

The academic journal for management issues in the chemical industry

Evipridis Lampadariou

## **Brexit and the UK chemical supply chain: A commentary on potential effects**

Andrea Maessen and Jan Haemer

## **Value pricing in the chemical industry – Rebooted**

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## **Raw Material Excellence in the chemical industry, a game changer turning cost into value**

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## **Mercury Free UV Lamp for Disinfection and Purification of Drinking, Process, and Waste Water – An Approach to as- sessing its Innovation Potential and Possible Market Entry Strategies**

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# Letter from the Editors

## Boon or bane - Acting in a highly regulated environment

Recent events in the world like for example the result of British referendum or the Paris Climate Agreement present that the chemical industry has to face a diverse set of challenges. Exemplary, the withdrawal of the UK from the EU could cause serious restrictions in trade or highly influence the subsidiaries operating there. Also the climate agreement lead to requirements the chemical industry needs to react to - for example by redesigning production processes to reduce carbon emissions. Hence, responding to these political developments in the early stages by adjusting the corporate strategy or making the right investments is nowadays necessary to stay competitive. Especially, managers of chemical companies have a tough task addressing those issues at the right point of time. In addition, they also need to find an adequate balance between the companies' business activities and the political environment in which they are operating.

Bearing in mind that Article 50 has not been activated yet, the article "Brexit and the UK chemical supply chain: A commentary on potential effects" by Evripidis Lampadarios points out different potential consequences for the British chemical industry. The 'Brexit' probably entails increased business opportunities for chemical distributors in order to enable chemical producers to focus on their core competencies.

In our Practitioner's section we welcome Andrea Maessen and Jan Haemer, who conducted a survey in early 2017 among 69 managers in the chemical industry. Besides the need for establishing a value-selling culture in chemical companies, the authors' findings comprise not only five myths about pricing new products but also five rules for successful value pricing.

The article "Raw Material Excellence in the chemical industry, a game changer turning cost into value" by Wolfgang Keller provides in-depth insights in how chemical companies can leverage latent procurement potentials. For a successful transformation companies should improve the 12 components along the raw material management model.

The first research paper in this issue "Digitalization in the process industries – Evidence from the German water industry" written by Marius Stoffels and Christian Ziemer analyzes how firms deal with digitalization and harness its opportunities. The empirical study shows that firms embedding IT strategy into their conventional business strategy are more keen to develop new business models.

The water treatment market is expected to grow constantly within the near future. Mike Boxtermann, Simon Korte and Thomas Jüstel addressing this topic with their article "Mercury Free UV lamp for disinfection and purification of drinking, process and waste water – an approach to assessing its innovation potential and possible market entry strategies". After introducing the innovative technology to the reader its market potential is evaluated.

Please enjoy reading the third issue of the fourteenth volume of the Journal of Business Chemistry. We are grateful for the support of all authors and reviewers for this new issue. The Journal of Business Chemistry will publish a special issue on "Digitalization in the chemical industry: beyond the buzz" in June 2018. Authors are welcomed to submit their manuscript before 28th of February. If you have any comments or suggestions, please do not hesitate to contact us at [contact@business-chemistry.org](mailto:contact@business-chemistry.org).

Ruth Herrmann  
(Executive Editor)

Thomas Kopel  
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# Commentary

## Brexit and the UK chemical supply chain: A commentary on potential effects

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Businesses assume that in developed countries, political stability is guaranteed. However, the result of the British referendum (June 2016) has altered the political arena and introduced an era of uncertainty and volatility, referred to as 'Brexit'. The UK chemical industry and its supply chain need to respond and changes might be in order. The routes to market could be changing and there appears to be a shift towards chemical distribution; particularly towards official and appointed chemical distributors rather than direct business and non-exclusive distributors. The emerging market conditions also demand higher flexibility and adaptability, pointing in the direction of small businesses (SMEs) rather than larger enterprises. Nevertheless, as these are the early stages of this process, it is difficult to ascertain whether the initial effects would be of a permanent or temporary nature until a state of equilibrium is again reached in the market.

### 1. Introduction

Without a doubt, the political environment affects and shapes business strategy and clearly impinges on business activity. No company - national or international, large or small - can conduct its business without taking into account the influence of the political environment in which it operates. The nature of this system, its institutions and processes, government involvement in the workflow of the economy and its attempts to influence market structure and behaviour - for instance laws and regulations, tax policies, financial support and loans - but most importantly government decisions have a significant impact on short and long term planning and performance. With political stability seen as a precondition for high industrialization, innovation and business success, recent events in the European political arena have altered the landscape and increased the level of volatility and uncertainty. The results of the British referendum (June 2016) have triggered an unprecedented set of events, addressed under the 'Brexit' umbrella, leading Europe and the UK into uncharted territory alongside with all businesses operating in this

geographical region.

An industry that is most likely to be affected by the aforementioned changes is chemical distribution. As being a significant contributor to the UK economy and employment, the potential effect(s) of Brexit on the UK chemical supply chain become of particular interest and are worth discussing in further detail. Regarding the industry itself, despite the fact that it is well-established and mature, it appears to be highly fragmented and therefore still subject to strong consolidation trends as well as high mergers and acquisitions (M&A) activities. The ever-increasing environmental (climate change, reduction in emissions, sustainable development, green chemistry requirements, corporate social responsibility) and regulatory (REACH, Classification, Labelling and Packaging of substances and mixtures (CLP), Biocidal Products Regulation (BPR), EU competition and information exchanging rules) pressures further contribute to the dynamicity of the market. Globalization and advancements in technology and logistics have already had a profound effect on the supply chain. Increased direct global competition, mainly from Europe and Asia, has caused a shift in the manufacturing focus and investment, with the UK now moving towards high

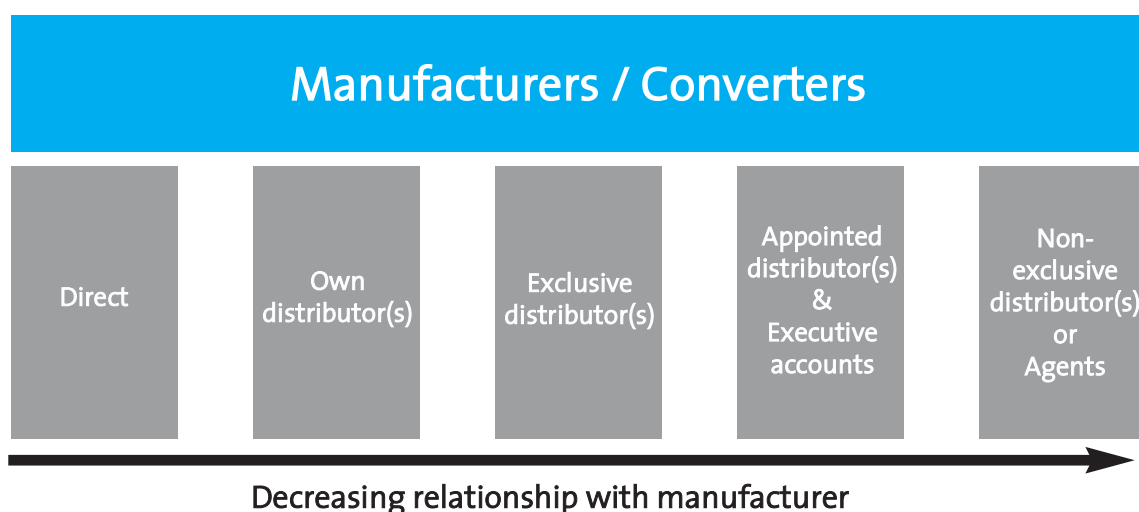
value, niche, technologically advanced applications and markets away from commodities. Inevitably, the manufacturing centre has gradually but steadily moved outside the UK, with only a few large manufacturers remaining alongside a number of smaller, but with strong presence, converters. Accordingly, traditional markets for instance Household, Metalworking and Lubricants, Textile, Leather and Paper, Agrochemicals, Coatings, Plastics, Food, Water treatment, Oilfield and Construction declined in recent years, whereas Pharmaceuticals, Nutraceuticals, Aerospace, Electronics and Personal Care segments presented growth and continuous development. It appears that even in traditional markets the focus is on specialized and niche applications. Consequently, research, product development and innovation remain relatively strong with several R&D centres located in the country. The North East, North West, Yorkshire, Humber and Scotland regions are still the main manufacturing areas. The medium to long-term trend appears to be a decline in the manufacture of large volume-low margin chemicals and specialization within the manufacturing sector (Chemistry Growth Strategy Group, 2014). This is going to be accompanied by an increase in the import of bulk chemicals and fuels and associated storage and distribution (Health and Safety Executive, 2014).

The underlying objective of this commentary is to discuss the potential effect(s) the Brexit has on the UK chemical supply chain in consideration of the different routes to market and the size of the enterprises (SMEs and LMNEs).

## 2. UK Chemicals distribution supply chain

Chemical manufacturers have traditionally distributed their own products and direct supply continues to account for around 90% of the total global distribution, leaving a 10% share for third-party distributors (Boston Consulting Group, 2010; IMAP, 2015). Direct supply is expected to continue for large end-users, accounting for the bulk of producers' output (Angermann M&A International, 2015). However, third-party distribution remains a vital link in the supply chain process as it offers a more flexible, cost-saving and value-adding way to increase market reach, especially to smaller customers (Grand View Research, 2013). As such, in the chemical industry, there is a very clear distinction between direct (including own distribution arm and subsidiary) and third-party supply, incorporating official (exclusive and appointed) distributors, agents (these do not take ownership of the product) and trading companies (these do not provide value added services) (IMAP, 2015). Specifically for the UK chemical industry, Chemagility (2008) identifies the typical supply chain arrangement and distinguishes the market entry strategies for overseas chemical producers into: (i) indirect export, (ii) direct export and (iii) local presence. Indirect export involves the use of chemical traders and export houses. Local presence refers to local production through direct presence or local ownership. Direct export incorporates: (i) direct sales from plant to customer (ii) the presence of a local office and/or subsidiary (own distribution arm), (iii) agents and (iv) distributors (appointed, exclusive and non-appointed).

Figure 1: Routes to market (source: own representation).



Based on above and with respect to the UK chemicals supply chain, five (5) routes to market have been identified. These are presented in Figure 1 below.

In more detail, manufacturers and converters may choose to promote their products either **direct** (i) – for instance Croda Chemicals with a policy not to use distributors – or through their **own distribution** (ii) arm to the end customer; for instance the case of BASF and BTC, where the latter is part of the same group but acts as a distributor of the former. There, all sales, marketing and logistical activities are undertaken and managed by the manufacturer and converter.

The only other way to reach customers and markets is through a third party distributor. Depending on the strength of the relationship (Chemagility, 2015 and 2008), these can be distinguished in:

(iii) **Exclusive:** All business is conducted through distributors-partners. There is often a formal, long-term agreement between the distributor and the chemical manufacturer - the 'Principal'. These buy and sell chemicals from producers and take title to the goods, responsibility for stocking and warehousing, before selling the products on to their customers under their own or their principal's brand name.

(iv) **Appointed:** Equally to the exclusive but with presence of executive accounts where the distributor is excluded from selling to certain companies, for instance Sasol and Shell Chemicals.

(v) **Non-exclusive distributors:** Operating under a traditional buy-sell arrangement, where the relationship is very loose and there is little commitment or loyalty on either side or **agents**. The latter do not take title to or stock goods, but receive a commission for their contribution in helping a manufacturer complete a sale. 'Chemical trader' is another term used to describe this type of distributors. As they are involved with the purchase and resale of commodities and buy from the producer or supplier offering them the best deal at the time. There is no close, long-term relationship with the manufacturer and they mostly rely on their suppliers' logistics to serve their customers.

Considering the market conditions (e.g. globalization, international trade, the market entry of Asian producers) and gradual decline in the manufacturing activity (e.g. reduced product and service offerings, downsizing), the strong presence and higher utilization of chemical distributors in the UK chemicals supply chain will be expected. Man-

ufacturers and converters need to deal with environmental and regulatory pressures, increased competition through globalization, high mergers and acquisitions activity, a need for innovation and raw materials availability as well as costs. Simultaneously, they are required to supply a wide range of products in differing quantities to a hugely diverse customer base. The varied degree of customer fragmentation, the strong presence of small customers in many markets and the differences in the composition of the customer by industry are also a particular challenge, as these require the infrastructure and processes to handle low volumes or a high diversity of products. Local presence is many times a necessity to appreciate and address the individuality of each market.

Distribution – against direct supply – comes as a business 'phenomenon' that reduces the complexity of product distribution respectively customer management and becomes a mean to mitigate costs and trade-related risks. Chemical distributors alleviate environmental and regulatory pressures and minimize logistical complications. They increase market reach to smaller customers (with very specific needs on technical, regulatory and logistical level) and niche, speciality industries while utilizing local knowledge and providing critical market information and feedback. Above all, they support manufacturers and converters concentrate on what they do best: manufacturing. In the recent years though, the distinction between 'manufacturers' and 'distributors' has become increasingly blurred, as an extensive range of services and products are merged to provide differentiated value-adding solutions (i.e. custom blending, bulk and non-bulk repackaging, managing customer inventories, imparting technical training and support).

With regards to the UK chemical distribution market, the industry mainly consists of large enterprises and multinationals (LMNEs) accounting for about 75% of the total market value and a very interesting mix of small and medium-sized enterprises (SMEs) holding the remaining 25% share (Chemagility, 2015). SMEs are enterprises that employ fewer than 250 people and have an annual turnover not exceeding EUR 50 million and an annual balance sheet total not exceeding EUR 43 million (European Union, 2003).

At this point, a distinction must be made between LMNEs and SMEs, as their 'modus operandi' is to become a point of differentiation in the Brexit era. In fact, SMEs have several features that distinguish them from larger firms that could potentially be a strong point of differentiation and a source of competitive advantage under the current market conditions. The absence of complex formal

management structures (mostly flat) and centralized decision-making (characteristic dominance of owner-managers in decision-making) combined with the lack of internal labour markets, provide SMEs with the distinct advantage of flexibility. This enables them to respond quickly and effectively to changes in the business environment and adapt to market trends. Despite the fact that smaller businesses have a limited customer base and fewer resources (financial, human, physical) available, they manage to maintain a distinct closeness to their customers, identifying needs and requirements in 'real' time. Consequently, they are in a better position to accommodate and service smaller customers and niche, specialized markets. Similarly, the absence of formality in the internal and external information and communication systems further improves response times and problem-solving, making SMEs more responsive than their larger counterparts. Even the fact that they tend to concentrate on current performance rather than taking a strategic focus and often engage in management 'fire-fighting', implies a high level of flexibility, adaptability and responsiveness to market changes.

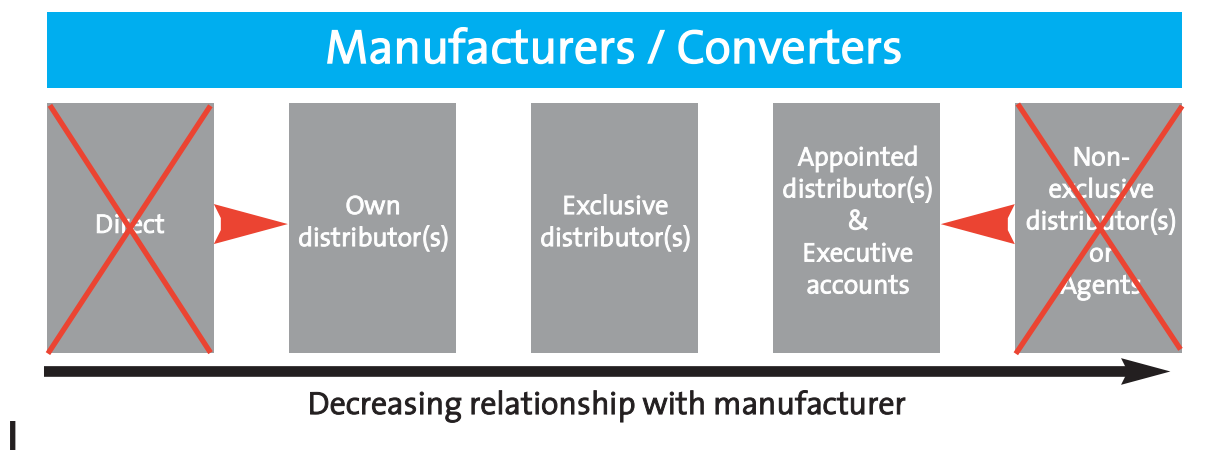
### 3. The 'Brexit' effect

Nevertheless, following the results of the British referendum in 2016, the above described working model might easily change (please refer to figure 1). Even though Article 50 has not been activated, so officially the 'Brexit' era has not set up on the markets yet, reverberations of the decision for the withdrawal can be felt. Despite continuous speculations and scenarios on the potential effects, so far just a few aspects have become visible to the public and industry alike. Uncertainty appears to be the only remaining constant as the UK moves into uncharted territory. To that end, 'Brexit' needs

to be investigated more as a phenomenon over a period of time rather than a singular event. However, it is worth noting that, as these are the early stages of the UK's withdrawal, it is difficult to ascertain whether the initial effects, as argued in this commentary, would be of a permanent or temporary nature until a state of equilibrium has reached the market again.

Regarding the UK chemicals supply chain, speculations and scenarios have already started causing some destabilization (definitely some increased strategizing activity) that could potentially inflict change on the routes to market. In fact, it is the continuing uncertainty that has been acting as a catalyst for these changes. With the markets being uncertain about when article 50 will be activated, there are speculations about the new landscape, for instance the new trade agreements between the UK and EU/ROW, existing regulations (REACH, BPR, CLP) and rules of conducting business, for example information exchange, competition laws and local representation. From a manufacturer and converter's point of view, it would be extremely difficult to strategize under these volatile conditions and with no clear strategy in place; the risk and potentially the cost of doing direct business in the UK could increase. During times of uncertainty and increased risk, distributors appear more appealing against direct supply as, due to local presence and market knowledge, are better equipped to deal with uncertainty and can become an effective mean to reduce and mitigate risk. They are also an effective way of keeping costs down for larger manufacturers in terms of human and physical resources and capital expenditure as well as coping with an ever-increasing level of market fragmentation. A further important influencing factor for distribution will be the distributors' information sharing and market intelligence input, for instance market conditions, key contemporary and future trends,

Figure 2: Routes to market - The 'Brexit' effect (source: own representation).





opportunities, competition as well as their contribution towards demand forecasting and planning, both invaluable assets to manufacturers' operations.

Therefore, there are clear indications that 'Brexit' could not only affect the routes to market but potentially shift the focus towards chemical distribution (as presented in Figure 2). Conversely, in times of hardship, a strong relationship and commitment including a good reputation on both sides is required, putting the non-exclusive distributors and agents at a disadvantage. The focus therefore might be on exclusive, appointed and own distributors who under formal distribution agreements and partnerships, would be called upon to manage uncertainty, change and deal with complications, bureaucracy and risks for the foreseeable future. In addition, this would also lead to an appropriate set of policies and procedures in place, adjusted to local market needs and requirements, to ensure proper management of the suppliers' products up to the end-users. Similarly, they could act as official legal representatives in the UK market, addressing legislative requirements so manufacturers and converters are able to focus on their core competences mainly manufacturing, logistics, research and product development as well as process improvements.

At this point, it is worth noting that even though current conditions seem to favour and 'push' towards exclusive, appointed and own distributors, this does not necessarily mean that direct business would not be a viable option after the withdrawal. The main argument remains that the former appear to be a more sustainable and cost-effective route to manage uncertainty, risk and high market volatility instead of the latter where strategizing and resource commitment is essential.

