 2014). This approach has the goal to generate detailed data and information that should support the decrease of uncertainties and increase the management of risks (Cooper, 2014, 2017b). It creates a hybrid system by integrating a business model canvas approach into the *Stage-Gate®* process and enables a custom-tailored process. Before applying the risk-based contingency model, these first three steps must be completed (Cooper, 2014; Kirk, 2013):

1) Identifying key uncertainties and unknowns
2) Highlighting critical economic assumptions
3) Determining the required data to validate these assumptions

By following this approach, the project team needs to define by themselves all deliverables which are required for the next gate. In doing so, a rigid and mandatory manual with a list of pre-defined deliverables and information required becomes invalid (Kirk, 2013). Thus, the generation of irrelevant information for the specific project can be avoided and results in the speed up of the NPD process (Cooper, 2014). Hence, this approach circumvents the evaluation of criteria which have no explicit value for the specific project (Cooper, 2014; Kirk, 2013).

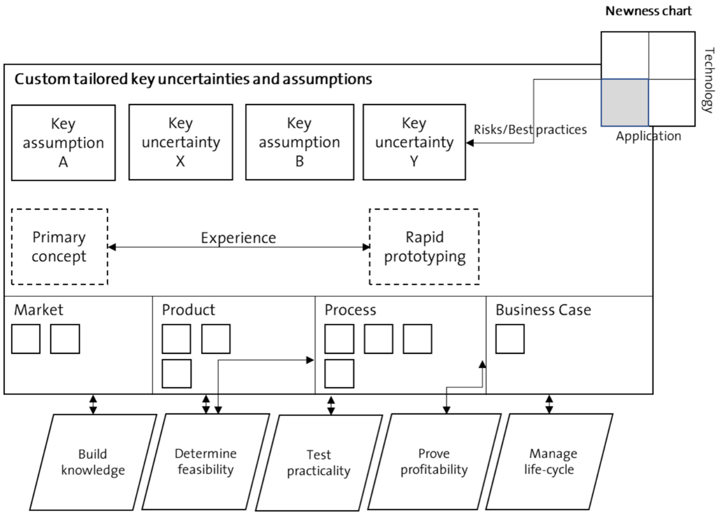
The assessment criteria are also flexible and can be adapted to the respective critical assumptions and uncertainties of the specific project. The set-up time of the project can be minimized by utilizing this process. In contrast, the original process requires the assessment and examination of all criteria (Cooper, 2014). Figure 6 shows Corning's risk-based contingency model.

2.2.4 Flexible *Stage-Gate®* processes

At the beginning of each project, the ideas collected must be categorized by their complexity, initiative risks, and precision of product definition to choose the most suitable NPD process.

Cooper and Edgett (2012) proved the importance of flexible NPD processes by identify-

Figure 6 Corning's risk-based contingency model (source: In allusion to Kirk, 2013).



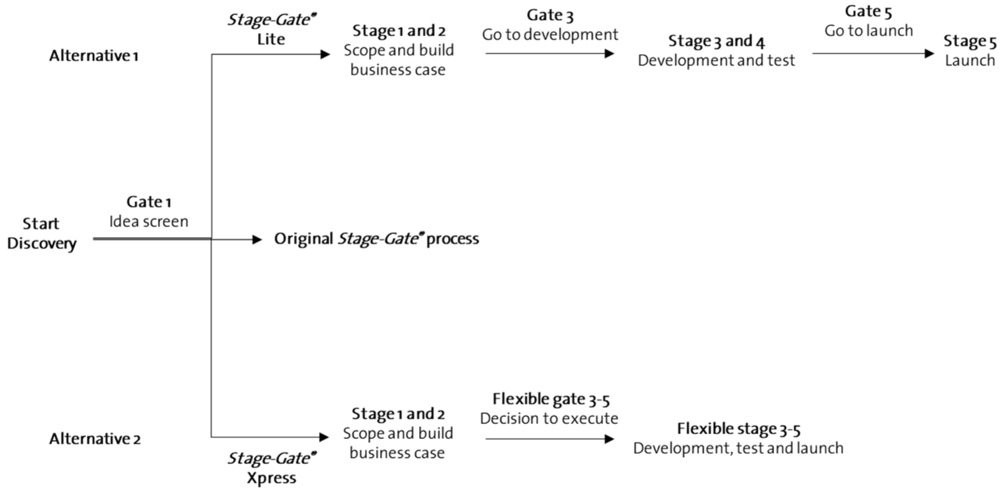
ing 75% of best-performing businesses using a scalable idea-to-launch process. In this context, flexible and scalable means that the execution time of the NPD process can be reduced or extended depending on each respective project. This gains in importance for accelerating the process while avoiding the waste of resources on disproportionate long development phases which are not necessary for every project (Cooper and Edgett, 2012).

The original *Stage-Gate®* process suits not to every project since many companies execute projects with different degrees of complexity. Therefore, flexible context-based *Stage-Gate®* processes comprising *Stage-Gate® Lite* and *Stage-Gate® Xpress* have been created to adapt and accelerate the NPD process. These context-based approaches allow skipping gates and stages to cope with different degrees of complexity (Cooper, 2014). In this context, synchronization of activities plays a crucial role in terms of accelerating and adapting the process (Cooper, 2014).