Considering the fact that the UK chemicals industry remains dynamic in the least, price sensitive, highly fragmented and continues to move towards more specialized, technically focused, niche applications, it is becoming apparent that SMEs might be a better supply position than LMNEs. Thus, it appears that the inherent characteristics of smaller businesses might be more suited for the current market conditions, providing them with a distinct advantage. Whether this advantage can be sustained in the long term – considering that there will be a reaction from larger and multinational companies – remains to be seen. At the same time, Brexit has significantly increased uncertainty and volatility in the market place, conditions that not only favour distribution in general but also require the flexibility, adaptability and quick responses that only smaller businesses can offer. As such, chemical distribution SMEs, due to their size, flexible man-

agement structure, informal strategy and quick decision-making should be able to respond more positively and timely to these conditions.

Overall, both Brexit and the current industry conditions seem to be favouring SMEs as a route to the UK chemicals market. Owners and managers would need to capitalize on the opportunity and adapt to the emerging landscape. An improvement on existing business practices is required with focus on performance, increasing competitiveness and ensuring business continuity. It is also becoming imperative for manufacturers and converters to make informed decisions regarding the assessment and selection of small chemical distributors to access the UK market. Likewise, various stakeholders need to focus on improving strategy formulation and decision-making process in order to support chemical distribution SMEs. Further research in the UK chemical distribution industry during the Brexit era is required to follow up on existing research (for instance Lampadarios, 2016a, b, c and d).

An equally interesting aspect of Brexit that is worth investigating and discussing in the future – as it falls slightly outside the scope of this commentary, but is most certainly related – is the effect it would potentially have on globalization. With globalization and international trade being key drivers for the chemical distribution industry in the recent years, a vote to leave the EU – thus, in a way, rejecting trade openness and labour movements – is causing serious concerns. In fact, Brexit is viewed as a major backlash or even a rejection of globalization; an event that has been feeding fears of deglobalization alongside the results of the US presidential elections and subsequent US policy changes. In the first instance, the increasing deglobalization pressures will most likely reinforce the importance of local 'players' (manufacturers and distributors alike) in their home markets but potentially 'dampen' their plans for international expansion. Further research is needed as the event unfolds itself.

#### 4. Conclusion

Brexit, more a phenomenon than a singular event, has the capacity to affect the routes to the UK chemicals market. Continuous uncertainty and increased volatility could potentially cause a shift in the supply chain towards official and appointed chemical distributors rather than direct business, non-exclusive distributors and agents. This could be due to the fact that chemical distribution is seen by manufacturers as a way to reduce uncertainty and mitigate risks while they concentrate on their core competences, for instance manufacturing, research and development, logistics ( see

Table 1: Conclusions (source: own representation).

	Current market conditions	Reasons for changes	Consequences caused by Brexit
Routes to market	<ul style="list-style-type: none"> <li>Direct</li> <li>Own distributors</li> <li>Exclusive distributor(s)</li> <li>Appointed distributors &amp; Executive accounts</li> <li>Non-exclusive distributor(s) or Agents</li> </ul>	<ul style="list-style-type: none"> <li>Increased uncertainty, volatility and risk</li> <li>Reducing costs of resources and investment</li> <li>Change in trade agreements</li> <li>Change in rules of conducting business</li> <li>Increased commitment required</li> <li>Need for official legal representatives</li> </ul>	Shift to the housing manufacturers and converters: <ul style="list-style-type: none"> <li>Own distributors</li> <li>Exclusive distributor(s)</li> <li>Appointed distributors &amp; Executive accounts</li> </ul>
Size of Enterprises	<ul style="list-style-type: none"> <li>75% Large and Multinationals</li> <li>25% SMEs</li> </ul>	<ul style="list-style-type: none"> <li>Mitigating risk and responsibility</li> <li>Requirement for local presence and market knowledge</li> <li>High fragmentation</li> <li>Move towards niche applications</li> <li>Adaptability / Swift decision-making required</li> <li>Flexible management structures required</li> </ul>	Shift towards SMEs (unclear to what extent until equilibrium reached)

table 1 summarizing the conclusions).

Conversely, chemical distributors in the UK mainly comprise of large enterprises and multinationals (LMNEs) with 75% market share and small businesses (SMEs) holding the remaining 25%. However, the inherent characteristics of the latter (e.g. flexibility, adaptability and closeness to customers) appear to provide them with an advantage not only under the current market conditions (e.g. high fragmentation, product specialization, reduction of manufacturing base and price sensitivity), but especially under the emerging landscape caused by the Brexit.

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# Practitioner's Section

## Value pricing in the chemical industry – Rebooted

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Value pricing has been a topic in the chemicals industry for decades. Still, according to Simon-Kucher studies in the industry, managers feel they have to improve when it comes to their ability to capture value through better pricing. The authors describe what helps to rigorously implement a value pricing approach in the chemicals industry. They outline how to understand “willingness-to-pay” (WTP), they challenge the “one-size fits all” approach and give an explanation why many segmentation model fail, they question traditional price metrics and their ability to capture value, they address how to define the right pricing strategy and they elaborate about value communication.

The authors show that it is time to reboot the thinking about value pricing. They lay out five rules that serve as your reset buttons.

### 1 Introduction

Over the last decade, chemical companies have become pro-active and professional in adjusting their capacity to volatile demand in order to protect prices and margins. As engineers hard at work, they manage their assets well to *protect* value. The more upstream the business model, the truer that is.

But how is the chemical industry doing downstream on the commercial side? How are they doing when it comes to their ability to *capture* value through better pricing?

In their own words: not well.

In early 2017, Simon-Kucher asked managers in the chemical industry in Europe where they see the strongest need for optimization in sales tasks, starting from strategy to organization to implementation. The result was very clear. The majority of the managers saw the most important improvement potential in establishing a value-selling culture (Simon-Kucher, 2017).

The good news is that the managers see how acute this need is. The bad news is that this is not

new. Haven't chemical companies invested considerable time and money over the last 15 years to select and develop their sales teams to be able to argue value and to capture value in pricing?

It's time for companies to step back and reboot their thinking around value pricing. The great news is that companies in all segments of the chemical industry have a lot to build on.

#### Reboot = Innovate

Innovations which can demonstrate true added value are the only way forward for the chemical industry, if managers want to make value pricing finally work to their advantage. This also means *business model* innovation and not merely *product and service* innovation. Let's begin with the latter.

Innovation power and value delivery is typically not the main bottleneck in chemicals. The chemical industry has highly qualified engineers in operations and strong R&D departments. Current innovations range from new material types to opportunities through new digital technologies. New

composite materials, for example, help to reduce component weight and the weight of cars significantly. Materials such as graphene from carbon are stronger, lighter, and more temperature-resistant than any chemical product before. New digital technologies allow companies to track how chemicals perform in operations and processes at their customer, a rich source of data which provides insights on how to improve the product continuously and/or enforce process efficiencies.

So where is the innovation bottleneck? Far too often it is in how chemical companies deal with pricing, and how they price their attractive and in some cases groundbreaking innovations.

### Pricing in general: Help sales argue value better

Increased competition, the hunt for volume, and shorter product lifecycles are putting downward pressure on prices in the chemical industry. At the

**Figure 1 Chemical industry: 5 myths about pricing new products and innovation (source: own representation).**

Pricing for new products and innovations fails most often because companies ignore key pricing and marketing activities until it's too late. But why is last-minute pricing so prevalent in the chemical industry? The reason is the entrenched mindset about pricing and product development, which is based on five myths and misconceptions:

**Myth #1:** *If you simply build a great new product, customers will pay fair value for it.*

“Build it, and they will come” is the mantra. It is a hope-sustaining mindset for innovators who face long odds, fueled with stories about the underdogs who were told “it will never work” until it does.

The first Harry Potter book that was rejected 12 times before finally accepted. Fred Smith's business plan for FedEx earned a failing grade in business school. We all love these stories. But we love them, in part, because they are exceptions to the rule. No one talks about the 95 percent of cases where the exact opposite happened.

**Myth #2:** *The new product must be controlled entirely by the innovation team working in isolation.*

These corporate “artists” need to work by themselves, sealed off from others who might pollute their ideas. Customers' perspectives? Many businesses believe that customers don't really know what they want, so asking them is a useless exercise. Challenging great ideas will result in ugly compromises, or worse, upset the geniuses building the next new big thing.

**Myth #3:** *High failure rate of innovation is normal and is even necessary.*

Today's businesses often believe that the more

attempts you take, the better your chance of finding the new big thing; the few winners bail out the many losers. If the new product, service or business model fails, there will be many more after it, and some of those have to succeed.

**Myth #4:** *Customers must experience new products before they can say how much they'll pay for it.*

Businesses believe it defies the laws of nature to determine how much a customer would be willing to pay for an innovation before the innovation is complete. How could customers possibly know what they are willing to pay for something until they see it?

**Myth #5:** *Until the business knows precisely what it's building, it cannot assess what it is worth.*

The business has to understand all the costs that will go into the product before deciding what to charge customers. This is particularly true if the business is operating in a cost-plus environment.

All these are attractive arguments. They seem to make eminent sense. However, reality is different: Steve Jobs is an absolute exception and his management philosophy can't be directly applied to the chemical industry. By designing your product around a price, your innovations will stand a far greater chance of surviving and thriving. Figuring how much customers will pay when the product is still in the concept stage will make your innovation process far more reliable. You will have a rigorous assessment of your product's true market potential at the *front end* of the innovation, not at the *back end*. You will not need to hope your product takes off in the marketplace after you launch it. You will know.

same time, procurement continues to become more and more professionalized. Your customers bring in skills and expertise in an effort to drive down prices or achieve the most favorable price-value relationship.

Some 39% of the respondents in the Simon-Kucher & Partners Global Pricing Study (Simon-Kucher, 2014) attributed these higher pressures to the rising negotiation power of customers. Increased price transparency stood out for 36% of the respondents. Another frequently cited reason was low-price competition, either from new attackers or from incumbents.

Facing these challenges and sticking to a cost-plus mindset in pricing leaves the sales teams in the chemical industry doomed. They are forced to withstand the heat in the price-focused discussions with their customers without the protection of value arguments. Is this fair support for the sales team?

### Pricing for innovations: A make-or-break decision

Value pricing is most important for new products and innovations, but this is also where it fails most often (see figure 1). A key insight of Simon-Kucher's Global Pricing Study was that almost three out of four new products (72%) fail to achieve their profit targets. Furthermore, one in four companies does not have a single new product in their portfolio that has achieved its profit targets. Is this the fate that the teams which developed these innovative products deserve? Not getting the pricing right for these will destroy the value of these innovations forever, wasting enormous opportunities (Tacke et al., 2014).

Below we outline five rules for successfully rebooting the idea value pricing. The key principles apply for product and service innovation, for business model innovations as well as for breathing new life into established products through re-positioning.

## 2 Five rules for successful value pricing

### 1. The “willingness-to-pay” talk: You can't price without it

Imagine that your sales team knew that the next customer they call on has three requirements, in this order. They want superior quality consistency, because it improves their machine uptime or their own end product. They want technical support available on call, because they have limited skilled technical resources in house. And they want a good price.

That is an ideal opportunity for value-selling.

What implications would these have on your offer design, price positioning, and value communications? Knowing this separates the companies who can differentiate from the companies who merely compete.

The problem is that so many companies never give themselves this opportunity. They never had the “willingness-to-pay” (WTP) talk with their customers. Without that talk, a pricing discussion during a sales call is like a pop quiz, a last-minute guessing game based on hunches or experience rather than knowing what *this* customer wants.

Rather than leaving pricing to the last minute, the offer design, price positioning, and value communications process should start with pricing. The product or offer needs to be designed around the price, not the other way around. Companies often have an idea what customers will say about their “willingness-to-pay” (WTP), but they have not actually asked them in order to truly understand it.

You have to have these conversations. Our clients position these discussions with their customers as “value talks”, not as pricing discussions to measure and define value. They take in different views, depending on who the decider is: the production guy, the R&D folks or the procurement.

The most important goals of these value talks or WTP talks is to understand the price range customers have in mind (meaning their overall WTP) and the extent of their interest in specific features (what matters and what doesn't). This will help to focus product and offer development on differentiation versus competition, knowing what customers will value at all and value most.

In the example above, the company making the sales call was convinced its offer was differentiated from competition by superior quality consistency, by having local stock in the country, and by good customer relations. But at the same time, they said their customers' top priority was getting the lowest price. The customer refuted that view when we talked to them.

Insights on WTP are also indispensable when it comes to assessing and monetizing solutions based on new digital technologies. The revenue and monetization model of new business models need a prototyping and customer testing. What is the WTP for a real-time data-driven process for water management, as provided by Ecolab (Blog Microsoft) as compared to the price of a water chemical? Would customers accept and value a process integration at all?

Customer feedback is essential. Companies typically capture it in multiple iterations in a pragmatic and quick form in order to understand what customers really value, but without taking too much time to market.

Having “the talk” and learning how you can best serve your customers is a win for everyone. It’s time to win.

## 2. “One-size-fits-all” and rigid solutions: Don’t default to them

We have not found a single market where customer needs are homogenous. So why do companies offer “one-size-fits-all” solutions?

There are two reasons. Either they develop products or offerings for the “average” customer, whoever that may be. Or they have at least one segmentation, which is nice in theory but hardly useful in practice because the segmentations are not actionable.

Your segmentation must become a driver of product design or offer development. To ensure this, you need to build it upon what you learned in Rule #1: a deep understanding of the customers, their needs, and their WTP.

In a recent consulting project for a coatings and adhesives producer, the client wanted to develop a customer segmentation in order to derive differentiated offerings. Their hypothesis was that they had two segments. The price sensitive segment would be best served with a “lean” offer at a competitive price, without any value-added service. The value-seeking segment would be willing to pay a premium for a premium offer. Even better, the client felt they could pigeonhole their customers into either the price-seeker or the value-seeker box. Once in the box, the customer would receive either the lean or the premium offering.

There was a kernel of truth in these hypotheses, but they were based on incomplete informa-

tion. The difference maker was the “value talk”, which in this case began with a customer survey. It revealed that almost all customers considered the fees for the value-added services for the premium offer as already included in the current product price. Offering differentiated service packages for different segments would have been very difficult to implement without risking price erosion by introducing the “lean” offer.

We recommended to de-bundle the offer and use service fees as mark-ups on product prices in order to quantify the value and make the product and service value transparent to the customer (see figure 2). We also recommended a slow migration from a premium offer towards a “lean” offer by taking out services for price sensitive customers. This would help mitigate the risk of price erosion.

Your ultimate goal is to help your customers self-select their segment, rather than selecting the segment for them and imposing a solution. Customers buy what they need and what meets their willingness or ability to pay. Providing them with options and letting them choose is how segmentation works best.

You have no obligation to serve every segment. Your obligation is to describe and thoroughly understand the most attractive ones in detail, in order to address them right.

## 3. The monetization model: Go beyond the traditional price metric

Chemicals are typically priced by the kg, ton, or liter. But such monetization models seldom reflect the true value of a product. Customers don’t buy products. To quote Peter Drucker (Drucker, 1954),

**Figure 2** Companies in the chemical industry offer products and services: 10 things which are easy to do in service pricing in the chemical industry (source: own representation).

1. Treat services as products  
... each service has to have a material number
2. Get your standard service offer crystal clear  
... all deviations from the standard will be charged
3. Display services on your invoice  
... even with a price of “o”
4. Charge services automatically  
... it is easier to take a charge off the invoice then to add it later
5. Avoid both nitty-gritty and excessive service pricing  
... the Ryanair case is not applicable to B2B chemicals
6. Share benefits 50-50 with your customer when pricing your services  
... it is not about optimizing to the last digit
7. Don’t attach price tags to all services  
... some are so special that they are priced “upon request” only
8. Grant the initial 3 to 5 service uses for free and then start charging  
... this eases the negotiation
9. Ramp up the charging of services slowly  
... first 50% of your customers, then address the next 30% and 20%
10. Use service charges when you want to avoid a behavior  
... and use privileges (discounts) when you want to reward behavior

they buy the added value or the benefits that the product and the manufacturers provide. Your monetization model needs to reflect this added value.

Take the case of lightweight composite materials. In automobiles, they help drivers reduce their fuel consumption, lower their emissions, and perhaps even pay lower taxes. They even help improve the overall driving experience. That is an impressive package of benefits. The car manufacturer, in turn, has a much more robust price-value position thanks to better product performance, has reduced costs, and may even profit from the positive impact on brand perception as it brings innovative technologies to market. That is another impressive package of benefits.

The chemical companies' traditional metric to price these lightweight materials would be per kg. But it should be clear that this model reflects neither the value of lightweight material (think benefits!) nor the specific value of the car components which use them. Only a price per component (including the component design) will be able to monetize this considerable value added.

Monetization models can confer significant competitive advantages on a new product. They can also be true game changers. When done right, the best monetization models are a win-win for you, your customers, and your customers' customers.

Think back to the Ecolab example and the real-time data-driven process for a water management solution. The added value is the ability to identify ways to operate a specific water treatment plant more effectively and efficiently on a continuous basis, based on gathered information and benchmarks. The value is derived from the solution, the combination of water chemicals and services. A model based on kg or bags of water chemicals doesn't align with this value. Instead, the monetization model should be based on an inexpensive or free installation of the hardware and a subscription price model to generate recurring revenue streams.

To quantify the value of the solutions, you have several options, and these often work best in combination. You can conduct expert panels with purchasers and engineers. You can conduct customer surveys. And you can draw on your considerable in-house expertise and estimate the value based on assumptions and approximations.

#### 4. The pricing strategy: Pick the winning option

In the previous section we said that the car company using lightweight materials has a more robust price-value position. The challenge for that company is how to take advantage of that newfound position. The answer lies in pricing strategy.

There are two basic options: price low for a pen-

etration strategy or aim high for a skimming strategy.

To make this decision a company needs to gather data on four pillars: value, price, cost, and volume. Understanding what customers are willing to pay, how the volume changes when you change the price, what potential competitive responses are, and how to react to them, is at the core here. The insights from this information shape the pricing strategy.

Let's take the launch of "green" products as an example. We recommended that a client offers "green" products at premium prices on top of their standard offering. This price strategy entails successively skimming the value by starting with the customers who are willing to pay the most. The customers have the choice to buy the cheaper standard solution or the premium "green" product. If capacity utilization targets do not allow for this high price niche strategy, marketing cooperation or joint ventures could make sense in order to relieve the volume pressure and allow for value capturing.

Our observation is that companies with well-defined pricing strategies are 40% more likely to capture their value potential than firms that don't have them (Sebastian and Maessen, 2010).

#### 5. The communication challenge: Focus on benefits, not features

Take a close look at this value proposition: "Shipping customers have achieved savings of up to 9% through improved ship fuel efficiency due to our recommendation of which coating to use".

The power of such a statement comes from the fact that it describes, explains, and quantifies a benefit. While this sounds simple, we routinely see companies struggle in the chemical industry with crafting this kind of value communication. They struggle because they don't quantify benefits. They focus on features customers don't feel are important. They don't thoroughly test value communication messages with customers.

Mastering the value communications is just as important as mastering the process of value delivery. If you can't clearly communicate your value, how can your customers understand why they need your offer and why they should pay for it?

The value message above on shipping comes from AkzoNobel. They use insights from Big Data to sell the value of their marine coatings. Millions of data points out of their labs, together with advanced analytics techniques, proprietary algorithms and models, generate a full cost-benefit analysis which helps the company identify the most fuel efficient anti-fouling coating under different



scenarios. They can make highly specific predictions that are dependent on vessel type, trading route, speed, and activity.

Segment-specific customization, monitoring, and continual improvement are vitally important to conveying compelling value messages. It is important to have marketing departments that gather marketing intelligence and compile market databases, as well as product managers who manage the supply chain. But they alone are not sufficient to support value communication. You need dedicated people in functions charged with value communication.

### 3 Summary and conclusion

We have laid out five rules to reboot your thinking on value pricing and help you rigorously implement a value pricing approach. Here is a brief recap:

- You need to design your products and solutions around the price, not the other way around (Ramanujam and Tacke, 2016). Have the value talk with customers. Although you may have an idea of what your customers are willing to pay, ask them directly and understand it thoroughly.
- Your segmentation must be actionable and based on a deep understanding of your customer base. Refrain from pigeonholing your customers. Develop differentiated offerings for the segments you want to serve, and serve them right.
- Prices by kg, ton, or liter seldom reflect the true value of a product. Challenge your monetization model. Done right, it can become a true game changer and create a significant competitive advantage.
- Your choice of pricing strategy is decisive. Aim to provide your customers with options. Skimming enables you to start capturing value from customers who are willing to pay the most. Companies with short- and long-term monetization plans are more likely to capture their value potential than firms that don't have them.
- Value communication is as important as value delivery. Develop compelling messages focused on important benefits. Tailor them to your segments, and continually improve them with a dedicated function charged with the value communication task.

Value pricing has been a topic in the chemicals industry for decades. Still, managers feel they have to improve. It is time to step back and reboot the thinking around value pricing. These five rules are your reset buttons.

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# Practitioner's Section

## Raw Material Excellence in the chemical industry, a game changer turning cost into value

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Raw material spend across the specialty chemicals industry is accounting for approx. 35% to 40% of net sales, representing their single highest cost position. Across the entire chemicals industry sustainable raw material cost reduction is even wider and often competing with other objectives such as maximum security of raw material and indirectly own sales products supply, consistent quality, high supply chain flexibility, and the right level of complexity in the value chain.

This article describes the evolution concept of value-chain oriented raw material management in the chemicals industry over the last 10 years, its individual components, and how first chemical companies have mastered their transformation to achieve the highest level of composite raw materials management performance, Raw Material Excellence. Procurement is no longer perceived as “cost center” but as “value driver” and hence instrumental for sustainable profits. In other words Raw Material Excellence is nothing less than a game changer.

### 1 Introduction

Over the last 10 years mid-size and large chemical companies have developed an innovative approach to raw material management. Additional functions along the value chain have accepted new roles in raw material management, e.g. quality control, product and application development, manufacturing, sales and marketing and controlling to name the key players. Cross-functionality is key to strive the balance between the above mentioned multi-dimensional objectives that have previously been perceived as incompatible (Leybovich, 2010; McPherson, 2016).

### 2 Raw material management – Raw Material Excellence

Exactly 10 years ago, some specialty chemical companies, e.g. manufacturers of coatings and additives, soon followed by companies serving other chemical segments such as fine chemicals, e.g. process flavors or vitamins, intermediates and pharmaceutical raw materials, e.g. high volume acids, alcohols or solvents, and even basic chemicals, e.g.

fertilizers, have begun to transform the traditional way of sourcing.

The objective of this business model innovation has been to refine the role of raw materials from being a “pure cost” to the company associated with some latent to obvious risks to supply chain and sales of finished goods to own customers towards “value creating building blocks” (Gorin, 2016).

In a number of value chain and procurement performance improvement projects, the raw material management framework with its current highest level of performance, Raw Material Excellence has been developed, applied and increasingly become popular across the chemical industry.

What makes this innovative approach unique and successful is combining, aligning and integrating a number of value chain components that often enough have previously been treated independently (VCNI, 2017). Only by ensuring management's commitment for a radical change towards a holistic approach, obtaining the buy-in of all affected players along the entire value chain and setting the expectation right that this transformation can easily take 24 months, the fundamental success criteria are put in place.

Figure 1 Chemicals industry procurement and value chain improvement based raw material management maturity model. The approach has been developed between 2007 and 2016. Raw Material Excellence, represents raw material management best practice in the Pre-Digitization-Era (source: own representation).

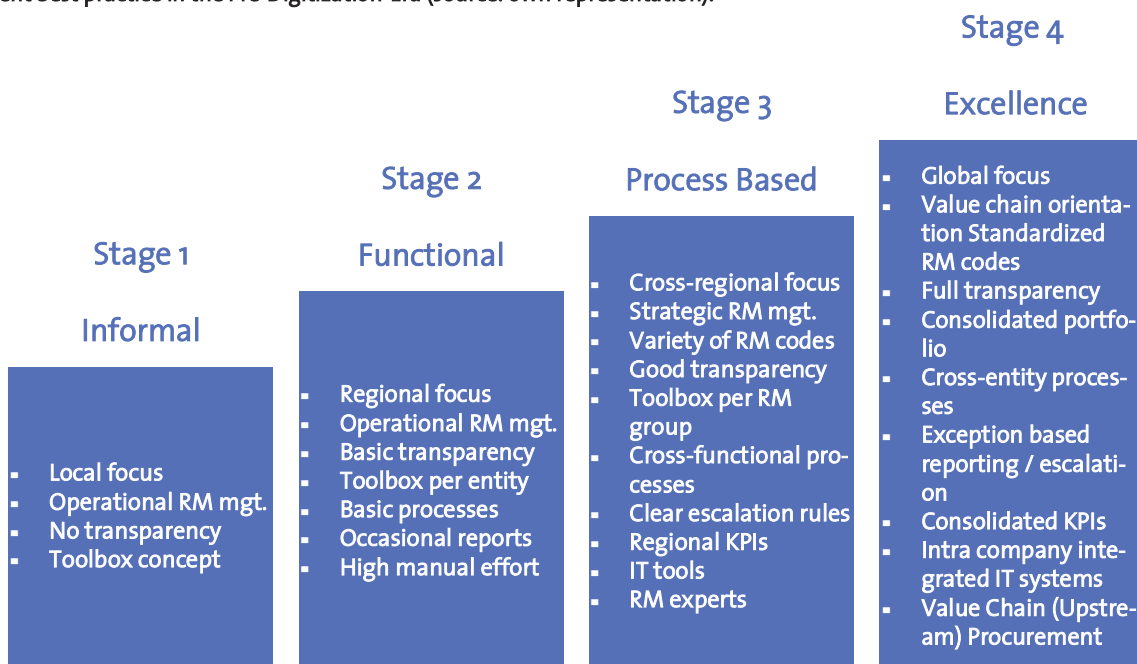
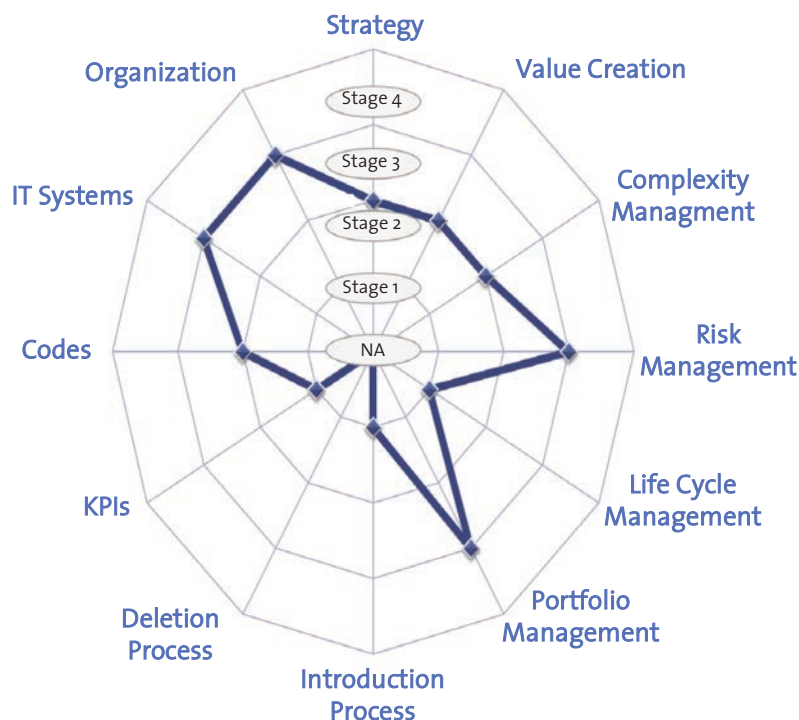


Figure 2 12 Components of the raw material management maturity model as of 2017 (source: own representation).



The model is currently covering 12 dimensions and is being applied throughout the transformation, from the initial performance assessment to define the status quo via target setting through implementation and post transformation reviews. The individual components are being introduced in the following paragraphs in detail. As with most models, the raw material management framework is a living model, undergoing steady expansions and extensions. Towards the end of this article, we will take a look at Raw Material Excellence 4.0 which is expected to be the next milestone or maturity stage thanks to the additional opportunities digitalization will provide for the value creation out of raw materials.

### 2.1 Raw Material Strategy

There are two success factors to succeed in raw material management and ultimately achieve the stage of Raw Material Excellence. The first one is to define a truly balanced set of raw material related strategic objectives (Heß, 2015). The second one is to be aware their interrelationships which often run counter to each other.

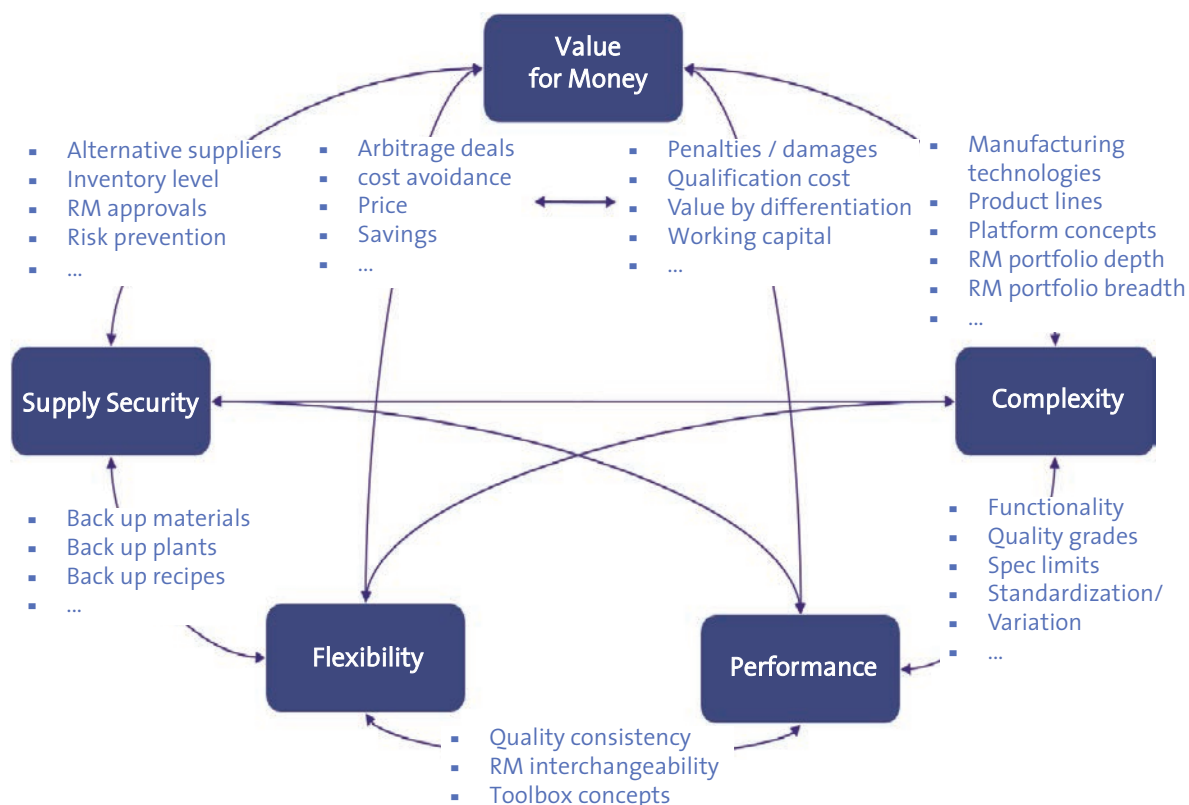
Value chain oriented raw material management

requires a thorough understanding of the suppliers' educts, their manufacturing technologies, the conversion of these chemicals in own manufacturing and formulation plants, own customers' technologies and their products and applications. Here is one example why this is so important. When you look at the disastrous impact residual silicones can have in an automotive OEM's paint shop, a coatings maker will do his utmost to ban silicone based lubricants from all his manufacturing, formulation and filling plants. The entire value chain however – and therefore the risk of silicone contamination, customer application failure and potential contractual penalties and damages - is much longer. Only if, for example, additives and resins suppliers' manufacturing and filling technologies are also free of silicone based lubricants, this critical-to-quality parameter is sufficiently taken care of.

It is instrumental to understand that raw material related objectives are complementary to classic procurement strategies which are traditionally much more focusing on suppliers, supplier management, cost and – increasingly – security of supply.

Security of supply as part of raw material management is taking an end-to-end perspective from

Figure 3 Raw material management strategic objectives (source: own representation).



the supply of raw materials through the delivery of own sales products to the customers and its implications along the entire value chain. We will discuss the details in the risk management section.

Complexity is addressing the number and types of materials used to manufacture own products and formulations. One key consideration is the trade-off between opportunities through standardization and specific quality requirements. Depth and breadth of raw material portfolio are without doubt two helpful but not exhaustive metrics to characterize complexity associated with raw materials in a meaningful manner, as we will see in the paragraphs dealing with complexity and metrics.

In order to ensure the desired performance, raw materials have not only to match own raw material, product and manufacturing process specifications. While some of them serve as process aid with no impact on the final product, others are crucial for customer's applications, most typically so called functional additives. One trade-off here is the need to differentiate, e.g. one material for one effect, vs the toolbox or platform approach, qualifying and maintaining fewer "multi-purpose" items. This is a good example for tensions in the overall raw material management strategy. Multi-purpose items may be more expensive but offer synergies of scale. Effect or application specific materials will be sold in lower volumes, potentially at better cost, but they blow up the portfolio and increase complexity cost. We will see more in the portfolio, material introduction, deletion and life-cycle sections of this article.

The same sections will provide more insights into the often desired but rarely fully achieved supply chain or value chain flexibility, the objective of which being to have a meaningful number of back-up solutions qualified. These include raw materials from other sources, those with slightly different specifications that still allow making products and formulation acc. to customers' needs, use of solids vs solutions and vice versa, if the – validated – process is allowing for that and so forth. While validated back-up options provide solutions to bottlenecks and technical issues, they increase portfolio size and complexity.

Value for money is probably best demonstrating the paradigm change when talking about raw material management instead "purchasing" or "procurement" of chemicals: The total-cost-benefit-perspective looks at one-off qualification, change over effort and ongoing acquisition cost of raw materials on the one hand side and on the total economic benefit they generate through their conversion to intermediates, products and formulations. Without taking the entire value chain into consideration, financial benefits from complexity

cost reduction in sourcing, quality, production and product management and sales price elasticity would be left out (Kerkhoff et al., 2009).

A complete raw material management strategy requires additional components which we will discuss under organization addressing new and additional, internal and cross-company, value chain oriented roles and responsibilities, IT tools and systems referred to as e-Procurement that are serving the same objectives and scope, and last not least performance management demonstrate the successes of raw material management/ Raw Material Excellence.

Another way of looking at the new approach how to deal with raw material management is the following: "Historically, procurement has looked in the rear-view mirror and out of the back window; now we can look out through the windscreen at the road ahead," says Andrew Coulcher, director of membership and knowledge at the Chartered Institute of Purchasing and Supply (Gascoigne, 2017).

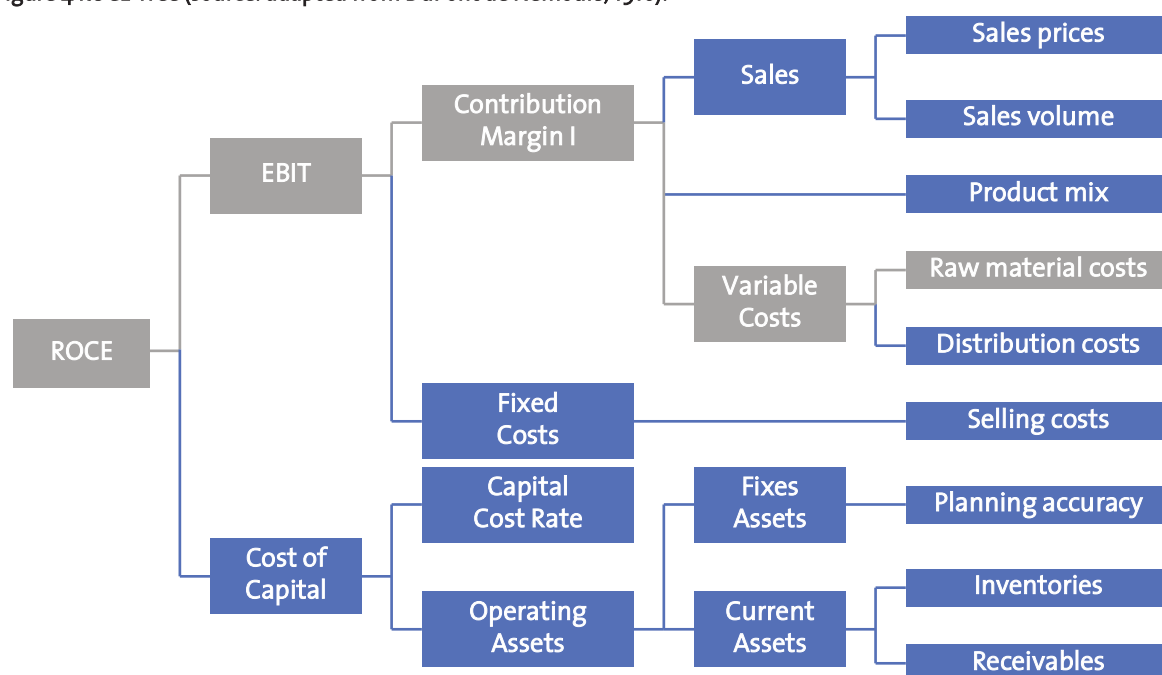
## 2.2 Raw material management Value Creation

The second component of the framework is dealing with the financial objectives of raw material sourcing and the value creation through its use in the company's value chain, encompassing some classic elements such as cost savings and cost avoidance as well as some more advanced objectives, e.g. complexity cost reduction and business profit increase (Gabath, 2010; Hofmann et al., 2012; Schuh et al., 2008).

Since exactly one century DuPont's ROCE tree has become the role model to qualitatively and quantitatively visualize value creation in chemical and other companies. Raw material management is complementing this proven, "output-oriented" approach by putting special emphasis on one of its inputs, raw material cost, and defining the mutual interdependencies to all other branches of the ROCE tree. For example, operating assets are being linked to raw material cost via "fixed assets", i.e. technology platforms and process technologies, since all of them are converting raw material in one or the other way. More apparent is the link of raw materials to "current assets" via inventories which are in turn a variable in the company's value chain risk management. Even the impact of raw materials on revenues needs to be considered: Sustainable cost reduction of raw materials may in some instances provide Product Management and Sales opportunities to win additional business and to sell additional volumes via adjusted sales prices without compromising on margin (Falter et al., 2017).

Over the last 10 years a best practice process to

Figure 4 ROCE Tree (source: adapted from DuPont de Nemours, 1916).



“turn cost into value” has emerged. Similar to the Stage Gate Process in innovation management, a multi-disciplinary approach is required here, too. Starting with the assessment of ideas to cut Total Cost of Ownership (TOCO) or to increase the value the raw material can provide to the company, two pathways are simultaneously pursued. Procurement experts are conducting classic supply market research to identify supply alternatives. Once they are successful and materials can easily be exchanged, the process is cut short. More likely, though, is the second route. Since the emphasis of the process is on value creation, the definition of an early business case and its iterations throughout the process are crucial. Once the initial business case has been confirmed, technical feasibility, impact on security of supply and customer involvement, e.g. for qualification and approval of modified final products are being defined. If after these checks the implementation still proves beneficial for the company, the concept is changing status and becoming an official project. To keep control over the portfolio of raw material value creation projects, the standard approach to multi-project-management is applied. Standardized metrics and stage gate decisions ensure the best projects to continue while others might be put on hold or stopped, e.g. in case of scarce resources. Timelines of the process depend a lot on the level of customer approval, quite popular in case of semiconductor

industry customers buying electronic chemicals, automotive OEMs purchasing coatings, pharmaceutical or food industry customers sourcing chemicals that might be critical-to-patient or consumer.