Whereas the full six-stage process of the standard *Stage-Gate®* process is suitable for major high-risk development projects, the lite version (*Stage-Gate® Lite*) has been created to handle projects with moderate risks, e.g. in terms of product modifications and improvements (Cooper, 2014; Leithold et al. 2015). Moreover, the express process (*Stage-Gate® Xpress*) can be utilized for small development projects, e.g. customer-based adaptions of single products (Cooper, 2014; Leithold et al., 2015). Figure 7 shows the *Stage-Gate® Lite* and *Stage-Gate® Xpress*.

For the acceleration of the NPD process, time wasters and blockages must be identified through value stream analysis and removed to increase efficiency of the process. Therefore, the most prominent options to fulfil these goals comprise 1) overlapping stages, 2) simultaneously executed activities, 3) dedicated teams assigned with adequate resources, 4) efforts to sharpen the fuzzy front end in terms of properly understanding the customer´s problem, and 5) defined support systems for the project management (Cooper, 2014; Leithold et al., 2015). The simultaneous execution of several tasks, including key-activities and overlapping stages, requires the permission to move ahead even though information are not fully available and validated (Cooper, 2014). Thus, the support and commitment of top management can enforce speed and flexibility of the NPD process. In doing so, multiple activities can be carried out in

Figure 7 Flexible and scalable *Stage-Gate®* processes as alternatives for the original *Stage-Gate®* process including *Stage-Gate® Lite* and *Stage-Gate® Xpress* (source: In allusion to Cooper, 2014).



parallel. This is much more suitable for development projects with several parallel tasks than a *relay race*, at which activities are successively executed (Cooper, 2014; Leithold et al., 2015). This kind of acceleration and flexibility also allows to move activities to an earlier stage than scheduled and to start with a following stage when the previous may not be completed yet. In particular, the necessity of these accelerated and adapted NPD processes increases due to increasingly shortened product life cycles in manufacturing industries such as the chemical industry (CHEMonitor, 2014; Roland Berger, 2014; Daubenfeld et al., 2014).

2.2.5 Combining novel *Stage-Gate®* processes: The *Triple A system*

Cooper (2014) combined the previous presented approaches in the *Triple A system*, which represents the next generation of idea-to-launch systems. The three main goals of the Triple A system are adaptivity (flexibility), agility, and acceleration to improve the original *Stage-Gate®* process. However, the framework how to manage NPD projects still remains the same, although the details of the process and its purpose are quite different. The *Triple A system* will probably be the underlying concept of all next generation stage-gating systems.

1) **Adaptivity/flexibility**: The integration of a **spiral development** approach ensures the fast design and production of prototypes while utilizing and integrating customer's feedback (Cooper, 2014). At the beginning, the product design and its value proposition may not be fully defined but becomes more concrete during the iterative process. Therefore, the product may be adapted based on the respective customer requirements. For each development process, flexibility can be ensured by uniquely defining and selecting the actions and deliverables required for each stage and gate (Cooper, 2014). For lower-risk projects, fast-track versions of the original *Stage-Gate®* process can be used to speed up the NPD process. The respective decision, which version is used, is based on an assessment of each project´s risks and opportunities. Finally, single activities can be flexibly assigned to several gates. Assessment criteria of each gate are also flexible

and not rigid.

2) **Agility**: The *Triple A system* integrates elements of the **agile development method**, like *sprints*, *Scrums*, and the necessity of involving all stakeholders into the NPD process, especially customers (Conforto and Amaral, 2016). The NPD process should culminate in moving nimbly from idea to market launch by utilizing the knowledge from agile software development. It also relies on a much leaner system which avoids bureaucracy and unnecessary activities during the development phase (Cooper, 2014; Karlström and Runeson, 2006).

3) **Acceleration/speed**: The *Triple A system* f ocuses on methods, which ensure the accel eration of the NPD process. Therefore, fluid s tages containing overlapping activities cul minate in an accelerated process and an early identification and evaluation of risks and uncertainties. It should not be withheld that flexible and accelerated processes re quire decision making even with less infor mation availability what could result in a higher failure rate. Thus, especially decision-makers like top management play a crucial role to accelerate and speed up the NPD pro cess. They must approve resources for the continuance of an NPD project, although not all necessary information may be availa ble.

Regarding the improvement or modification of the *Stage-Gate®* process, **Adaptivity**, **Agility**, and **Acceleration** should be kept in mind as core elements whenever conducting an NPD process or implementing a new *Stage-Gate®* process into an organisation. In the next chapter, an example of how a chemical company can adapt its *Stage-Gate®* process for NPD will be presented.

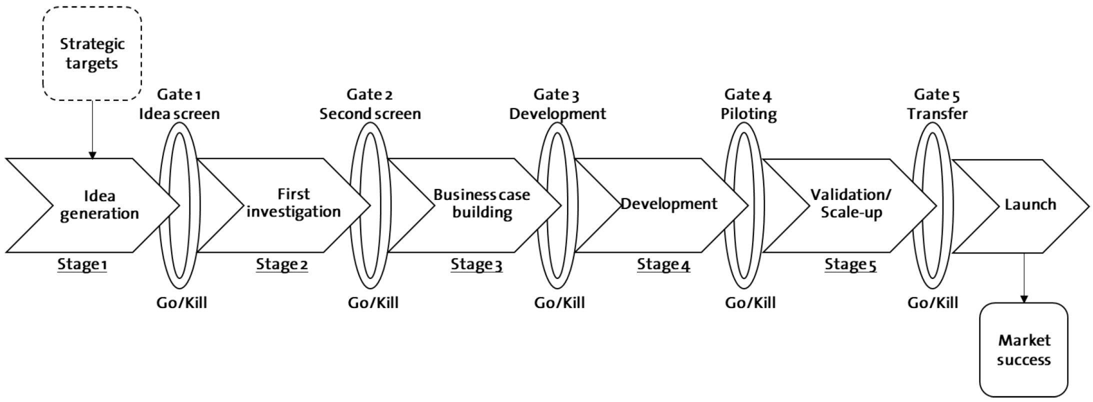
3 Customizing the *Stage-Gate®* process: an example from the chemical industry – The *I2P3®* process

Evonik Creavis GmbH introduced the *I2P3®* process, which is adapted to the chemical industry by including an evaluation of the whole industrial environment (Wojciechowski et al., 2019). In addition, the *I2P3®* process takes all three dimensions of the triple bottom line into account: People (societal aspects), Planet (ecological aspects), and Profit (economic aspects) (Wojciechowski et al., 2019). Figure 8 shows the whole *I2P3®* process, which comprises six stages like Cooper´s original *Stage-Gate®* process. Within the *I2P3®* process, substantiated decisions are based on a set of categories and criteria focusing on all three dimensions of the triple bottom line concerning sustainability, which are specifically assessed and examined during the gate decisions (Wojciechowski et al., 2019). These three categories have been selected since they are considered to be particularly relevant for the chemical industry. Besides, further sub-criteria have been defined to specify each category (Wojciechowski et al., 2019). For instance, global warming potential based on a 100-year timeframe is a criterion within the category of reduction of Greenhouse gases emissions (Wojciechowski et al., 2019).

The *I2P3®* process contains two kinds of criteria, qualitative and quantitative. While quantitative criteria are described by continuous values, qualitative criteria provide multichotomous scores based on a benchmark. This ensures a comparative assessment and allows qualitative values to be semi-quantified (Wojciechowski et al., 2019). Quality and validity of the information of each criterion is increased with the project´s progress (Wojciechowski et al., 2019).

Since new innovative ideas are uncharted when entering stage 1, the quantitative assessment of criteria because of data quality is challenging and not well-founded at the fuzzy front

Figure 8: Structure of the I2P3® process (source: In allusion to Wojciechowski et al., 2019).



end. Therefore, rather qualitative criteria are used at the beginning of the process. However, the continuous assessment of the People, Planet, and Profit dimensions ensures an increasing data basis in addition to rising data quality during the process (Wojciechowski et al., 2019).

At the beginning of the *I2P3*® process, a product or process improvement or novel idea is generated, which is filed into the *I2P3*® process by the idea generator and subsequently discussed during a first gatekeeper meeting (Wojciechowski et al., 2019). Within this first assessment, primary estimations of the market and technical feasibility are required and assessed by a Life-Cycle-Management (LCM) expert to create insights into how the product could affect the sustainability criteria (Wojciechowski et al., 2019). In case of a positive verdict, the idea generator is allowed to continue and collect all data, which are mandatory for the gate 2 assessment (Wojciechowski et al., 2019).

In congruence with the original *Stage-Gate*® process from Cooper, gate 2 assessment contains a more detailed evaluation resulting in a more refined appraisal of all relevant criteria since it comprises more detailed information on the exact product development (Wojciechowski et al., 2019). However, the accountable project manager will present the most likely scenarios based on semi-quantitative information (Wojciechowski et al., 2019). This approach ensures the evaluation of positive and negative characteristics of the idea. Further resources will be released, if the idea was positively assessed to pass gate 2 and to advance to stage 3 (Wojciechowski et al., 2019).

The assessment of gate 3, 4 and 5 is similar since the respective criteria contain the same data and factors used in gate 1 and 2, but vary with their accuracy (Wojciechowski et al., 2019). Thus, the *I2P3*® process is not a rigid but flexible process, which can be adjusted when necessary depending on the respective project and situation (Wojciechowski et al., 2019).

Within the validation and scale up stage (stage 5), the entire project´s viability and estimated impact on the sustainability criteria is scrutinised (Wojciechowski et al., 2019). After a successful assessment of all gate 5 criteria, the newly developed product or process reaches the launch stage (Wojciechowski et al., 2019). In doing so, the *I2P3*® process comprises the economic, ecological and social impact of the project, which are necessary to successfully introduce the product into the market and to comply with regulation. The *I2P3*® process can be easily adapted to a changing market environment and new qualitative scoring approaches can be integrated (Wojciechowski et al., 2019). Indeed, the high flexibility of the process requires a good understanding of the market and sustainability requirements of the customers (Wojciechowski et al., 2019).