In any case, if a value creation project has achieved the desired return on invest can only be demonstrated, if the company is tracking sales and margins on the one hand side and total cost, i.e. including one-off changeover cost and ongoing cost base reduction, for the period defined in the business case.

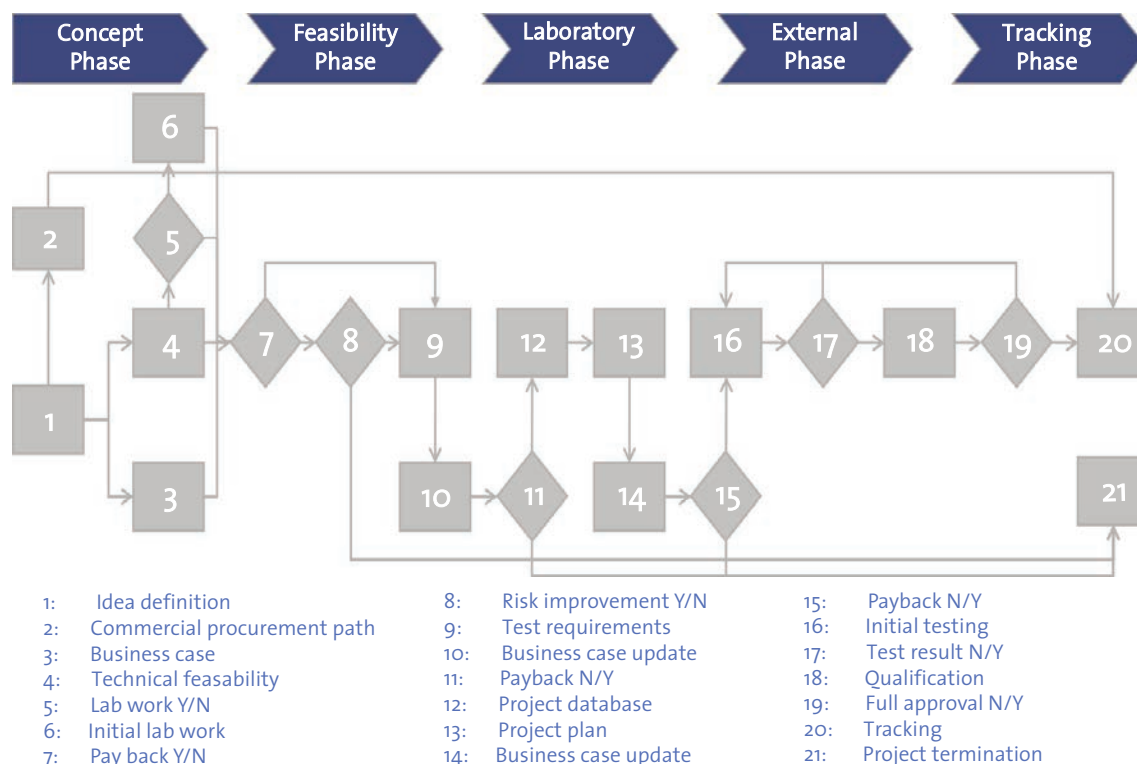
### 2.3 Raw Material Complexity Management

One of the first and most popular statements you are coming across when talking about complexity of value chain, supply chain, product or raw material portfolio is “we have to reduce it” (VCI, 2012). Raw material management is taking a different, much smarter approach instead (CCI, 2013).

The main issue with complexity is the lack of ways to measure it accurately, a consequence are poor transparency and non-fact based judgments on good or bad, value adding or value destroying complexity (GEP, 2017).

The proven approach taken by a number of chemical companies is to first get transparency on the number and type of raw material variations, such as grades, packaging size and type, chemical and/ or trade name, potentially in several languages

Figure 5 Raw Material Value Creation Process (source: own representation).



etc. (Fang, 2017). The second step is to get control over the use of the true “chemical building blocks” in the value chain with a chemical building block meaning the essential characteristics of a raw material, e.g. chemical identity (CAS in case of pure chemicals) and purity or concentration. One of the most impressive examples for unrecognized, costly complexity has been a quite popular solvent, Butyl acetate 98% to 100% used by a coatings manufacturer in 4 regions. 37 product lines in 4 Business Units have been using no less than 22 variations of one and the same solvent without seeing the obvious in their already largely harmonized enterprise resource planning (ERP) system.

Besides the sheer number of raw materials and variants as one driver of complexity, an often neglected facet of raw materials’ use needs to be taken care of, the level of sharing raw materials across sites, plants, manufacturing technologies and processes, products and formulations. To understand the concept and impact of raw material toolboxes, technology and product platforms, “raw material family trees” are helpful models. Looking at the usage lists of raw materials, i.e. from an early stage in the value chain to a late one, and then at the BOMs (bills-of-material), i.e. taking look the

other way round, you can derive very comprehensive “raw material family trees” to visualize the fortune of a raw material in a chemical company’s value chain. Once conducted right, the number of “independent raw material family trees”, i.e. those without or with very limited overlaps to others, and the position and number of “branches” and “crotches” in the family trees point out main complexity drivers. Under the lead of so called raw material experts, the impact on complexity cost but also on other parameters such as cycle times and inventory levels can be assessed and ultimately the right measures taken to get control over unwanted complexity. However we need to keep in mind that for very good reasons there is also some intended or mandatory complexity. If final product or application performance is enabled by a functional molecule, replacing it for the sake of standardization and complexity reduction is a no-go. Toll manufacturers may not be able to pull this lever either, if they rely on the BOMs of their customer. Manufacturers of fine chemicals for pharmaceutical use may be obliged to use pharmacopeia grade raw materials for some products, while other product lines benefit from lower cost alternatives.

By defining a lead parameter, e.g. the CAS num-

ber, and understanding the contents behind occasionally poor master data material group owners/lead buyers have been recognizing commonalities and differentiators among the 22 Butyl acetate variants, e.g. identical suppliers offering different prices to different plants. Not only bundling opportunities as a procurement lever have been obtained by this exercise, also supplier competition has been increased, better prices have been achieved and last not least by becoming aware of different approved suppliers, risk mitigation measures have come on top – for free.

What sounds straight forward is in reality depending on some conditions that are today not always in place as required yet. Comparability and transparency require a mature ERP system, a well set-up and maintained Business Warehouse and – often the key issue – high quality master data.

## 2.4 Raw Material Risk Management

Already 10 years back raw material sourcing risk management has been a high to very high priority for specialty and fine chemical companies – if you listened to procurement managers and Chief Product Officers (CPOs). Taking a closer look into their organizations has revealed a slightly different picture, though. Only 40% of companies have had sufficient expertise in house, 35% of them explicit risk management processes in place and none of them dedicated risk management IT tools or systems implemented to successfully identify, evaluate and mitigate raw materials risks at that time (Keller, 2008).

More and more chemical companies have recognized the importance of value chain risk management (Schuh et al., 2012). Few of them are explicitly highlighting their efforts in the raw material area, though. A good exception is Givaudan, “to be forewarned is to be forearmed, which is why the comprehensive raw material risk management system is an excellent tool for Givaudan. At Givaudan, raw materials sourcing risk is a cross-functional consideration. Identifying and mitigating risk is integral to securing supply and satisfying customer needs” (Rogaar, 2017).

One can say a paradigm change has taken place. The number of companies within and beyond the chemicals industry with explicit and IT enabled risk management capabilities or the intention to implement it short-term has more than doubled to 85% in the meantime (McGovern, 2014). Business and procurement managers are no longer looking at risk management effort as – in the worst case – “nice-to-have” insurance premium. Fortunately, the perspective has widened to the better. Securing the supply from raw material through delivery

of sales products along the entire value chain has become a business priority. There is a number of good reasons for this, e.g. service and security of supply becoming a differentiation against low cost market intruders from Middle and Far East, avoidance of contractual penalties and damages, reputation as reliable partner and ultimately shareholder value.

What has dramatically changed towards the better in raw material risk management is a consistent approach going far beyond the traditional, fragmented approach, focusing often on a handful of metrics only, such as material ABC analysis by volume or value and the business impact in case of value chain interruptions. One successful, more holistic risk management process is encompassing of 4 process steps owned by a dedicated individual, often but not necessarily a member of the raw material management organization. Once a significant enough raw material risk is being detected, a well-trained task force representing all affected value chain functions is switching mode from stand-by to active and is taking care of the activation of the cross-functionally created specific risk mitigation plan, the short term, i.e. problem solving, and long-term, i.e. avoidance of recurrence and lessons learned, mitigation plan. In order not to waste cost and time of raw material experts and representatives from procurement, product development, manufacturing, quality control (QC), commercial and finance it is vital to maintain and update a raw material risk database regularly. In recent risk management implementations a number of 8-12 metrics has become best practice to characterize raw material related risks and their impact on the value chain.

Looking at the different types of risk management metrics it becomes obvious that multi-disciplinary expertise is required to make the process successful, mainly for the non-data based and hence somewhat subjective parameters.

Along the risk probability dimension, “the upstream functions” of the value chain are primarily asked for their judgment. Raw material QC knows best about the “number of standard and back-up approvals” for material-product-combinations, procurement will take a perspective on the “existence of alternative suppliers”, “supplier relationship” and “market situation” and raw material experts on “availability of alternative materials” not only in the market but also across product lines, sites, businesses and region within the own company – transparency provided. Depending on responsibility for different types of inventory in the chain, procurement, supply chain, commercial or finance will cover the “stock levels”.

The business impact dimension will require



more contribution from the value chain “downstream functions” such as product management, sales/ key account management and finance. They’ll assess the impact of a materialized risk on – lost - sales products “volume”, “revenue”, and “margin” and on the “number and size of affected customers”. The latter parameter and the “competitive threat”, i.e. the ongoing loss of business as a consequence of a customer changing an unreliable supplier, are particularly important for key business decisions, e.g. the allocation of remaining stock to the privileged customers.

Here is a good example for the benefits of raw material risk management addressing the entire value chain. A fine chemicals company has conducted a thorough risk assessment of their approx. 350 raw materials and has been very much surprised about the top scoring item. The fact that purified water has scored highest is mainly due to two aspects. First, it is literally being used in 100% of all products manufactured in that site. Therefore 100% of sales revenue and margin are affected, i.e. the business impact can’t be higher. Secondly there is a very modern, high throughput water purification unit on site. Unfortunately, there is no back up. Should the unit fail, no effective risk mitigation measure is in place to secure deliveries to customers.

Thanks to the implementation of the holistic

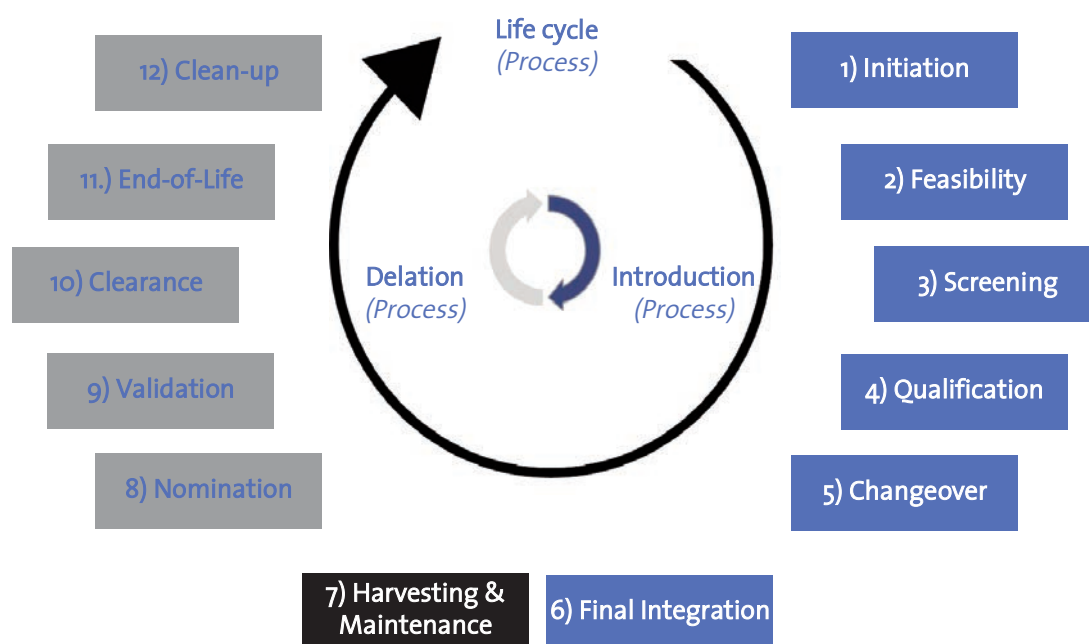
risk management process at the client, a back-up facility has been built shortly after the assessment.

## 2.5 Raw Material Life Cycle Management

One of the least known, most ignored but increasingly important processes in raw material management is life cycle management (Mancini et al., 2013). The rationale is simple. When you look at raw material portfolios across chemical companies and interview procurement managers and technical raw material experts more than 90% of them are stating, their material portfolio has been growing over the last years, but exact numbers are not available, though.

In other words, the proliferation of raw materials in chemical companies is due to a lack of portfolio and of life cycle management, both processes being closely connected. The main difference is that classic raw material processes such as raw material introduction, the main use of raw materials (i.e. their conversion in manufacturing processes) and raw material deletion are event-based processes, whereas portfolio management is time-based (i.e. taking a perpendicular view at raw materials or a snapshot at the month end or end of the quarter in order to analyze the performance of the entirety of raw materials, make decisions and initiate further raw material options).

Figure 6 Stages in the Raw Material Life Cycle Process (source: own representation).



The life cycle of a raw material is spanning the entire period from the concept to introduce a new material within a chemical company through its termination (Lacy et al., 2013), i.e. the deletion of all master data in the ERP system. A raw material's life cycle can range from a few weeks, e.g. when making a limited number of batches of a seasonal product as toll manufacturer for a customer, through decades and even longer, often applying to commodities such as acids, salts and solvents.

We are taking a closer look at the raw material introduction process and the material deletion process separately. These processes can be considered as "Investment phases" in the ROI equation. The center part of the life cycle process, the "Harvesting & Maintenance" represents the "Return phase". It is the phase of value creation off the raw material. It includes the entire period a company is using the material for the production of intermediates and finished goods and to modify the material itself or its specification to serve changing technical, regulatory or finished goods customers' requirements or other additional purposes.

## 2.6 Raw Material Portfolio Management

Chemical raw material portfolios often show the same characteristic as entropy. Both of them tend to continuously grow. However, chemical companies can keep their raw material portfolios well under control, if they implement proper portfolio management processes, tools and metrics to detect trends early and confirm the effectiveness of measures approved (Ulber et al., 2010; Beiersdorf, 2017; Rajagopal, 2014).

There is quite a number of different types of reasons that drive portfolio size and hence value chain complexity if left unaddressed. Acquisitions and mergers add raw materials to the existing pool of raw materials. Cost reduction and risk mitigation measures associated with partial replacement of expensive or risky raw materials is also driving the material numbers up. Commoditization of existing or introduction of new sales products may require raw materials with new or better functionality, again increasing the number of items in the toolbox.

A two-edged measure is the introduction of multi-purpose "one-size-fits-all" raw materials and similar approaches such as toolbox, platform or shared materials concepts. While the idea is obvious, some practical implications are often insufficiently considered. Instead of pursuing a "two-out-one-in" policy to reduce the number of items in the portfolio, chemical companies often face subtleties such as existing contracts with customers, that

may refuse the material change in a formulation and hence the termination of the raw material. Another classic issue is the cost burden commodity type sales products will face if the average cost for the new material is slightly higher than before. Product managers often find good reasons to not subsidize the higher raw material cost at the expense of their products' contribution margin. One of the most obvious obstacles is of course longer term contractual obligations with suppliers, e.g. volume or take-or-pay clauses.

Portfolio management's front end process, raw material introduction, is rather popular in chemical companies (Cordis, 2017), since it is so similar to innovation processes. At the back end of the portfolio process, the raw material termination or house-keeping process is far less popular. Successful portfolio management implementations are telling us, the weight of the termination process must be equivalent to the weight of the material introduction process. If it is less, the company is managing growth of item numbers but not a portfolio of value creation building blocks. Opportunities to clean-up the portfolio include for example complexity reduction programs, standardization or harmonization approaches driven for example by requests from the business to pursue more cost-efficient bundling opportunities, sales product or manufacturing technology end-of-life and others more.

Regular snapshots looking at the number of active raw materials, the ones being introduced and the ones being terminated help monitor the portfolio trends and its target achievement and – together with other portfolio metrics discussed in the KPI chapter - define corrective actions such as speeding up new material introduction, raw material rationalization waves, standardization or harmonization projects etc. These snapshots have often been used for monthly or quarterly reports and are now being applied more regularly. This is mainly due to two reasons. One is the need to keep the portfolio of value creating items better under control, since it offers significant technical and commercial opportunities for chemical companies. The other one is the increasingly automated creation of multi-dimensional portfolio reports that can now be done within minutes but what has been taken days only 10 years ago. The use of the snapshots for monthly or quarterly business reviews is why we look at portfolio management taking a time-based, perpendicular management view compared to the primarily event-based, i.e. milestone or gate oriented, introduction, deletion and other raw material related processes.

Since raw material performance data beyond their sheer number are coming from a number of value chain functions, e.g. procurement, raw mate-

rial experts, production, product management, sales and finance, it is clear that raw material portfolio management, too, has to be a cross-discipline approach, often orchestrated by raw material experts.

A role model raw material portfolio rationalization approach has been undertaken by a diversified specialty chemicals company consisting of 4 - with regard to raw material handling - autonomous business units (BU), almost 20 manufacturing sites in 4 regions and 5 core manufacturing technologies each. The overall raw material portfolio consisted of 4.000 items structured in 5 standard material groups. By implementing portfolio management guidelines such as "two-out-one-in", material introduction and deletion processes, clearly defined targets, the consequent application of "toolbox" concepts and - most importantly, the cross-functional approach, the company has achieved an overarching success within 18 months. Step 1 has led to a reduction of 24.6% by sharing materials across different manufacturing technologies within every single BU. Step 2, the sharing of raw materials across business units with every single region has increased that reduction to 38.4%. After step 3, the sharing of key raw materials across the regions, the number of raw materials taken out of the portfolio has reached an impressive mark of 46.1%.

## 2.7 Raw Material Introduction Process

New raw material introduction is a cross-functional process very similar to the well-established stage gate innovation process (Cooper, 2002) or its alternative, the Phase Gate process (McGrath, 1996) addressing additional business perspectives. The main benefit of this process is to allow control over the raw material portfolio, in particular about its Total-Cost-of-Ownership vs its total value add to the company and its complexity, to name a few.

When adapting the stage gate or better the phase review process to raw material management, chemical companies have to define their phases and objectives by phase first. What sounds trivial is the opposite in fact. Through intelligent definition of milestones Procurement may benefit from an early combination of commercial and technical levers. Once the proof of concept is available, Procurement is well prepared for negotiations with current and alternative suppliers. The current one will recognize the seriousness of the customer, when he is showing the progress made in the qualification of alternatives. Alternative suppliers will recognize that his sales price has to not only to beat that of the competition. It must also allow the customer of finance the one-off qualification cost.

A proven process model, implemented in almost 10 projects in fine, specialty and even in one base

chemical company has evolved, consisting of 6 phases. In the Initiation Phase (1) basically the idea and the necessity to introduce a material to the portfolio are assessed. Key points are the initial check with the global portfolio which in turn requires the transparency mentioned before and the decision at the gate which pathway to pursue. Pathway 1 is the voluntary choice to modify or create at least one new product formulation through the use of a new raw material – supplier combination with the required performance. Pathway 2 pursues the voluntary approval of a new raw material – supplier combination with the raw material ideally being identical to an already existing raw material, a so called „one-to-one“ exchange. Pathway 3 is a reactive, firefighting approach to solve a business issue through a flexible approval of a new raw material – supplier combination, e.g. via a short track.