With the introduction and implementation of the *I2P3®* process, Evonik Creavis GmbH has responded to changing market environments of the chemical industry, in which customers increasingly ask for sustainable products. As a consequence, it individually adapted the standard *Stage-Gate®* process to meet changing customer requirements, but also to accelerate the NPD process (Wojciechowski et al., 2019).

4 Conclusion

Until now, the basic framework of the original *Stage-Gate®* process by Cooper is still used as a guideline how NPD processes can be structured. However, single activities and deliverables may be adapted to specific industries and projects to manage NPD processes effectively and efficiently.

For both physical and non-physical product developments, advanced *Stage-Gate®* processes were presented in this paper, which are suitable to bring new products and services quickly, efficiently, and profitably to market. Best-practice firms serve as a role-model for how to design and implement advanced NPD processes to deal with changing market and customer requirements. *The Triple A System* allows adaptivity (flexibility), agility and acceleration (speed) of NPD processes. In addition to the presentation of these flexible, adaptive, and scalable *Stage-Gate®* processes, the main purpose of this review is to convey the need of custom-tailoring the NPD process. Therefore, every firm should be admonished to adapt their NPD process or to use different types of NPD processes according to its industrial landscape and to every single project. This can help firms to develop NPD capabilities to outperform their competitors in the long-term. Finally, chemical companies may especially use agile methods to develop new (digital) services and business models around their physical products.

5 Outlook for future research

Over the last decade, much qualitative research in terms of working hypotheses and model development has been published regarding the improvement and flexibilization of NPD processes, whereas these new approaches find no broad application in any industrial sector so far. Therefore, it is the researchers´ task to evaluate the benefits by conducting empirical analyses and thus, creating the basis that enforces firms of different industrial sectors to have confidence in these new approaches. This confidence will then help firms adapting and redesigning their NPD processes.

Furthermore, success factor analyses and how their relevance change during the NPD process should be conducted to provide a well-founded playbook how these new approaches can successfully be implemented and managed in practice. For this reason, success factors for every industry and every single phase of the NPD process must be identified at a first level. This will help to obtain insights into the crucial factors yielding success. This knowledge will help firms to custom-tailor their respective NPD process by providing information on the suitability of NPD processes for certain industries and single projects to improve successful NPD and to help firms to outperform competitors in the long-term.

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Introduction to Innovation Management

Application of Kuhn's theory of scientific revolution to the theory development of disruptive innovation

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The aim of this article is to review the theory of disruptive innovation over the course of its development and analyze its theory building process. The analysis is framed through the theory of scientific development proposed by Thomas S. Kuhn (2012). The novel application of Kuhn's framework highlights crucial developments and faults. It is assessed how the development of disruptive innovation matches the four stages of scientific development: crisis, revolution, normal science and the accumulation of anomalies. It is demonstrated that this framework is a successful means of conceptualizing the development of disruptive innovation. The theory is currently at the stage of normal science. The two potential anomalies are evaluated. It is concluded that controversies surrounding definitions are not an essential threat to the theory. Establishing predictive value on the other hand is a critical point in future development of the theory. It is shown that the future of the theory depends on whether the latter point is resolved.

1 Introduction

Theory building is an essential but challenging activity in innovation management research (Sutton and Staw, 1995). It facilitates the development of a field, provides angles for theoretical analysis and ultimately leads to theories that are applicable in the real world (Wacker, 1998).

The aim of this article is to review the theory of disruptive innovation over the course of its development and analyze its theory building process. The analysis is framed through the theory of scientific development proposed by Thomas S. Kuhn (2012). It will be assessed how the development of disruptive innovation matches the four stages of scientific development: crisis, revolution, normal science and the accumulation of anomalies. The analysis will show that disruptive innovations has gone through Kuhn's stages. It is currently in the stage of normal science. Two potential anomalies are identified, one of which has particularly strong implications for research and practice. Identifying anomalies is of particular importance, because the identification of weaknesses enables targeted research to address challenges within a theory (Carlile and Christensen, 2004). The theoretical and practical implications of the analysis will be discussed. Some predictions regarding future developments of disruptive innovation can be derived.

Disruptive innovation is one of the most influential frameworks for thinking about innovation both in innovation management research (Tellis, 2006) and for practical use in companies and organizations (Butler, 1988). Reviewing the intellectual history of disruptive innovation is of particular interest because it promises much needed direction for future research and clarification of unresolved controversies (Christensen et al., 2018).

Theoretical developments and concerns inform practical application (Mir and Watson, 2000). Based on the identified anomalies, caution is recommended in use in managerial practice. The practical implications may prove very impactful, given the popularity of disruptive innovation (Tellis, 2006).

The implications of analyzing disruptive innovation through the stages of science proposed by Kuhn offers implications not just for business studies, but for history and philosophy of science, albeit in a more modest way. Application to the development of a particular theory puts it to the test. The peculiarities of the dynamic and practically oriented field of innovation management research promise a novel and interesting field of application. Furthermore, this article showcases how Kuhn's theory can be used as a framework for analysis for deriving practical implications and predictions.

2 Theoretical framework

Conceptualizing the development of disruptive innovation within a theoretical framework fosters understanding of the theory building process and the theory itself. Furthermore, it may help determine the present state of the theory and identify areas in which further investigation is necessary.

In the following, the theory of disruptive innovation will be understood and analyzed through the terms of Kuhn's theory of scientific revolutions first introduced in 1962 (Kuhn, 2012). The theory is widely accepted and used in both philosophy of science and practical analysis. It has even been utilized by the main thinker behind disruptive innovation to categorize cycles of theory building in management research (Carlile and Christensen, 2004). Moreover, it has been used to conceptualize certain moments in theory development of disruptive innovation (Christensen, 2006). Yet, a broader analysis of the overarching theory development to contextualize these comments is lacking. In this article, an attempt will be made to understand the overarching narrative of the development of disruptive innovation through Kuhn's theory. It is first necessary to briefly introduce the theory as a means of analysis in the following.

Kuhn stresses that science revolves around paradigms. A paradigm is an accepted model or pattern that shapes the way in which research is conducted (Kuhn, 2012, p. 23). It is important to note that a paradigm does not need to apply to a large field such as physics but may shape fields and sub-fields of any scale. Especially in humanities and social sciences, several paradigms may coexist to an extent. Transitions may be rather fluid. (Kuhn, 2012, pp. 6-8)

An essential concept introduced by Kuhn is the division of the process of scientific change into phases. Once a field has been established, it progresses into a phase called normal science. Normal science revolves around the present paradigm. Questions resulting from it and phrased in terms of it are solved with means prescribed by it. Scientists typically turn towards relatively detail-oriented questions in this phase. Experiments are designed to expand the depth of knowledge and understanding through the paradigm (Kuhn, 2012, p. 7).

Through the process of normal science, anomalies may be revealed. The paradigm can initially withstand these anomalies or may be adapted to accommodate them. However, over time anomalies accumulate and become increasingly hard to ignore. This leads to the next phase, a period of crisis. Crises may be resolved within normal science, but if normal science continues to fail to account for the anomalies, a scientific revolution must follow (Kuhn, 2012, p. 52).

A scientific revolution is characterized by a paradigm shift. Underlying assumptions are challenged in a radical way. A new paradigm replaces the previous one. Once the new paradigm has been established, normal science resumes (Kuhn, 2012, p. 92).

3 What is disruptive innovation?

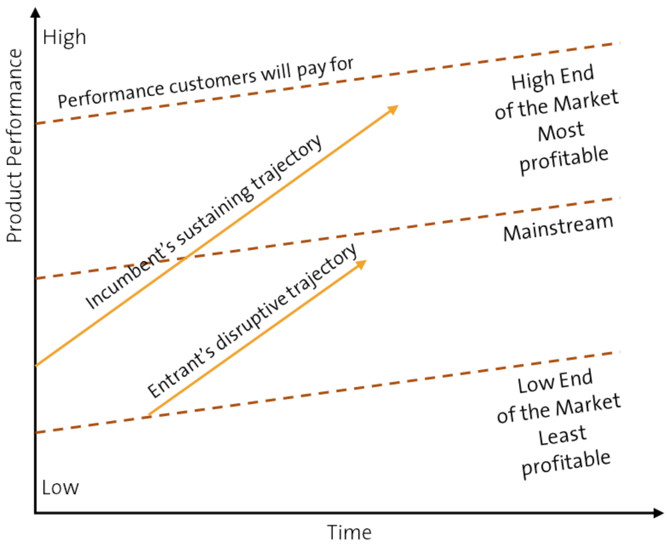
First, a brief overview of the theory of disruptive innovation is provided, introducing the stages and assumptions of the model. The thus established groundwork is the basis for the chronologically structured analysis in the following.

The theory of disruptive innovation is based on the observation that some incumbent firms fail despite good management (Christensen, 1997). To explain this, a distinction is introduced: sustaining versus disruptive innovation. In contrast to sustaining innovations, which are introduced by incumbents to improve existing solutions, disruption is defined as “a process whereby a smaller company with fewer resources is able to successfully challenge established incumbent businesses” (Christensen et al., 2015).

Initially named disruptive technology, the broader phrase disruptive innovation has replaced that term since 2003 (Christensen and Raynor, 2003). A disruptive innovation may occur, when incumbents focus on existing, high reward customers, but leave others underserved. An entrant then takes advantage of the situation and targets the underserved customers by offering a more suitable, often less expensive product. The disruptive technology initially underperforms compared to previous solutions and thus does not immediately threaten the incumbent. The incumbent continues to focus on their core, high-value customers, introducing sustaining innovations to meet their demands. When successful, the entrant begins to move upmarket towards the mainstream, overcoming initial limitations of value and potentially making the incumbent obsolete eventually (Christensen, 1997).

This process of disruptive innovation has typically been symbolized in variations of Figure 1. Incumbents tend to focus increasingly on higher value customers. In turn, they leave room for entrants to place their product or service at the lower, less profitable end of the market. The product performance trajectories show that the entrant firm increasingly challenges

Figure 1 The trajectories of customer demands and companies in the market over time (source: Christensen et al., 2015).



the incumbent and takes over the mainstream from there (Christensen et al., 2015).