The Feasibility Phase (2) aims to prove the economic and technical feasibility. Key is the qualification approach to be taken. This very much depends on the criticality of the raw material to own products and formulations as well as the number of affected products, technologies and customers. Its end point is the Go or No-go decision to qualify the raw material at business level.

In the Screening Phase (3) potential materials and supplier are being assessed through samples, pre-defined key analytical and formulation tests. End point is the decision whether or not to pursue the qualification at lower Business Team and/ or Product Line level. Typically preliminary material IDs are used in the ERP system for test materials in order to save some effort and not to blow up the number of active materials in the portfolio.

In the Qualification Phase (4) the suitability of the material-supplier combination for specific business areas, e.g. entire Business Units or underlying Business Teams, product lines or technologies is being confirmed. The phase endpoint is the decision to start the changeover and the scale up. As soon as the decision is made to introduce the material, a permanent material code needs to be assigned.

In the Changeover Phase (5) the material is being transferred from lab scale to own and customer plants. The approval of the predefined pilot or target customers marks the phase end. The Final Integration Phase (6) ends with a proper project close-out, lessons learned and business case review once the raw material has officially been introduced in the value chain and all supporting IT systems. Strict discipline is required to assign and change the master data, e.g. the different status of raw material codes to ensure transparency on the raw material portfolio and its pipeline.

## 2.8 Raw Material Deletion Process

The Raw Material Deletion process is the counterpart to and at least as important as the raw material introduction process for the company, the portfolio and the life-cycle process. In other words, it is the main means to keep raw material complexity under control and its absence in many chemical companies is the main driver for their proliferated material portfolios.

Its design and implementation principles, e.g. organization, phase structure, KPIs and IT systems have to be closely aligned with the portfolio and introduction processes.

Starting points for the deletion process can either be time-based, e.g. as result from monthly or quarterly portfolio reviews, or event-based, e.g. upon termination of sales products at the end of their life cycle, inventory and subsequent portfolio reduction of no- and slow-movers, portfolio rationalization programs, the divestiture of a business and others more.

The nomination Phase (8) serves at defining and validating the opportunities and rationale for raw material deletion. All candidates are put on a long list of to-be-terminated raw materials and ideally marked in the ERP system accordingly.

In the Validation Phase (9) all candidates are assigned a "restricted use" status, i.e. the material shall not be used for new product and formulation recipes, purchasing orders need to be double checked with the remaining demand for sales products etc. The business impact of all candidates needs to be assessed relating to supplier obligations, own sales product life-cycles, need for customer information/approval, risk, and cost, to name the most important ones. The confirmed list of deletions is the main deliverable of this Phase.

Clearance Phase (10) is rather operational, focusing on aligning known demand with purchase orders, using the remaining stock at hand for production or otherwise, e.g. reselling or disposal. The objective and end point of this Phase is zero stock. In the End-of-Life Phase (11) the official life cycle status is set to "terminated". This status can typically not be assigned in an ERP system if there is any remaining stock anywhere in the business; this is why the endpoint of Phase (10) is so important. Once a material is officially terminated and marked as such in the ERP system, the portfolio count is reduced by one. This way ensures transparency on the correct number of materials in the portfolio but requires proper master data management.

## 2.9 Raw material management KPIs

When establishing raw material management

in a chemical company it is instrumental to provide a meaningful set of key performance indicators (KPIs) for several reasons (Eschinger, 2014; Wagner and Stephan, 2007). Metrics and KPIs already existing in a chemical company should be leveraged to the extent possible. New ones should only be added if add additional insights and value can be created.

A typical dashboard of raw material experts is containing KPIs reflecting their main areas of responsibility. For complexity and raw material portfolio control, the number of active raw materials, those in the new material introduction pipeline, the number of to be terminated ones and the number of deletions have proven very effective. These data can be used to characterize raw material portfolio depth, i.e. the number of different grades within a raw material group, and portfolio breadth, i.e. the number of different raw material groups, relatively simple at corporate, business unit or regional level. All of these data are relatively simple, well defined data and should be readily available in IT systems.

Regarding cost and value creation it gets slightly more difficult. Exact definitions for cost savings, cost avoidance and sustainable reduction of the raw material cost base are required. This requires a solid alignment with procurement on the one hand side and product management or sales on the other side. The organization must agree to distinguish between the impact of a particular measure and the bottom line impact. For example a material cost reduction multiplied by a year's purchasing volume results in a COGS (Cost Of Goods Sold) reduction that can be seen tracked in the product cost calculation and the P&L. In year one the impact of the measure and the savings are identical. In sub-sequent years, there is no further bottom line impact. However the impact of the measure is a permanent new material cost base. Remember, raw material cost is often the single highest cost in a chemical company. A reduction from 40% to 38% or even lower is one of the most attractive objectives of implementing raw material management and achieving the Excellence stage.

Risk management performance measurement is getting even more complex, since it is not only data and convention based, it is to a certain extent subjective. The first set of risk related data is straight forward, i.e. the numbers of monopoly, single, and dual sourced and that all other raw materials. They are helpful for initial risk profiles. The best practice risk management approach is rather comprehensive and builds on the combination of risk probability and business impact. The description of risk probability requires a set of hard data, such as the number of alternative materials and suppliers in

general, the number of approvals and inventory levels. Judgment regarding the market demand-supply- balance and the supplier relationship or reliability regarding this particular raw material is subjective.

Business impact calculations include besides the data based volume of finished products affected, revenue impact, contribution margin impact and number of customers impacted the subjective parameter “competitive threat”. It represents an estimate how likely competitors can take advantage from the situation by being able to supply alternative products to the customers and steal business.

Since raw material management includes also a number of different project types, e.g. to reduce raw material cost, increase raw material value creation, introduce new raw materials, delete obsolete ones to name the most common ones, a set of project management metrics is also required. Companies applying leading project management practices including project controlling should not have an issue to provide standard project management data covering the classic dimensions time, cost, quality and risk. Only if these basics are not in place, raw material management will have to apply these metrics to justify new projects and prove their success.

A common challenge in various implementations in about 10 different chemical companies has been the quality of raw data used to calculate the KPIs, databases and systems operated in isolation, e.g. LIMS systems, project databases, several ERP modules, CRM systems, business warehouses and not to forget a lot of Excel datasheets. Performance measurement and reporting have often at the beginning of the improvement projects been pulled together manually. Despite during the implementation major progress regarding the level of automation is typically been achieved, monitoring and reporting is expected to significantly benefit from progress in digitization.

## 2.10 Raw Material Codes

One main reason for unwanted and unrecognized complexity at the front end of the value chain is the lack of consistent raw material coding systems. The implications are twofold.

Firstly, transparency on raw material portfolio and raw material value potential is limited. Recall the example of 22 different Butyl acetate SKUs (Stock Keeping Unit) in one chemical company. Commercial procurement levers such as the chance to bundle demand and increase supplier competition through standardization and harmonization cannot be pulled, if there is no visibility up front.

Since any improvement opportunity is addressing only a fraction of the overall potential the likelihood that it will be turned down is high.

Secondly, it drives unwanted downstream complexity and associated complexity cost. A company unknowingly maintaining multiple identical items, so called “clones”, and several extremely similar and in principle exchangeable items, so called “twins” in their portfolio, spends a lot of wasted effort on material related master data in ERP systems, e.g. material master file, bills-of-material of products using the clones and twins, quality control specifications and tests, safety data sheets, split purchase orders, labels, warehouse space, inventory value, customer notification and approvals and so forth.

Both upstream and downstream complexity and their implication on the business have often been a reason to standardize coding systems in chemical companies. One of the leading practices for a value chain oriented classification addressing materials, intermediates and products has been developed in 2000 by about 10 companies, most of them chemical ones, such as BASF, Bayer, Evonik (Degussa, one of its predecessor organizations), Solvay and Wacker, called eCl@ss.

In a number of implementations eCl@ss and in house developed solutions have been introduced in chemical companies over the last 10 years. In house solutions are often not quite as comprehensive as the industry standard. What most of them have in common is the recognition that only properly defined and maintained master data ensure transparency and control over the raw material portfolio and if wanted over intermediates and finished products, i.e. the downstream value chain.

A positive side effect of state of the art coding systems and industry standard is the impact on post-merger and post-acquisition integrations. Often enough it has taken years to fully harmonize materials and downstream intermediates and products. With recent progresses in classification standards, IT systems and the level of automation, a lot of effort and time has been saved. Since a lot of raw material information is hard data, expectations are high, that progress in digitization will add further significant value.

## 2.11 Raw material management Organization

The preferred organizational set-up for raw material management is a unit of raw material experts that understand the entire value chain from the suppliers’ materials and technologies through the customers applications (Radziwona et al., 2014; Feldmann, 2015), often referred to as upstream procurement or technical upstream.

Their key contribution is ensuring that only materials will be identified, qualified, sourced and used that fulfill all downstream value chain requirements, i.e. for the own company's products and formulations requirements as well as those of customers' applications. These requirements cover numerous different dimensions that may, if not being addressed in a holistic manner by taking a value chain view, run counter to each other. Other objectives they pursue are security of inbound and thereby indirectly outbound supply, low Total-Cost-of-Ownership, agility and flexibility of operations by providing approved alternatives to standard materials, control over raw material portfolio complexity and its impact on the downstream value chain.

The new raw material experts function requires a unique, mixed skillset. A new manager's challenge is to motivate and recruit candidates from various functions, e.g. product management or key account management that have insights in customers' applications and requirements, R&D and application development that understand the functionality and impact of raw materials on finished products, and procurement that have intimate knowledge on supplier markets, market intelligence, relationships and so forth. Developing raw material experts is not a matter of weeks and is a major investment (Gaiziunas, 2009). It rather takes 18 to 30 months as several implementation projects in the chemical industry show.

A multi-dimensional matrix structure has proven to be the most efficient organizational set up for the raw material expert unit. The matrix is typically composed of five to six parameters such as business units, raw material groups, regions or countries, processes and IT tools or systems. This set-up ensures dedicated and high quality raw material group specific know how, strategies, utilization guide-lines, specifications, introduction, deletions and so forth. Clearly defined and communicated objectives and manageable, i.e. limited scopes for each expert are not only crucial for the success of the experts, they are also fundamental for the buy in and ongoing support of other value chain functions.

Raw material experts must not be considered as a competition to commercial procurement (Widmann et al., 2015). Instead they provide additional, complementary capabilities to the company under the roof of upstream procurement or technical procurement. In most cases they are a part of the procurement organization. Nevertheless establishing this new function and assigning key value chain responsibility to it is often a major cultural challenge to chemical companies that must not be underestimated.

### 3 Conclusion

To turn "cost" into "value", nothing less than a business transformation is required. Over the last ten years a number of innovative and proactive chemical companies has recognized this potential of raw materials as value creating building blocks (Royal Dutch Shell, 2017) instead of looking at them as a sheer cost.

Key element for raw material management is the assignment of dedicated raw material experts that understand the external and internal value chain from own suppliers educts through own customers applications. They take responsibility for raw material management processes, tools, systems and metrics. They are an instrumental link in a chemicals company's value chain.

A good summary for a successful transformation of the procurement function and the achieved mindset change is David Powell's statement "Procurement has gone from being the poor cousin, to a partner at the heart of business decision" (Powell, 2016).

Management commitment requires a professional state-of-the-art change management and communication along the value chain, i.e. across the entire organization, assign sufficient resources and allow the time required, often between 18 to 30 months.

Once chemical companies are ready and committed to this innovative approach and have achieved the highest stage of maturity, Raw Material Excellence, they can expect to significantly increase EBIT, e.g. from 10% to 12% or 13%. The full benefit of holistic raw material management is going far beyond financial savings. Improved inbound and outbound supply performance service, complexity adjusted to the right level required for a particular business while being agile and responsive are additional benefits from this business model innovation.

Raw material management is an option that pays out. It is a dynamic approach invented and applied in numerous value chain improvements in the chemical industry (GDCh et al., 2016). It is expected to develop further in parallel with the progress of digitization towards a new maturity stage, Raw Material Excellence 4.0 within the next five years (Glas and Kleemann, 2016; Schmidt et al., 2015).

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# Research Paper

## Digitalization in the process industries – Evidence from the German water industry

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Research on the adoption of digital technologies has largely omitted the process industries. In this study, we address this research gap by presenting empirical evidence from a questionnaire survey comprising 86 responses from members of the German Water Partnership (GWP) association. Our results indicate that firms in the water industry lay emphasis on projects harnessing digital technologies, while the execution and implementation still faces significant challenges that we discuss below. Correlation analysis reveals that firms that have interlaced conventional business strategy with IT strategy stronger prioritize the development new business models in the course of digitalization than their counterparts who do not have a digital business strategy. Due to the new ways of value creation, delivery, and capture enabled by digital technologies, we evaluate the usefulness of a concept named the layered modular product architecture in context of the process industries and relate it to the need for developing a digital business strategy. We close this article by deducing several implications for managers.

### 1 Introduction

Recent developments in digital technologies bring about considerable business opportunities but also impose significant challenges on firms in all industries. While some industries, e.g., newspapers, have already profoundly reorganized the mechanisms of value creation, delivery, and capture during the course of digitalization (Karimi & Walter, 2015, 2016), many process-oriented and asset intensive industries have not yet fully evaluated and exploited the potential applications (Rigby, 2014). Although the process industries have successfully used advancements in technologies to optimize processes in the past (Kim et al., 2011), digitalization poses an unprecedented shift in technology that exceeds conventional technological evolution (Svahn et al., 2017). Driven by augmented processing power, connectivity of devices (IoT), advanced data analytics, and sensor technology, innovation activities in the process industries now break away from established innovation paths (Svahn et al.,

2017; Tripsas, 2009). In contrast to prior innovations that were primarily bound to physical devices, new products are increasingly embedded into systems of value creation that span the physical and digital world (Parmar et al., 2014; Rigby, 2014; Yoo et al., 2010a). On this new playing field, firms and researchers are jointly interested in the organizational characteristics and capabilities that are required to gain a competitive advantage (e.g. Fink, 2011). Whereas prior studies cover the effect of digital transformation on innovation in various industries like newspaper (Karimi and Walter, 2015, 2016), automotive (Henfridsson and Yoo, 2014; Svahn et al., 2017), photography (Tripsas, 2009), and manufacturing (Jonsson et al., 2008), there is a relative dearth of studies that cover the impact of digital transformation in the process industries (Westergren and Holmström, 2012).

The process industries are characterized by asset and research intensity, strong integration into physical locations, and often include value chains that are complex and feature aspects of rigidity (Lager

et al., 2013). Multiple sectors like the chemical industry, water industry, food and beverage, generic pharmaceuticals, utilities, as well as forest and steel fall into this category (Lager et al., 2013). Under conditions of rapid environmental developments like technological advancements, the process industries' ability to respond to change is often limited in the short term (Lager et al., 2013).

In many countries, industry associations drive discussions about digitalization. In allusion to the concept of "Industry 4.0" the German Water Partnership (GWP) association defines the term "Water 4.0" as the application of digital technologies for the evolution of holistic cyber-physical-systems that enable efficient, real-time monitored, and reliable water supply with a maximum amount of transparency for producers and users [italics added by authors] (GWP, 2016, p.4). In order to evaluate how members of GWP translate the notion of Water 4.0 into their business reality, in this study we investigate the water industry's status quo in digitalization.

In this paper, we pursue several objectives. First, we introduce the concept of the layered modular product architecture into the process industries and discuss its applicability. Second, we present descriptive data from a questionnaire survey conducted within the GWP to provide an overview of key digitalization priorities and challenges. Third, we analyze the relationship between digital business strategy and a firm's propensity to engage in business model innovation in more detail. Finally, we discuss how business model innovation is related to a layered modular product architecture and conclude with implications for practitioners.

## 2 Digitalization in the water industry – A new innovation logic for the digital age

The interchangeable use of the terms digitalization and digitization is misleading in the debate about digital transformation. To clarify the meaning of digitalization and distinguish it from digitization, a group of renowned information systems scholars refer to digitalization as "the transformation of socio-technical structures that were previously mediated by non-digital artifacts or relationships into ones that are mediated by digitized artifacts and relationships. Digitalization goes beyond a mere technical process of encoding diverse types of analog information in digital format (i.e., "digitization") and involves organizing new socio-technical structures with digitized artifacts as well as the changes in artifacts themselves" (Yoo et al., 2010b, p. 6). An example for digitalization-driven changes of socio-technical structures in the process industries is the transition from reactive maintenance

towards predictive maintenance. In the latter, a network of connected sensors enables plant operators to determine the residual life distribution of a system's critical components in order to optimize the maintenance schedule and improve the overall reliability of the system (Kaiser and Gebraeel, 2009). This kind of innovation affects socio-technical structure. For example, reliable water supply systems have a tremendous impact on social life and also affect the economic prosperity of entire regions (United Nations Report, 2016).

In the transformation process of digitalization, practitioners and scholars alike are specifically interested in how the system of value creation and capture is changing (Barua et al., 2004). In this regard, a growing stream of empirical research focusses on the impact of digital technologies on value creation through new product development (Marion, et al., 2015). In this regard, the changing nature of product architectures is presented as a major challenge for innovation managers (Yoo et al., 2012; Yoo et al., 2010) but also entails tremendous business opportunities (Rigby, 2014).

### 2.1 The layered modular architecture of digital technology

Product designs can be described following two types of product architecture: integral and modular (Henderson and Clark, 1990; Sanchez and Mahoney, 1996; Ulrich, 1995). While an integral product architecture is characterized by tightly coupled elements that are highly interdependent and aim at optimizing the product as a whole, a modular architecture is defined by standardized interfaces that allow for facile exchanges of the components, which, in turn, enables changes in the functionality of the product (Ulrich, 1995; Yoo et al., 2010a). Modular products are therefore popular in environments that require high levels of flexibility. In a new organizing logic that is driven by an increasing implementation of digital technologies into physical products, additional layers of value creation emerge that uncouple the functionality of a product from its physical components (Yoo et al., 2010a). As illustrated in Table 1, the additional layers comprise a network layer, a service layer, and a contents layer that build on top of the physical device (Yoo et al., 2010a). Each layer fulfills different functions in the product architecture. As Yoo et al. (2010a) delineate, the device layer includes a physical machinery layer (e.g. hardware components) and a logical capability layer (e.g. operating system) that provide control over the physical device and enable connections to other layers. Similarly, the network layer consists of two layers, one for physical transport (cables, pipes, transmitters, etc.)

Table 1 Layered modular architecture of digitally enhanced products (Source: Based on Yoo et al., 2010, p. 727).

Layered modular product architecture	Example 1: Mobile phone	Example 2: Industrial pumps
<b>Contents layer</b>	Pictures, videos, text, user profiles, copyright, geo-time stamps, etc.	Data from sensors, ownership, copyright, encoding methods, etc.
<b>Service layer</b>	Telephony and applications: social media, route planner, voice recognition, etc	Water pressure and transportation, predictive maintenance, etc.
<b>Network layer</b>	<ul style="list-style-type: none"> <li>Logical transmission: UMTS / LTE</li> <li>Physical transportation: Charging cable</li> </ul>	<ul style="list-style-type: none"> <li>Logical transmission: TCP / IP</li> <li>Physical transportation: pipes and cables</li> </ul>
<b>Device layer</b>	<ul style="list-style-type: none"> <li>Logical capability: the operating system (e.g. android, iOS, windows)</li> <li>Physical machinery: mobile phone hardware i.e. display, speakers, microphone, processor, etc.</li> </ul>	<ul style="list-style-type: none"> <li>Logical capability: operating system</li> <li>Physical machinery: physical components including microelectronics (processors, sensors, etc.)</li> </ul>

and one for logical transmission (e.g. TCP/IP, peer-2-peer). In the service layer all functionalities are bundled into an interface that serves the user (e.g. mobile applications, addressable pump in an operating system). This layer is supplied by the overarching contents layer that stores all data (text, video, sound, etc.) and metadata (copyright, geo-tags, etc.).