It must be pointed out, that disruptive innovation as a theory and as discussed in the context of this article is tied to the mechanism rather than properties of the products or service. The colloquial use of the term disruptive sometimes obscures the distinction. The term radical innovation is used instead to refer to a product or service that fundamentally changes and redefines a market, because it is so novel and different (Christensen, 2006). It can be introduced by either incumbents or entrants.

The theory views innovation from a market-based perspective of technology demand (Adner, 2002). This is illustrated by the emphasis put on establishing the concept of value networks early in theory development. Value networks are "the context within which a firm identifies and responds to customers" needs, solves problems, procures input, reacts to competitors, and strives for profit' (Christensen, 1997, p. 32). Market-based in essence, the concept also highlights how a company's actions and internal structures are shaped by the market.

The theory of disruptive innovation was first proposed by and remains closely linked to Clayton M. Christensen. In view of the extraordinary influence it has had on academia and managerial practice alike (Tellis, 2006), it has arguably become the most important theory in innovation management research in the last two decades (King and Baatartogtokh, 2015).

4 Development of the theory of disruptive innovation

4.1 Crisis of the previous paradigm in Innovation theory

Since in the terms of Kuhn, the history of disruptive innovation necessarily begins at a point of crisis of the previous paradigm (Kuhn, 2012), the question arises: Had the previous stage of normal science in innovation management research disintegrated to an extent which can be conceived of as crisis prior to the introduction of disruptive innovation?

Preceding disruptive innovation, the state and direction of innovation management research has been described as neither consistent, nor conclusive (Wolfe, 1994). Several theories and distinctions were competing; disorder in the field and disagreements over even the most basic terms and approaches were prevalent (Gopalakrishnan and Damanpour, 1997).

At the time, multiple theories were competing in the field of innovation management research. Theoretical angles such as the resource-dependent view of the firm (Pfeffer and Salancik, 2003), continuous and discontinuous technological change (Dosi, 1982) and architectural innovation (Henderson and Clark, 1990) among others were popular and did establish useful and influential angles for thinking about innovation. Arguably, neither of them managed to establish itself as the dominant framework because each had specific shortcomings in capturing innovation. A detailed analysis of the shortcomings of each theory is beyond the scope of this work, which is why the focus will be on the S-curve theory of innovation. This theory in particular catalyzed the development of disruptive innovation.

The S-curve theory of innovation was widely used in innovation management at the time (Foster, 1986). The theory established, that the development of technological innovation follows the shape of S-curves. When a technology is first introduced, development begins slowly. It then accelerates when more competitors jump onto the technology. Development begins to slow down when the technology approaches its limit and only incremental improvements are possible (Asthana, 1995; Brown, 1992).

Major limitations of S-curve model of innovation have been pointed out by Christensen. He criticized the way it is causally structured and its lack of predictive power, calling special attention to the specific discrepancies between market entrants and incumbent firms (Christensen, 1992a) as well as the narrow focus on technology that disregards architectural and market innovation (Christensen, 1992b).

It can be concluded, that the field of innovation management research was indeed going through a time of crisis pre 1997. Observations not consistent with the S-curve model of innovation paved the way for a new paradigm.

4.2 The revolutionary character of disruptive innovation

The scientific revolution is a key element of Kuhn's theory. Therefore, it needs to be assessed whether disruptive innovation has in fact revolutionized the field.

The beginning of the theory of disruptive innovation is Christensen's (1993) extensive historical observation of the quickly evolving disc drive industry between 1956 and 1990, where he first proposed the distinction between sustaining and disruptive technologies. The concept was gradually expanded to describe phenomena previously unaccounted for in other industries such as printing and department stores (Bower and Christensen, 1995).

In parallel, groundwork for a larger theoretical framework was laid by developing the concept of value networks in collaboration with Rosenbloom (Christensen and Rosenbloom, 1994, 1995). The concept of value networks was an attempt to theorize the abstract space in which firms act in a novel way. Although too narrow a term to become a new paradigm in itself, the concept was crucial for conceptualizing the contingencies of disruptive innovation.

The essential feature of a scientific revolution is the establishment of a new paradigm, such as a consistent and comprehensive scientific theory. Until 1997, theoretical terms that should later become the theory of disruptive innovation had been used to explain specific phenomena, but these descriptors had not been established as a general theory.

Disruptive innovation was fully established as a comprehensive theory with the book "The Innovator's Dilemma" (Christensen, 1997). It quickly gained critical acclaim and notoriety among managers and academics alike (Thomond et al., 2003). At this stage, disruptive innovation became a dominant paradigm of innovation management research.

It can be concluded that the field indeed went through a stage of revolution. In the next section, it will be assessed whether a stage of normal science has followed its establishment as a dominant paradigm.

4.3 Disruptive innovation arriving in normal science

Following a scientific revolution, a phase of normal science revolving around the new paradigm of disruptive innovation is entered. In practice, this phase is characterized by the following aspects: use of the theory as a means of analysis, exploration of its practical application, and refinement of the theory by adding nuance. This results in a large body of research being produced.

The first defining aspect of normal science is the use of the theory as a means of analysis. Disruptive innovation is indeed being applied successfully to new contexts to gain insights into innovation in specific fields. So disruptive innovation has been used to analyze phenomena as diverse as Airbnb and the rise of informal tourism accommodation (Guttentag, 2015), the response of newspapers to the internet (Gilbert, 2001), and the impact of genomics on treating rare diseases in biopharmacology (Ahn et al., 2019). Christensen's more recent books very clearly fit this sense of normal science, too: the concept of disruptive innovation is applied to further removed subject areas such as health care (Christensen et al., 2009), education (Christensen et al., 2016) and higher education (Christensen and Eyring, 2011).

Another characteristic of normal science is the refinement by adding nuance and theorizing details. In recent years, there have been numerous examples of this in disruptive innovation, such as an analysis of the peculiarities of micro entrants (Markman and Waldron, 2014), how threat perception impacts the reaction of an incumbent (Gilbert, 2006) and characterizing systemic disruption (Ansari et al., 2016).

The practical applications of the theory are discussed in "Seeing What's Next" (Christensen et al. 2004) and "The Innovator's DNA" (Dyer et al., 2011). Disruptive innovation is often used to give practical guidance to managers for identifying and dealing with disruption (Butler, 1988).

In normal science, a large body of research is produced, since relatively few publications are necessary to establish a theory, but rising acceptance of the paradigm produces an increasing number of publications. As can be seen in Figure 2, researchers' interest in disruptive innovation has indeed been on the rise. The large and growing body of research serves to confirm that the theory has entered normal science (Clarivate Analytics, 2019).

It has been demonstrated, that disruptive innovation currently clearly fulfils the criteria of normal science. The next step is to investigate whether anomalies have become prevalent.

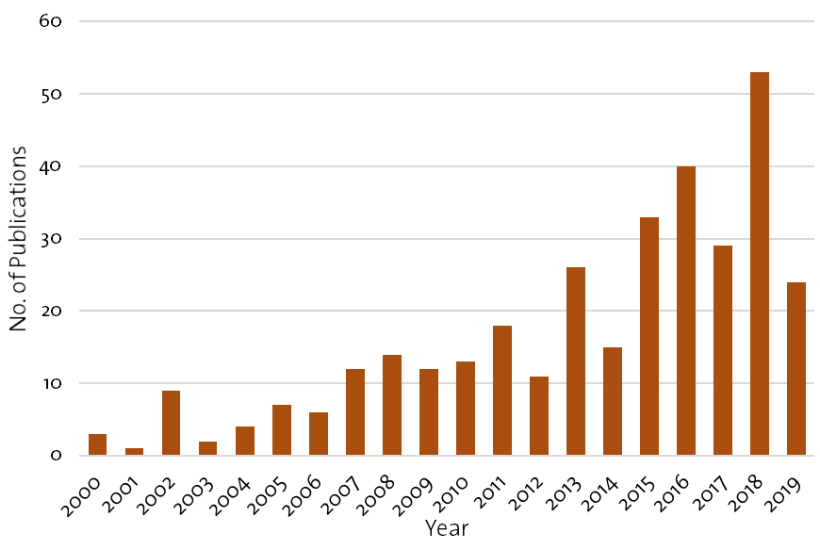
4.4 Consideration of controversies as anomalies

Thus far, it has been firmly established, that the theory of disruptive innovation is in the phase of normal science. But can this be expected to continue or is normal science on the verge of collapse? To answer this, it needs to be examined whether anomalies are present and if so, how many and how severe a threat they are to the theory. To investigate anomalies and their implications, a detailed look at the two main controversies surrounding the theory is necessary: definition and predictive value.

4.4.1 Definition

An issue that has repeatedly been raised by critics is one of definition. Danneels (2004) alleges, that the definition of disruption is neither precise nor consistent, arguing mainly that the characteristics for recognizing disruptive

Figure 2 Number of publications containing the phrases ‚disruptive innovation' or ‚disruptive technology' in the fields of management, business and operations research management science published between 2000 and 2019, source: Clarivate Analytics, 2019).



innovation are not specific enough and fail to account for radical innovation by incumbents. The scope and specificity of the definition is addressed by Tellis (2006): He asserts that it is unclear, whether the claim, that a disruptive innovation after having conquered more niche customers goes on to outperform incumbents and eventually overtakes their core customer base, is part of the definition, raising the question of whether disruptive innovation can only be identified in hindsight.

The confusion surrounding the definition may be related to the term “disruptive”. It is rich in connotation and prompts numerous associations that are not part of the scientific definition. Thus, it is often understood as less specific than intended. One issue is the confusion with radical innovation. Danneels (2004) concludes that disruptive innovation fails to account for observation that radical innovation is often introduced by incumbents (Chandy and Tellis, 2000). In fact, the dichotomy of radical versus incremental innovation is completely distinct from sustaining versus disruptive innovation. Sustaining innovation in Christensen’s sense may well be radical.

Tellis' (2006) criticism serves to illustrate another common misconception: disruptive innovation is often understood as referring to a product or service at a fixed point in time, but is actually intended to refer to a process instead (Christensen et al., 2015). If the former was the case, disruptive innovation could only be identified post hoc. This is not the case: Disruption of the market, implying that the entrant succeeds in taking over significant portions of it, is one of the predictions the model makes for the process of disruptive innovation, not part of its definition. From Kuhn’s framework, it can be predicted that the issue hence will not be critical for the future success of the theory.