The evolution from integral to modular product architectures enabled innovators to create new products by combining modules in novel ways. Today, the layered modular architecture of digitally enhanced products provides firms with the opportunity to innovate and compete on each layer largely without affecting offers on other layers. But still, the layered architecture invites firms to offer integrated solutions that span more than one layer to leverage synergies between them. For example, a device producer might profit from offering solutions on the content layer in order to learn how clients use their content with the objective to further adapt the device to the clients' needs.

Although being primarily applied in industries that fabricate electronic products, the layered modular product architecture also proves useful for the process industries, in which products are often raw materials rather than digital savvy components (Lager et al., 2013). However, due to the increasing

engagement in services and platforms that are offered as complementary values to the initial physical product, firms find themselves competing and collaborating on new layers of the product architecture, possibly facing novel competitive landscapes (Bharadwaj et al., 2013a). The environment of rapidly evolving technologies requires continuous reflection about the firm's position in the network of value-creation, which draws attention to the importance of strategic partnerships which enable the leveraging of network resources to boost firm performance (Lavie, 2006). Regarding the positioning of firms in value networks, Pagani (2013) proposes that firms who position themselves at what she refers to as control points i.e. the positions of greatest value and/or power in a system, are able to influence how profits are allocated and eventually obtain a competitive advantage. In a layered modular architecture, each layer comprises its own control points that distinguish the success between firms competing or collaborating on the same layer. Collaborating with firms that hold control points on different levels of the architecture might result in complementary resource configurations and, thus, unlock new market opportunities. Throughout all actions that a firm pursues in this product architecture, alignment between innovation activities and the position in the value

network should be considered. In the course of digitalization, ensuring organizational alignment between internal activities and the external environmental circumstances is a task for strategic management, which is why firms should have a digital business strategy.

## 2.2 The role of digital business strategy

During the last decades, IT strategy has been subordinate to, and in the best case, in alignment with conventional business strategy (Bharadwaj et al., 2013a). Over a long period of time, influential decision makers perceived information technology as a supporting factor that was not designed to grant a competitive advantage over competitors, and therefore neglected it as an integral component of business strategy at the corporate level. In recent years, products have increasingly become digitally connected and are now able to be embedded into systems of value creation that exceed physical boundaries (Rigby, 2014). Scholars argue that IT, and, more specifically, an integrated IT strategy has become a potential source of competitive advantage (Bharadwaj et al., 2013a; Bharadwaj et al., 2013b; Pagani, 2013). In this context, digital business strategy refers to an “organizational strategy formulated and executed by leveraging digital resources to create differential value” (Bharadwaj et al., 2013a, p. 472). Due to the new technological and personnel requirements and the uncertain returns that the implementation of digital technologies bring about, formulating a digital business strategy can produce internal consistency between digital transformation activities. In this study, we therefore investigate how many firms in our sample have developed a digital business strategy and who is in charge of it.

## 3 Methodology

Data collection was performed among members of the German Water Partnership (GWP), which includes original equipment manufacturers, plant operators, consultancies, construction firms, chemical providers, research institutes, and financing partners. GWP forwarded our questionnaire survey to one contact person inside each of the 350 member companies and reminded them with two mails to participate. After five weeks, 86 respondents completed the survey, resulting in a response rate of 24.6% calculated in relation to the number of members in the association. Respondents mainly hold the position of chief executive officer, head of department, and related functions that qualify them as appropriate respondents for the topics covered in this survey. On average, respondents fur-

ther bring over 17 years of industry experience, while they spent 13.5 years in the company they currently work for.

We operationalized our measurements as follows. In order to evaluate the current key aspects of digitalization in the water industry, we draw on a survey previously conducted by Siemens among its clients in Germany and adapted the wording of some items (Siemens, 2014). Concerning digital transformation, the survey covers the topics of firm priorities, potential benefits, internal and external resistance, and digital business strategy. Respondents evaluated firm priorities on a seven-point Likert scale offering continuous degrees of importance: 1 = very important to 7 = not important at all. Potential benefits as well as internal and external sources of resistance were equally assessed on a Likert scale using a range of agreement from 1 = fully agree to 7 = fully disagree. We were also interested in how far respondent firms had formulated a digital business strategy, for which we offered four different choices: 0 = No response, 1 = No, 2 = Yes, partially, 3 = Yes. Further, we investigated who was responsible for developing a digital business strategy and assessed if the respondents' firms had set up a central unit for digitalization related issues. Additionally, we performed Spearman's rank order correlation between the perceived importance of business model innovation and the degree to which a digital business strategy exists. The results were calculated using SPSS version 23.

## 4 Results

In order to assure the fit of our findings with the water industry's general perspective on digitalization, we included all respondents in our analysis. Although we herewith accept answers from heterogeneous industry segments in our data set, this approach has the advantage of retaining a broad scope of perspectives and therefore contributes to a more holistic view on the state of digitalization in the water industry. In the descriptive representations below, the graphs consider the top two boxes from the Likert scale i.e. “important” and “very important”.

### 4.1 Digital transformation priorities

First, respondents classified which functions or purposes they address with digital technologies and which of them are most relevant for their firm. According to the results depicted in Figure 1, more than two third of all respondents prioritized visualization and transparency, process automation and standardization, and data extraction from machines and sensors as key functional areas that

Figure 1 Assessed as belonging to the top two categories: “very important” and “important” (Source: Own representation).

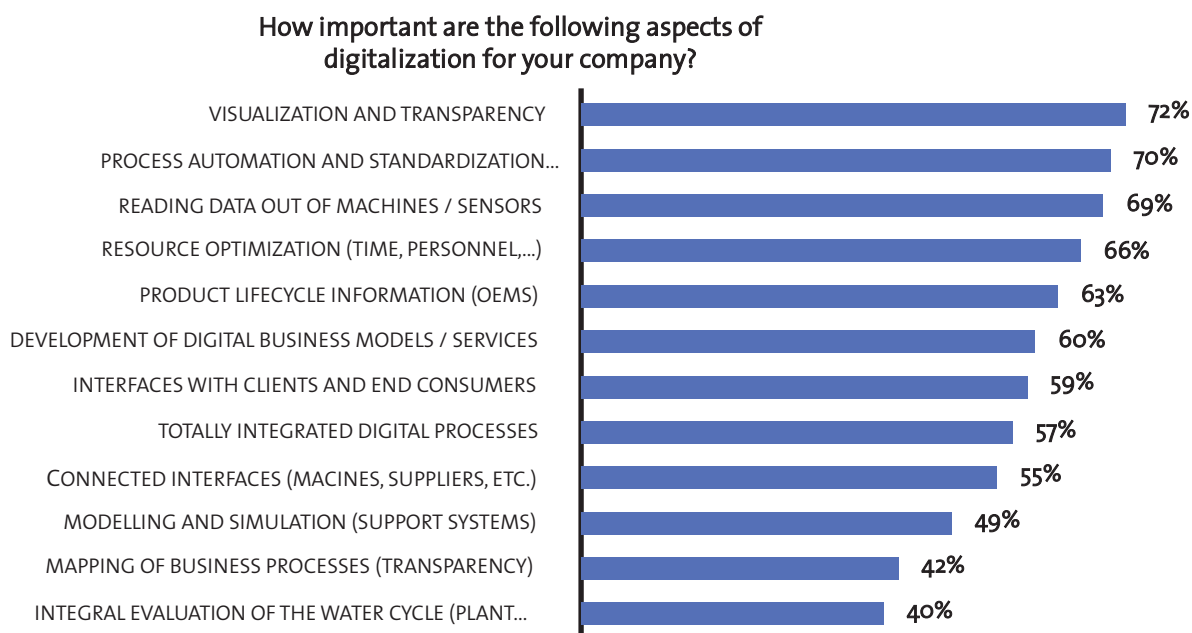
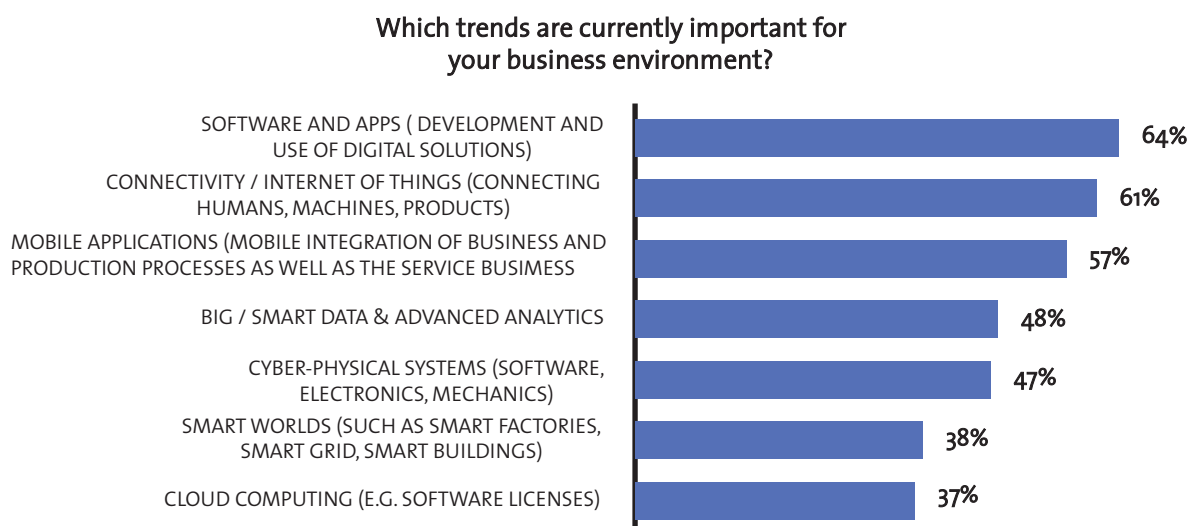


Figure 2 Assessed as belonging to the top two categories: “very important” and “important”. (Source: Own representation).



are currently addressed. Companies further underline the optimization of resources and the use digital solutions to gain transparency in their product lifecycles.

Figure 2 presents the major digitalization-related trends that are currently important for the

respondents’ firm environment. Most notably, the development of software and apps is a major topic in conjunction with machine connectivity i.e. the internet of things, and mobile applications that enable the integration of production processes with other functional areas. Further, cloud computing

Figure 3 Assessed as belonging to the top two categories: “very important” and “important”. (Source: Own representation).

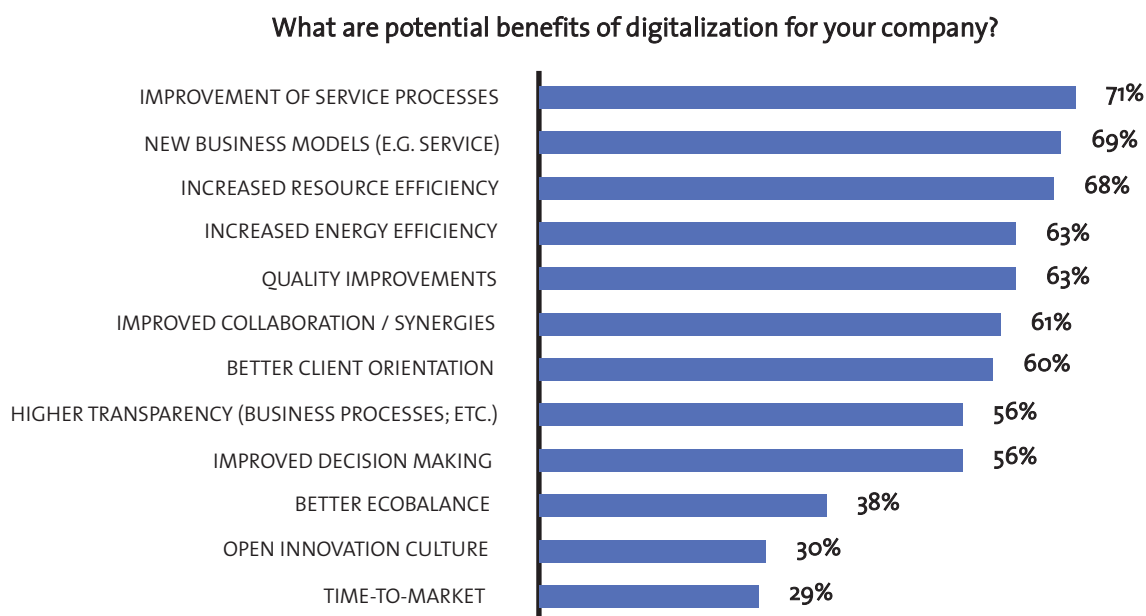


Figure 4 Assessed as belonging to the top two categories: “very important” and “important”. (Source: Own representation).



is perceived as an important digital solution in the business environment by 37% of respondents.

#### 4.2 Potential benefits of digital transformation

By engaging in digital transformation, GWP members aim to achieve various benefits for their companies, which are shown in Figure 3. According to the results, more than two out of three respondents expect to improve their service processes. Further, the participating companies see digitalization as a means for developing new business models and gaining higher resource and energy efficiency. In addition, digitalization of communication and interaction between parties is expected to not only increase collaboration efficiency but also enhance the relationship between firms and their clients by enabling stronger client orientation (60%). The unprecedented amount of available data enables firms to gain higher process transparency (56%), which, in turn, facilitates managerial decision-making (56%). Respondents have lower expectations when it comes to increasing environmental performance, establishing an open innovation culture, and shortening time-to-market.

Figure 4 summarizes which circumstances would facilitate the implementation of digital technologies. In this context, 71% of all firms agree that the training and inclusion of employees is the most relevant shortcoming. In addition, data should be

made compatible between applications and platforms (70%) and improved data security (66%) is supposed to increase confidence in the application of digital technologies. Implementing digitalization as a process of analyzing, planning, directing, and controlling/verifying is perceived to be an additional driver (65%). Respondent firms acknowledge that digitalization needs to be further included in business strategy (64%) and support that evaluation of prior successful and failed projects might support implementation of digitalization.

#### 4.3 Resistance to digital transformation

Besides the drivers and enabling technologies for digital transformation, we assessed the most influential internal and external barriers. As Figure 5 indicates, the most important internal barriers are unclear benefits (49%), ambiguous IT specifications (47%), and a lack of sufficient internal know-how for planning and implementation (45%). Fear of data theft is a considerable impediment for one third of the companies in our sample.

The barriers that reside within the organizations' external environment are summarized in Figure 6. Most prominent in this respect is the lack of technical standardization (55%). The following two barriers, namely the missing demand for digital solutions from customers and suppliers (51%), and the perception that the market is not ready yet (48)

Figure 5 Assessed as belonging to the top two categories: "very important" and "important". (Source: Own representation).

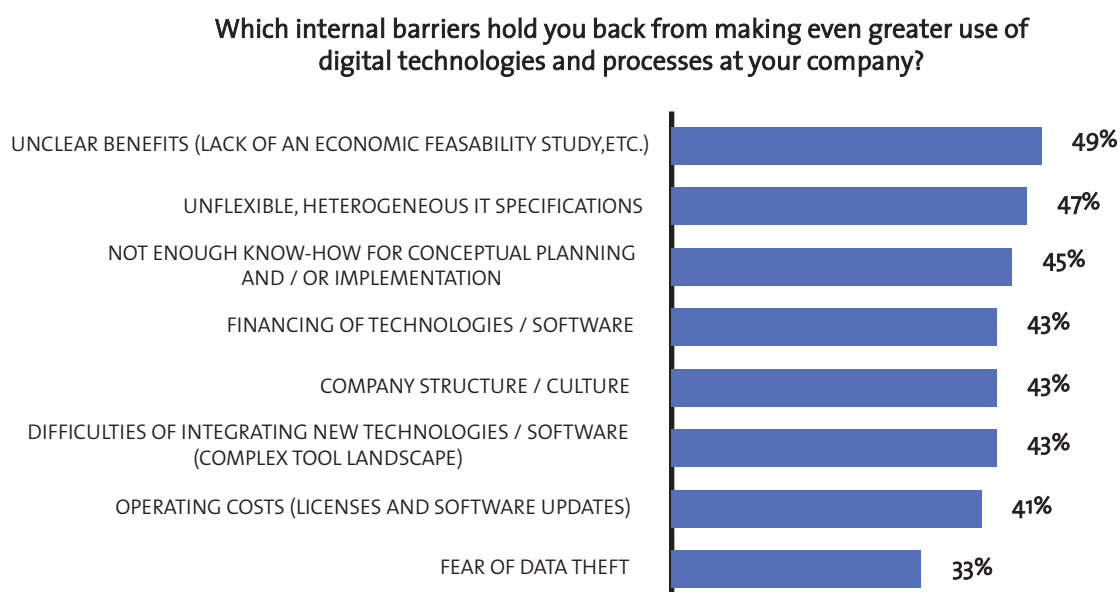
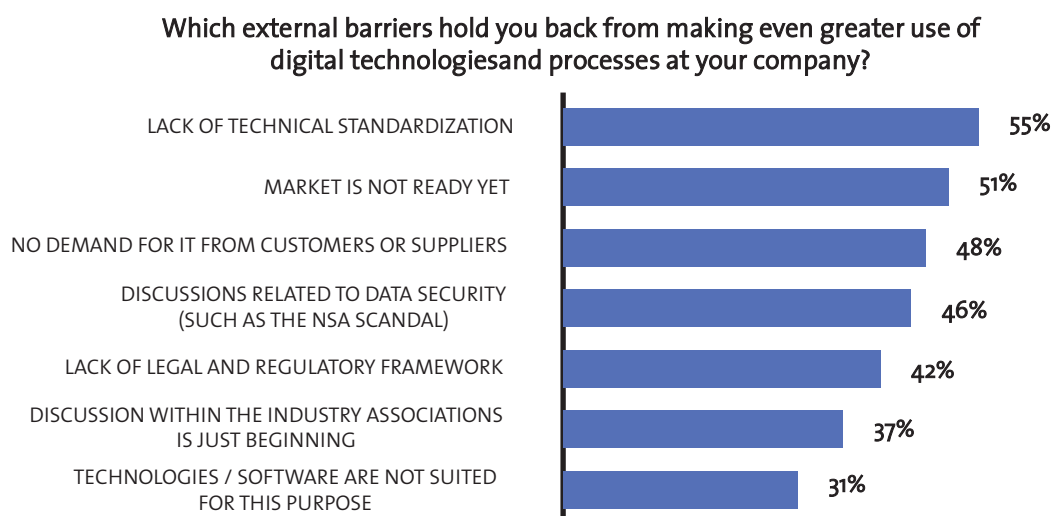


Figure 6 Assessed as belonging to the top two categories: “very important” and “important”.  
(Source: Own representation).



suggest that producers and clients in the water industry are more hesitant to apply digital technologies when being compared to other industries (Siemens, 2014). The unsatisfying progress in discussions within associations and the lack of a legal and regulatory framework are moderately important barriers. Only 31% of respondents think that technology itself is the bottleneck for implementation.

#### 4.4 Digital business strategy

In order to assess whether our respondents were sufficiently knowledgeable to be considered for further analysis, we analyzed their functions in the company in a key respondent check. According to the respondents' position in the company, respondents mainly hold top-level management functions but also middle management and other functions that account for substantial knowledgeable about the firm's strategy are included in the analysis. Figure 7 depicts the number of firms in the sample that have completely or partially formulated a digital business strategy. The responses show that while half of the firms have partially formulated a digital business strategy only 11% have already accomplished this task. Besides 10% of non-reported answers, 28% of the companies in the sample have not yet developed a strategy that integrates digital transformation objectives.

In a consecutive question not shown in the figure, we were interested who is responsible for formulating the digital strategy for the company. In

52% of responses, the executive board is responsible for creating a digital business strategy in collaboration with IT experts. In addition, 15% have established a digitalization team to implement digitalization as a process into the company while in other firms corporate strategy (6%), the executive board alone (6%), IT (5%), and others (15%) are responsible for this task.

#### 4.5 Correlation analysis

With the aim to explore the relationship between digital business strategy and the propensity to engage in business model innovation in more detail, we performed an additional correlation analysis. As we use both ordinal and continuous scales for our measures, we use Spearman's rank order correlation and present the results in Table 2. To perform correlation analysis, we used the degree to which firms have formulated a digital business strategy (DBS) as well as indicators for the willingness to pursue business model innovation (BMI). The latter includes “Development of digital business models / services” (BMI1) from the list of digitalization opportunities in Figure 1, and “New business models (e.g. service)” (BMI2) from the list of digitalization priorities in Figure 2. Further, we include the number of employees and the firm age. We find that having a digital business strategy has a weak/moderate positive correlation with prioritizing business model innovation as an opportunity ( $\rho=.373$ ;  $p<0.01$ ) and internal priority ( $\rho=.369$ ;  $p<0.01$ ).



Figure 7 Degrees to which firms have formulated a digital business strategy (Source: own representation).

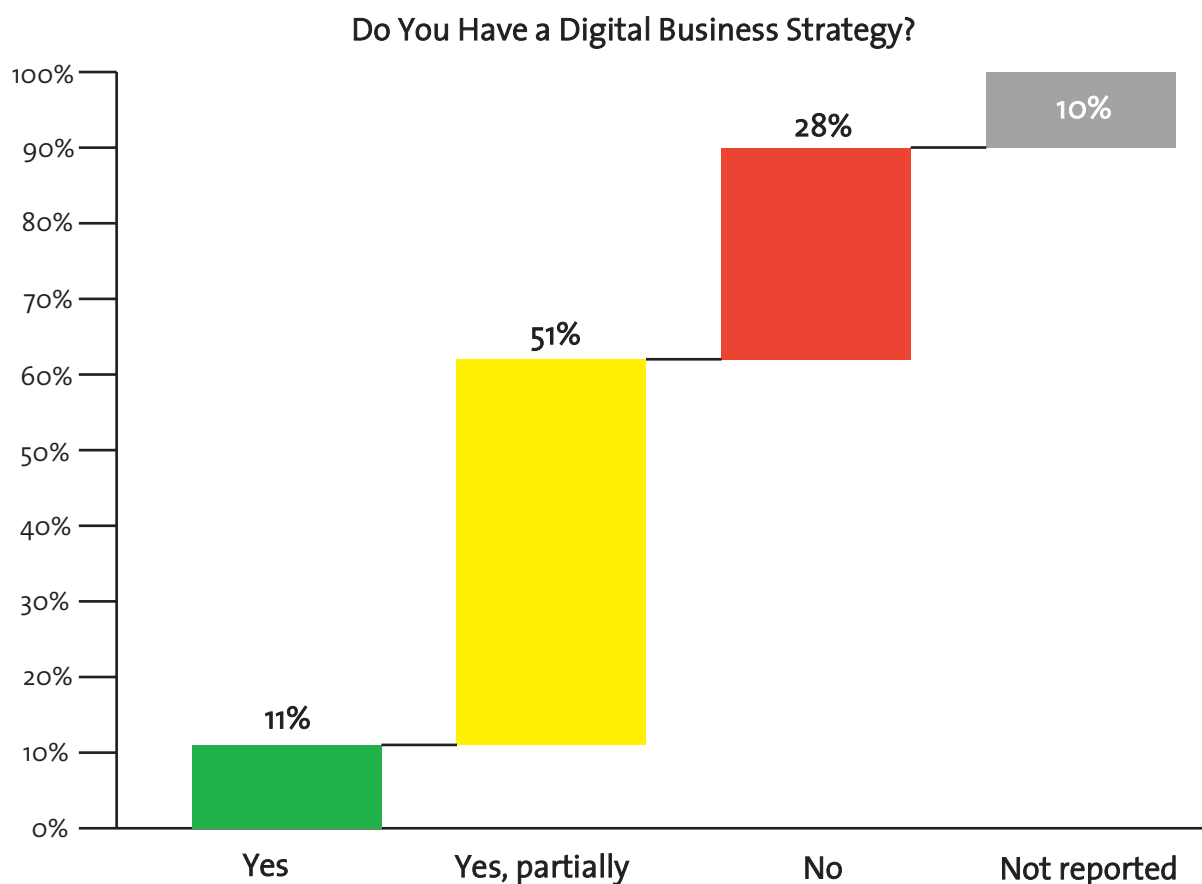


Table 2 Spearman's rank order correlation matrix (Source: Own representation).

Measures	Mean	SD	Min	Max	1	2	3	4	5
1. DBS	1.81	0.64	1	3	3				
2. BMI 1	5.51	1.50	1	7	.373**	1			
3. BMI 2	5.74	1.38	1	7	.369**	.527**	1		
4. Employees	2.29	1.21	1	5	.242	.197	.202	1	
5. Firm age	3.38	1.20	1	5	.022	.079	.045	.640**	1

\*\* Correlation is significant at the 0.01 level (2-tailed).

## 5 Discussion

In the German water industry, digital technologies are regarded as important drivers for achieving superior results in diverse functional areas. In congruence with the concept Water 4.0 the gathering, transmission, and analysis of homogenized data is used for process automation, optimization, and improved decision making, among others. As the results from our study indicate, firms in our sample consider efficiency-related innovations as important cornerstones of digitalization, but at the same time acknowledge novel business opportunities. Specifically, offering new services and developing novel business models are important objectives. In this concern, correlation analysis revealed that developing new business models is more important to firms that have formulated a digital business strategy. As a business model can be best described by the process of value creation, delivery, and capture (Teece, 2010) it is evident that in the course of digitalization the business model of almost every industry will encounter significant changes in one or all of the three dimensions. Only through formulation of a digital business strategy that aligns digitalization efforts across multiple organizational functions, firms will be able to sustain advantages that were gained through business model innovation, as business models are sufficiently generative and easy to imitate (Teece, 2010).

Car manufacturer Volvo has demonstrated the value of developing a digital business strategy in its “connected cars” initiative from 2010, in which they included guidelines for the use of platforms and cloud technology (Svahn et al., 2017). Despite the success in transformation, the profound implementation of digital technologies into Volvo’s DNA made the car manufacturer experience organizational resistance that was caused by a shift in organizational culture and identity (Svahn et al., 2017; Tripsas, 2009). In a study based in the camera industry, Tripsas (2009) concludes that coping with changes in firm identity can be catalyzed by firm strategies that connect the use of novel technologies to internal capabilities, routines, and beliefs.

In the GWP, the majority of firms state that investments in integration and training of employees (71%) would accelerate the implementation of digital technologies. At the same time, 45% indicate that internal know-how about new technologies is not sufficient. The numbers support the impression that the speed of technology development is faster than what organizations are able or willing to implement. Research on technology acceptance delineates that the speed of technol-

ogy adoption is a function of the technology’s perceived usefulness and ease of use (Venkatesh & Davis, 2016). Coining an organizational culture that embraces technological advancements with curiosity and playfulness is the duty of top-level management, while communication of achievements and use-cases throughout the company might foster the perceived usefulness.

Digital technologies offer numerous opportunities for business model innovation. Formulating a digital business strategy might serve as a starting point for developing novel business models that might even be multi-sided. Multisided business models are not only interesting for digital leaders (e.g. Google, Facebook, YouTube) but for almost every other company. The multi-sidedness of a business model can be perceived as a firm’s ability to capture value from one business through various revenue streams, possibly residing within different layers of the product architecture. In the example of an industrial pump, the manufacturer might generate sales not only by selling the pump (device layer) but also by offering additional value like predictive maintenance as a service, which, in turn, is nurtured from the content layer through analyzing a continuous stream of real-time data (Bharadwaj et al., 2013a).

Evidence from academic literature highlights the importance of customer and supplier readiness for increasing firm performance through digitalization (Barua et al., 2004). Respondents in our study indicate that a lack of market readiness (51%) and customer demand (48%) are major barriers for implementation of digital technologies. This raises the question in how far firms should engage in developing innovative digital solutions in the face of uncertain market conditions. As digitalization is a basic technology that affects all industries (Brynjolfsson and McAfee, 2014) it is only a matter of time until the entire market will be more familiar with digital solutions. Until then, firms that develop viable digital solutions might be able to profit from the early stage in the technology life cycle and strengthen their strategic position in this field.

The development of holistic and integrated solutions requires most firms to engage in collaboration with partner firms, because companies rarely cover all relevant layers in the digital product architecture on their own. Harnessing the resources of alliance partners i.e. network resources can provide firms with a competitive advantage and is a powerful tool for firms in uncertain environmental conditions (Lavie, 2006). An example for this is the collaboration of the utility company Eon and Google who together provide solar energy solutions for real estates in Germany. While the locally established company Eon is responsible for the hard-

ware, Google's satellite data has all the information about the sun exposure of roofs. Potential customers are thus able to get a realistic calculation of the power generated by potential solar panels on their roofs. The joint service combines the hardware competence from a local incumbent (device layer) with meteorological and geographical data (content layer) into a convenient user experience. Eventually, Eon's and Google's complementarity of resources on different levels of the product architecture enables them to unlock new revenue streams.

## 6 Managerial implications

This study provides several implications for managers. First, firms that do not have a digital business strategy yet, should start to align and integrate IT strategy and business strategy to tackle implementation of digital technologies in a structured approach. Second, firms are not self-sufficient in the digital age and need strong collaboration partners. Therefore, managers might use the layered modular architecture as a starting point for identifying potential partner firms on different layers of the product architecture with the joint goal of developing holistic customer solutions. Third, firms across all industries have shown that digital technologies enable novel ways of creating, delivering, and capturing value. To position themselves, firms might experiment with novel business models themselves or gain access to them through acquisitions or collaborations. Fourth, digital transformation requires a shift in firm culture and identity, both of which are most notably coined by the firm's top-management. Providing space for experimentation with new technologies and communication of prior results are viable means for increasing acceptance among employees.

## 7 Conclusion

In this work, the authors present a study on the state of digitalization in the water industry. We discuss the applicability of the layered modular product architecture in the process industries and assess the importance of having a digital business strategy. The results from our questionnaire survey indicate that the use of digital technologies is perceived as an important opportunity for business development in the future, while real-world implementation still faces significant challenges. Our results further support that firms who have formulated a digital business strategy are more inclined to develop new business models in the course of digital transformation.

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## Research Paper

# Mercury Free UV Lamp for Disinfection and Purification of Drinking, Process, and Waste Water – An Approach to assessing its Innovation Potential and Possible Market Entry Strategies

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Ultraviolet radiation sources found many application areas in science and technology. They play an important role within several markets worldwide today. One of these markets is disinfection and photochemical purification of water which has been a growing market for many decades. At the moment low pressure mercury discharge lamps are the state of the art technology. Although they have been developed towards an impressive maturity level, they still show many drawbacks as e.g. strong temperature dependence. Therefore, this paper is dedicated to a mercury free alternative radiation source for this market, namely so called phosphor converted excimer discharge lamps. They are in the centre of present R&D activities, since they offer several advantages compared to the mercury discharge lamps such as very little temperature sensitivity, a high customisability of the emission spectrum, a large form factor, and instant full radiation power after they have been switched on. A brief description of the technology of phosphor converted excimer lamps will be sketched and furthermore their potential as a possible game changer for water disinfection and photochemical water purification market areas will be highlighted.

## 1 Introduction

The development of ultraviolet (UV) emitting radiation sources may be traced back until 1910 when the first realization of a discharge vessel comprising gaseous Mercury was mentioned in literature (Perkin, 1910). Ever since did the technology of generating electromagnetic irradiation by gas discharges involving the impact excitation of gaseous Mercury mature to a well-developed and reliable concept used worldwide in compact and linear fluorescent lamps.

By today, although already outperformed by light emitting diodes (LEDs) technology w.r.t. efficiency and lifetime, there are still a lot of Mercury based discharge lamps in use for general lighting

(US Department of Energy, 2012). However, the business field of UV emitting lamps offers a broad variety of lamp types from low-, over mid-, to high pressure Mercury discharge lamps. These lamps have been well established and are easily commercially available (Oppenländer, 2003). In 2011 the market size for UV disinfection equipment was estimated to be 885 million USD (Hanft, 2011). By 2015 the overall market volume for UV disinfection equipment increased to even 1.4 Billion USD (Ramamurthy, 2015). This tremendous incline of the market volume clearly indicates the rapid growth of the market for UV disinfection equipment, which is expected to grow even further in the next decades.

The growing interest in UV sources for disinfection and especially water treatment appears to be

in line with the prevailing challenges in that fields, such as an effective disinfection of surfaces or fluid media from hazardous microorganisms or an effective water cleaning from organic pollutants, such as hormones, antibiotics, and other drugs (Li et al., 2009; Oppenländer, 2003; Morimoto et al., 2004). For disinfection purposes, the application of photons emitted from a UV radiation source, with wavelengths from 250 nm (UV-C) to about 300 nm (UV-B), appear to be most suitable, as organisms exhibit strong absorption with maxima in the respective region caused by the molecule of life, the DNA (Zimmer and Slawson, 2002; Sastry, 2000; Hijnen et al., 2006). Whereas the direct photolytic cleavage of pollutants (e.g. hormones, drugs, hydrocarbons or by-products) requires higher energetic UV-C radiation, which is most effective at a wavelength shorter than 250 nm (Kowalski, 2009)

This work will summarize insight into the technology of state of the art UV radiation sources (chapter 2), viz. mercury discharge lamps and light emitting diodes (LEDs) as well as Xe comprising discharge lamps with and without wavelength converting phosphors. The advantages and innovativeness of excimer lamps is shortly explored in chapter 3 while in chapter 4 the advantages of the phosphor converted excimer lamps as an advanced alternative to mercury discharge based UV radiation sources is discussed. In chapter 5, this paper offers an evaluation on the status and impact of phosphor converter excimer discharge lamps in application, highlighting disinfection and purification of water, based on the parameters for product program evaluation set by Cooper in 1990.

## 2. Technology of UV Emitting Lamps

### 2.1. State of the art

The market for UV radiation sources is currently governed by two different technologies, namely mercury containing discharge lamps and UV emitting (Al,Ga,In)N (Aluminium Gallium Indium Nitride) based LEDs (Oppenländer, 2003).

Mercury containing gas discharge lamps are the most commonly applied UV source as far as applications relying on high energetic UV radiation between the UV-C (200 – 280 nm) and UV-B (280 – 315 nm) range is concerned. In addition to that, phosphor converted mercury discharge lamps still find application in UV lamps for cosmetic and medical purposes as well as a diminishing application in general lighting in shape of so called “neon tubes” or fluorescent lamps (US Department of Energy, 2012; Ronda, 1995). The general device setup consists of a tubular glass discharge vessel which is equipped with two internal metal electrodes at the

ends. The discharge vessel usually contains a gaseous filling consisting of evaporated mercury and a noble gas e.g. argon or neon to ease the ignition process and to buffer electrons. The thermally emitted electrons from the heated cathode follow the pathway of the electric field towards the anode side. Being accelerated by the applied electric potential, the moving electrons will collide with the buffer gas or evaporated Mercury giving rise to its electronic excitation via a transfer of kinetic energy performed by inelastic collisions. The excitation energy is thus governed by the kinetic energy of the free electrons, which depends on the applied field strength as well as so-called average free length of path, i.e. the mean distance that an electron travels in between of two consecutive impacts (Lister et al., 2004) In particular, the free length of path strongly depends on the gas pressure. Therefore, the applied filling pressure has a pronounced impact on the efficiency and emitted spectrum. With regard to the filling pressure, mercury discharge lamps are subdivided into low-pressure, i.e. the pressure is below 1 -10 mbar, into medium-pressure, i.e. the filling pressure ranged from 1 to 5 bar, and into high-pressure discharge lamps, wherein the filling pressure is larger than 5 bar (Oppenländer, 2003; Van Der Meer et al., 2015).

For the generation of UV radiation solely low- and medium-pressure lamps are of relevance, since high-pressure lamps mainly emit in the visible range and are thus used for general lighting and projection purposes (Morimoto et al., 2004). In other words the enhancement of the pressure results into a red shift of the spectral power distribution due to re-absorption, which also means that the efficiency of the emission of UV radiation declines with increasing pressure.

For further clarification of the different emission spectra due to the gas filling pressure, figure 2 depicts the emission spectra of a typical low and medium pressure Mercury discharge lamp.

For disinfection and especially water treatment purposes low pressure Hg discharge lamps emitting predominantly at 185 nm and 254 nm are widely in use (see figure 1). In the meantime, this lamp type is well established and thus applied at the point of use of water, e.g. in households as well as in very large-scale industrial or community applications. Even though the underlying technology of mercury containing discharge lamps and their corresponding applications are developed to an impressive maturity level, there are some shortcomings which allow the entry of competing technologies into these markets. The most obvious drawback, which is shared by all types of mercury discharge lamps, is the presence of the heavy metal mercury, which implies an environmental risk, e.g. in case

Figure 1 Emission spectrum of a Hg low pressure lamp (source: own representation).

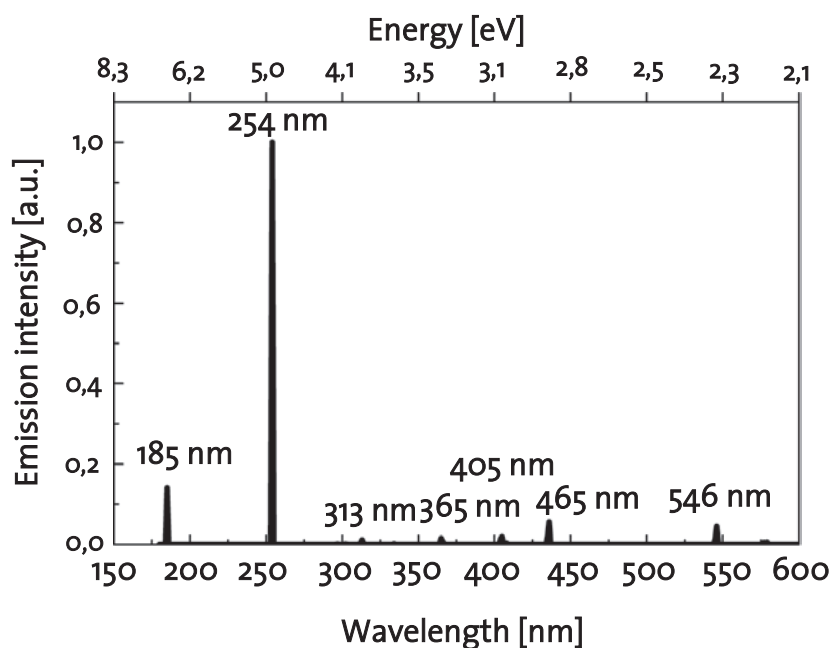
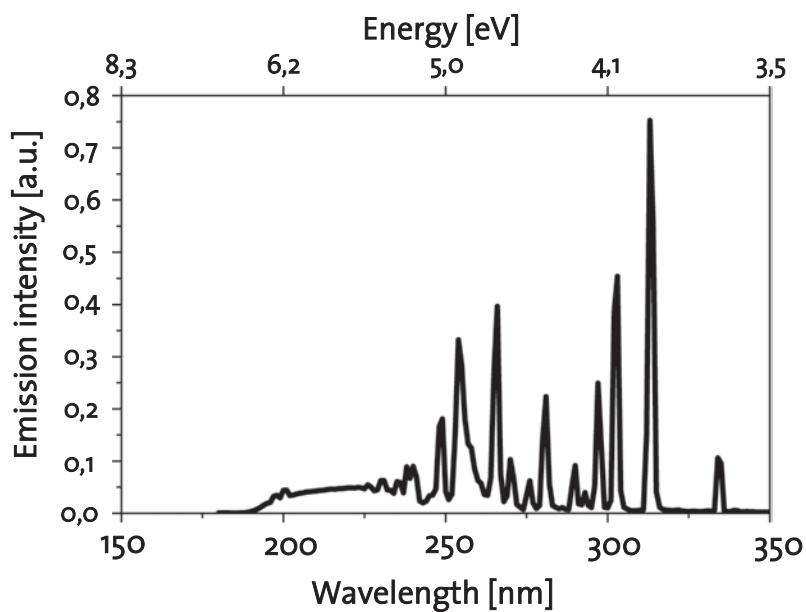


Figure 2 Emission spectrum of a typical Hg medium pressure lamp (source: own representation).



of lamp fracture or due to improper device disposal. In particular, low pressure lamps have additional operational drawbacks or limitations which have to be faced, such as the fragile quartz glass body, a strong dependence of the UV output on ambient temperature, the demand for continuous water flow in terms of cooling, the limitation to continuous rather than pulsed operation, and finally the observed run-up phase until full UV output is reached (Oppenländer, 2003; Chatterley and Linden, 2010).