Christensen himself concurs that a different name such as “Christensen effect” may have prevented misunderstandings, which arise from the carious connotations of “disruptive” (Christensen, 2006).

In conclusion, the controversy regarding definition of disruptive innovation is not so much an anomaly, but rather a misunderstanding being framed as such.

4.4.2 Predictive Value

As laid out above, allegations that the theory has little to no predictive value because the concept can allegedly only be applied post hoc, are unfounded. The predictive aspects may still fail for other reasons, this will be examined in the following.

There is comparatively little statistical data supporting the predictive value of disruptive innovation (King and Baatartogtokh, 2015). Rather, the theory is largely built on case studies and in-depth qualitative analysis. Qualitative techniques often evoke skepticism (Shah and Corley, 2006) but narratives can in fact be essential for building theory that is novel and interesting – Eisenhardt and Graebner (2007) argue that since it is “deeply embedded in rich empirical data, building theory from cases is likely to produce theory that is accurate, interesting, and testable”.

The predictive value of a theory cannot only be called into question on the grounds of quantitative, but also qualitative data. If a theory is based on and explains case data, it is essential for the predictive value that the concepts apply to a variety of cases and fields. The applicability should overall hold up independently of the educated observer if the narratives are indeed universal. This was tested by King and Baatartogtokh (2015), the results call the claims of the theory into question. They surveyed and interviewed experts on 77 cases sourced from previous discussions by Christensen and Raynor, which had been categorized as examples of disruptive innovation. The study revealed, that experts did not agree with their interpretation. There was substantial disagreement over the assertion, that the cases matched four key criteria of disruptive innovation: That sustaining innovation was present to begin with, that incumbent companies overshot customers' needs, that there was a way incumbents could have responded successfully and that incumbents were displaced by new technologies. These criteria are indeed central to disruptive innovation. If there is a flaw here, it does not stem from a misunderstood definition, but a flaw in the theory as a whole.

The question arises, whether the criteria for disruptive innovation are narrow enough to allow for objective categorization. Unambiguous interpretation is a necessary condition for accurate application and reliable prediction. Some evidence for claiming that the theory is intersubjectively valid and does lead to improved prediction has been provided by Raynor (2011, pp. 41–45), who observed greatly improved prediction capability in business students who had learned about disruptive innovation. Although a clear improvement was observed, the results still show that interpretation is anything but obvious and unambiguous.

It follows, that the theory is lacking in unambiguous interpretability and application, which affects its prediction value. In terms of Kuhn, this poses an anomaly. Further research needs to be conducted; time will show, whether the anomaly can be overcome within normal science by narrowing and clarifying the terms of the theory or if it will ultimately lead to a crisis.

Out of the two anomalies discussed, the second has shown to pose a serious threat to the theory. Kuhn's framework is predictive, there are two options for a theory that is challenged by anomalies. Either, they can be resolved by clarifying the terms. Based on this analysis, the prediction is warranted that disruptive innovation will not be fundamentally challenged by questions surrounding definitions. The legacy of the theory rather hinges on its predictive value. The objection is relatively fundamental. As an anomaly, it may be hard to overcome, which is why it is likely that it will be a dominant issue in future debate. Future work is needed to for theory building and to assess the scope of the problem.

5 Conclusion

The analysis has demonstrated, that Kuhn's theory is a useful means of conceptualizing theory development in innovation management research.

It has been shown how theory of disruptive innovation has progressed through the stages of theory development proposed by Kuhn. Disruptive innovation emerged in a time of crisis in the field of innovation management research. It has further been demonstrated that the introduction of the concept can clearly be conceived of as a scientific revolution. Ever since, the research revolving around disruptive innovation has been in a phase of normal science and anomalies have been investigated. Currently, there are two major controversies surrounding the theory: There has been discussion about the definition of disruptive innovation, and the predictive value of the theory has been called into question. The first controversy is based on misunderstandings, and thus is not a critique that threatens the theory. The predictive value on the other hand has indeed been exposed as an anomaly in Kuhn's terms. Specifically, it has been criticized, that cases often do not unambiguously match the theory as well as previously assumed, and varying interpretation even within the realms of disruptive innovation theory may lead to varying results. The latter anomaly may pose a serious threat to the theory of disruptive innovation. In the terms of Kuhn, anomalies may either be resolved within normal science or lead to the ultimate breakdown of a theory. The analysis has shown that the area of predictive value will be a critical point in the future development of the theory.
Predictions and direction for further research can be derived from the analysis through Kuhn's framework. The current stage of dominance is endangered; the future of the theory hinges on whether the pending issues are resolved. The analysis has shown that further

thought must go into if and how predictive claims can be substantiated. The question demands quantitative insights into predictions and theoretical refinement. At this point, the suitability for objective categorization of innovations is questionable. If the theory cannot meet the current challenges, other theories may outcompete it.

The issue of predictive value is especially relevant in practical application: Companies should be aware that concerns have been raised surrounding the use of disruptive innovation to gain accurate and reliable predictions. Supplementation with additional predictive tools for innovation management may be advisable in practice.

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