Another presently applied technology are solid state light sources, viz. UV emitting LEDs based on a nitride type semiconductor chip. These were first mentioned in scientific and patent literature for general lighting purposes in 1994. Since then LEDs have disrupted the conventional technologies used in the lighting industry (Nakamura et al., 1994; Baretz and Tischler, 1996). Solid state light sources rely on electroluminescence, which is the recombination of oppositely polarized charge carriers, in the case of inorganic LEDs within a pn-semiconductor crystal. The energy of the emitted electromagnetic radiation is thus equal to the semiconductor band gap. Due to the continuous development of the fundamental semiconductor technology the market for UV radiation sources experienced a strong encroachment by (Al,Ga,In) LEDs during the last decade. This is particularly true for UV sources that cover the UV-A (315 - 380 nm) range. They have strongly changed the market for UV-A sources as they offer a broad variety of products solely dependent on the semiconductor composition. A glance into recent literature reveals the ongoing development of UV-B and even UV-C emitting LEDs, which are to some extent already available in commercialized products (Chen et al., 2017). J. Chen, S. Loeb and J.-H. Kim (2017) give in their article a valuable overview of the development of UV emitting LEDs for disinfections from the early 2000s until today. Others emphasize the potential of LED radiation sources for water disinfection in comparison to the well-established Mercury low pressure lamps (Chatterley and Linden, 2010). Those paper do not forget to mention that, unless a huge potential in general, an extensive use of UV-C and UV-B emitting LEDs for disinfection is currently limited due to poor optical output power, low lifetime, and high device cost. This particularly holds for LEDs with an emission spectrum in the UV-C range, which is required for disinfection purposes. For direct photolysis of organic pollutants short UV-C radiation (< 250 nm) is required, which is even more challenging w.r.t the above mentioned shortcomings (Chen et al., 2017). An additional problem with regard to the application of LEDs in already established devices, as e.g. flow-through reactors for water

treatment, is the demand for an imperishable and long-term stable package, which effectively shields the LEDs from contact to ambient air, moist or water whilst it enables an efficient out-coupling of the generated UV-C radiation. To our best understanding, established package materials, like epoxy resin, poly methyl methacrylate (PMMA, plexiglass), or even flexible silicones suffer from degradation upon exposure to a high flux of high energy UV photons (Chen et al., 2017; Barton et al., 1998; Fischer et al., 2013; Arques-Orobon et al., 2015).

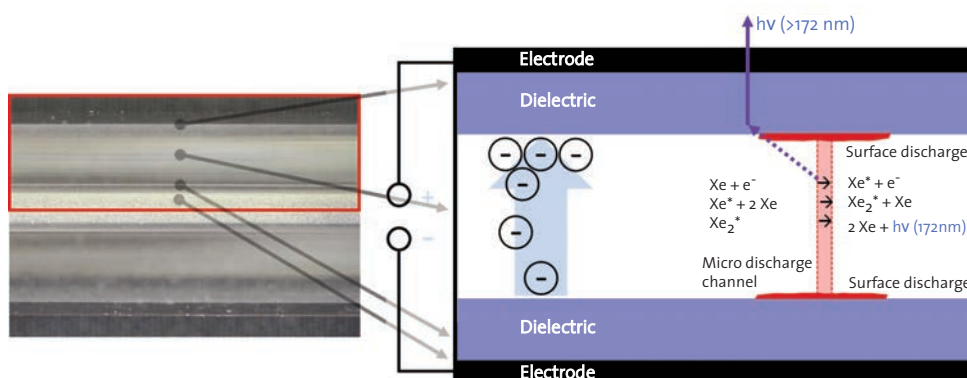
In summary: Recent literature nicely illustrates steady improvement of deep UV emitting LEDs and as well points out the large potential in water treatment and disinfection. However, it appears that there are certain years of further development to pass, before efficient UV-C emitting LEDs will emerge as a competitive technology on the market for disinfection and water treatment. In contrast to that mercury discharge lamps have reached a mature technology status, which means that the given technological potential is nearly exploited. Neither can their inherent disadvantages be technically overcome nor appears this technology to be adaptive for upcoming challenges.

## 2.2 Alternative Technology: Mercury free excimer discharge UV Radiation Sources

Since Hg discharge lamps and LEDs suffer from several drawbacks, as explained before, scientists have found an alternative technology. These are the so-called excimer lamps. Since excimer lamps are basically discharge lamps, the portfolio of gas discharge lamps experienced a serious diversification once excimer lamps were first described in 1857 (Kogelschatz, 2003). So-called excimer lamps, or excilamps rely on the generation of excimer species via a dielectric barrier discharge which takes place in a gas-filled discharge vessel. The word “excimer” is made up from the two words “excited” and “dimer” and may thus be understood in accordance to excited dimer (Oppenländer, 2003). The excimer emits its excitation energy in form of electromagnetic radiation upon radiative relaxation into its dissociative ground state (Kogelschatz, 2003). In contrast to a discharge which forms between two conductive metal electrodes, only separated by a certain gas, does the excimer discharge experience a hindrance by at least one dielectric layer, usually glass or quartz, which separates the electrodes. Depending on the gas filling, different excimer species evolve. Literature lists certain excimer species which show characteristic emission of UV or vacuum UV radiation, such as  $\text{Ar}_2^*$  (126 nm),  $\text{Kr}_2^*$  (146 nm),  $\text{Xe}_2^*$  (172 nm),  $\text{KrCl}^*$  (222 nm) or  $\text{XeCl}^*$  (308 nm) (Oppenländer, 2003;



Figure 3 Photograph of a tubular excimer lamp (left) and a schematic sketch of its construction and operation mode (right) (source: own representation).



Kogelschatz, 2003; Ledru et al., 2006; Kogelschatz, 1992). From the variety of excimer species that are reported in literature, xenon excimers, generated from the noble gas xenon, arose as the most efficient and stable for the realization of a dielectric barrier discharge lamps. Those lamps comprise a quartz glass discharge vessel which is filled with a certain pressure of Xenon gas and two suitable electrodes, which are shielded from each other by at least one dielectric. This dielectric is in most cases given by the discharge vessel itself but other materials are feasible (Kogelschatz, 2003; Kogelschatz, 2000). Figure 3 gives a schematic illustration, as well as an accompanying photograph of one, simple set-up and operation mode for a Xe dielectric barrier discharge lamp.

These lamps are typically driven by short 1 - 10 ns pulses of high voltage, usually 1 - 10 kV, and a peak current of about 0.1 A in order to generate dielectrically hindered discharges, which are also called glow discharge in literature (Kogelschatz, 2000; Boyd and Zhang, 1997). Actually, the generation of excimers is observed if electrons flowing through a micro-scaled discharge channel, collide with Xenon atoms and thus transfer kinetic energy to Xenon atoms resulting in electronic excitation (Eliasson et al., 1988). Subsequently, the excited Xenon atom can react with another Xenon atom upon forming an excimer. The following losses of excessive binding energy and vibronic relaxation into certain energetic states are governed by a complex interplay between the excimer species and atomic Xenon in a three body interaction. Regarding Xe excimer emission, there are four energy levels of interest: Two higher vibronic excimer energy states give rise to the emission of high energetic photons with wavelength at 148 nm (8.38 eV) and 152 nm (8.16 eV)

upon relaxation into the ground state. Two lower vibronic excimer states which give rise to the emission of lower energetic photons with a mean wavelength of 172 nm (7.21 eV) or 186 nm (6.67 eV) Boyd and Zhang, 1997). The two high energetic emission bands are usually called first continuum whereas the lower energetic emission bands are referred to as second emission continuum. The electronic ground state is non-binding and dissociates within the timescale of nanoseconds after relaxation, thus providing optimum conditions to avoid output loss due to reabsorption. As the non-radiating relaxation pathways are governed by three body interactions, does the overall emission spectrum of a certain Xe dielectric barrier discharge (DBD) lamp strongly depend on the Xe filling pressure. Furthermore, does a higher working pressure aid excimer formation to a certain extent, as three body collisions are promoted by a higher density of Xe atoms. In applications the xenon pressure usually exceeds 250 mbar, resulting in a strong quenching of the first continuum in favour of the second emission continuum (Ledru et al., 2006). In addition to the implementation of a relatively narrow band 172 nm emitter, the diminishment of the first emission continuum results in a prolonged lifetime of the quartz discharge vessel, which could otherwise take serious damage due to solarisation by high energetic photons over time (Schreiber et al., 2005).

### 3. Mercury Free Excimer Lamp - An Innovative VUV Radiation Source

The Xenon excimer DBD lamp embodied a true and rather radical innovation at its time of development. This innovation already entered the market in form of several applications, such as photo-

lithography, photo-polymerization, photo-etching, photo-enhanced MOCVD (metal organic vapour deposition), ozone generation, and last but not least plasma display panels (Oppenländer, 2003; Morimoto et al., 2004; Kogelschatz, 2000; Hauschildt and Salomo, 2011). In certain areas, Xe excimer lamps already compete with the established low pressure mercury discharge lamps. This is caused by the fact that low pressure mercury discharge lamps also partly emit a fraction of about 12% of the overall output in the VUV region, viz. at 185.0 nm (6.70 eV) (Kowalski, 2009). In comparison to the low pressure Hg lamp, the narrow band 172 nm emitting Xe excimer DBD lamps offers some advantages. For example the high average power density of VUV radiation, an emission spectrum solely located in the VUV range, the relatively low lamp surface temperature, and the absence of mercury as well as instant-on and short pulse operation. The latter three advantages are possible game changers in some application areas.

#### 4. Phosphor Converted Xe Excimer Lamps – An Innovative and Tuneable UV Radiation Source?

The concept of phosphor converted Xe excimer lamps was already addressed in 2002, e.g. by Philips and Ushio. This technology appears to be a consequent and incremental further development of the VUV emitting excimer DBD lamp technology (Feldmann et al., 2003). The application of a radiation converter in order to transform the high energetic 172 nm VUV photons towards less energetic UV photons (190 - 380 nm) opens up a sort of platform concept, wherein the Xe excimer platform is modified by a UV phosphor. The principle of wavelength converting phosphors itself, is well known from its

application in mercury discharge lamps for general lighting. In these lamps for general lighting, UV radiation originating from the Mercury discharge is converted into visible light by a suitable phosphor layer coated onto the inner side of the discharge vessel (Ronda, 1995; Feldmann et al., 2003; Ronda, 1997). Furthermore, this approach also found application in present solid state light sources, i.e. white LEDs, wherein the spectrum of a blue emitting (In,Ga)N chip is converted into a white spectrum in line with the application aimed at (Krames et al., 2007; Cho et al., 2017; Bando et al., 1998).

What appears to be most interesting is the full conversion of the 172 nm emission originating from the Xe excimer discharge into either a slightly less energetic VUV emission or an emission within the UV-C range (200 - 280 nm). Both approaches aim for the treatment of water in terms of photolytic cleaning from organic pollutants or disinfection. The latter approach has also potential for the treatment of surfaces and gaseous media. Furthermore, the conversion into the UV-B/A region could be useful for energy selective driven photochemical reactions. Suitable phosphors, their most intense emission peak, and their possible applications are given in Table 1.

Another quite uncomplicated approach for the realization of a phosphor converted Xe excimer lamp is the direct application of a suitable phosphor as coating onto the inner wall of the discharge vessel. From a technological point of view, this is relatively easy to achieve via a so-called up-flush coating procedures. The lamp body, as printed in figure 3, is filled with a phosphor suspension by applying a small vacuum, sufficient for a laminar vertical rise of the phosphor paint. The phosphor material adheres on the surface of the vessel. The slow enhancement of the pressure towards ambi-

Table 1 List of phosphors, wavelength conversion and possible application areas (source: own representation).

Composition	Emission upon 172 nm Excitation ( $\lambda_{max}$ )	Application area
$YPO_4:Nd^{3+}$	192 nm	AOP, $NO_3/NO_2$ cleavage, AOP by $OH\cdot$ generation
$YPO_4:Pr^{3+}$	235 nm	AOP, Disinfection
$YPO_4:Bi^{3+}$	241 nm	AOP, Disinfection
$YPO_3:Pr^{3+}$	265 nm	Disinfection
$BaZrSi_3O_9$	285 nm	Disinfection

ent pressure allows remaining an excessive layer of phosphor on the lamp body. Subsequently, the lamp body is heated in order to evaporate all organic materials. The inorganic phosphor remains as a thin layer on the inner wall of the discharge vessel. The lamp is then filled with an appropriate amount of dry Xenon gas. In a last step the discharge vessel is closed by sealing, which also ensures that the phosphor is shielded from ambient gases, such as oxygen, water (moisture), or wear corrosion by friction. However, the phosphor is in intimate contact to the Xenon discharge channels, which occurs in lamp operation.

The innovative potential of phosphor converted Xe excimer lamps lies in its inherent advantages as discussed in chapter 3 and the wavelength conversion, which may promote this technology to a serious competitor for mercury based devices and open up new areas of application. Especially the property of wavelength conversion reveals an outstanding opportunity to spectrally shift the device's emission from the VUV range ( $< 200$  nm) up to the near visible edge of the UV-A range (380 nm) by the choice of phosphor or the composition of a phosphor blend. This approach can be regarded as a spectral toolbox, allowing the implementation of tailored lamps for specific applications like the disinfection of particular germs, for the cleavage of specific micro pollutants like hormones or drugs or even the promotion of precise photochemical reactions.

The feasibility to construct tailored lamps may end up in more efficient radiation sources in comparison to the established mercury discharge lamps because the device emission spectrum may be tailored according to the spectral absorption maximum of a photochemical system involved in a targeted process. Moreover, they bear the advantageous features of excimer discharge lamps, like the lack of mercury, instant-on and fast switching cycles.

Presently, there are only few fully commercialized products operating with phosphor converted Xe excimer lamps which are regularly available on the market. This product is named "Instant Trust Marina" and is supplied by Philips for the treatment of drinking water on boats and ships. The reason for this lack of products is mainly due to technical problems and material lifetime issues, which arise from the much more challenging conditions caused by the hazardous discharge (accelerated electrons and cationic species) being in close contact to the phosphor.

Besides the demand for more elaborately constructed electronic drivers, giving rise to a high efficiency in excimer generation and respective emission, a commercially successful implementation of phosphor converted excimer lamps requires a

detailed study of involved components and materials. This e.g. covers the choice and long-term stability of the dielectric, which depends on the discharge vessel or the applied electrode material. With respect to this, a lot of knowledge has already been gained throughout the development of phosphor free 172 nm emitting Xe excimer lamps. However, a serious issue that has not been covered yet is the behaviour and stability of the applied phosphor materials. The research project Fluoro UV (funding no. 01LY1303B) as funded by the BMBF (German Federal Ministry of Education and Research) and carried out under the involvement of the Munster University of Applied Sciences, GVB GmbH, Tailorlux GmbH and the DLR (German Centre for Air and Space Travel) exactly addresses this important topic. Therefore, this research project covers the whole product chain, from phosphor synthesis, characterization and improvement, to the lamp manufacturing and lamp maintenance evaluation, the analysis of phosphor aging and the exploration of suitable protective countermeasures as well as the actual evaluation of manufactured lamps in water treatment. Recent results demonstrate the high efficiency of materials like  $\text{YPO}_4:\text{Bi}$  and  $\text{YPO}_4:\text{Pr}$  in Xe excimer lamps for the direct photolysis of sulfamethoxazole in aqueous solution. This especially holds for the efficient reduction of the measurable amount of total organic carbon (TOC) in which the excimer lamps outperform a reference Hg low pressure amalgam UV luminaire (Nietsch and Jung, 2017; Nietsch, 2017). A significant reduction of TOC content clearly indicates that sulfamethoxazole is not solely cleaved into shorter organic species, but that it is nearly completely cleaved photolytically including any intermediate generated species. Beyond revealing the huge potential of phosphor converted Xe excimer lamps, the Fluoro UV project also points out ways to an understanding of the most profound challenge, namely the rather poor device lifetime. Contributions to this field are especially achieved by conducting detailed analysis of the aging behaviour of the applied phosphor type and the implementation of protective particle coatings as well as further countermeasures to ensure a prolonged device lifetime. However, as trend-setting findings have been made, it appears that there still remain some challenges to enable phosphor converted excimer lamps becoming a real game changer regarding the UV business.

## 5. Evaluation of the Market Potential of Phosphor Converted Xe Excimer Lamps

The following subchapters aim to evaluate whether or not the phosphor converted excimer

lamp is a true innovation. For this purpose it appears feasible to apply a diverse set of evaluation criteria deduced from recent literature. The basis for this set of criteria is an article from R. G. Cooper (1985) dealing with the evaluation of strategies for new product programs (Cooper, 1985). Since, this article does not aim at discussing strategies for new products, the list was slightly modified to focus on criteria supporting the assessment of phosphor converted excimer lamps as an innovation at a rather early technical state.

## 5.1. Nature of New Product Developments

### 5.1.1. Degree of product innovativeness

To this point it is not valid to discuss the degree of innovativeness based on a certain product. The technology of phosphor converted Xe excimer lamps can actually be applied to a broader sector, which could potentially be used in a broad set of products. Therefore, it is noteworthy that there is already one established product on the current market for disinfection of drinking water, which is designed for the treatment of water with germicidal UV radiation given by a phosphor converted Xe excimer lamp. This product is named "Instant Trust" (Philips) and includes a combination of a Hg free (Excimer) lamp driven UV disinfection vessel and different water filters. The Instant Trust Marine aims for the germicidal treatment of drinking water on boats in small scale of 1000 L/h (Philips Corporation, 2017). The local limitation as well as the technical limitations given by a short product life cycle in combination with a small, rather household scaled application do not exploit the full potential of this technology. Especially when recent and upcoming scientific progresses are taken into account. Depending on the exact realisation of the energy conversion via phosphors combined with Xe excimer lamps, e.g. the use of phosphors or phosphor blends, different lamp geometries, scales and lamp powers, a variety of possible applications is addressable. Amongst those, the most prominent ones, which have already been mentioned and discussed in this paper, are given by the treatment of fluid media (mostly water), gases and surfaces for disinfection and clarification from organic pollutants. Beyond that it appears to be likely that upcoming products relying on phosphor converted Xe excimer lamps may e.g. target applications in the treatment of process exhaust gases (e.g.  $\text{NO}_x$  reduction), photochemistry, photobiology, optical spectroscopy, and material science. Chapter 4 gives a more detailed view into essential technical features and resulting possibilities for application. Concluding it appears to be reasonable to point out the tremen-

dous innovative potential as given by phosphor converted Xe excimer lamps, which could lead to a variety of commercialized products.

### 5.1.2. Product Quality Level

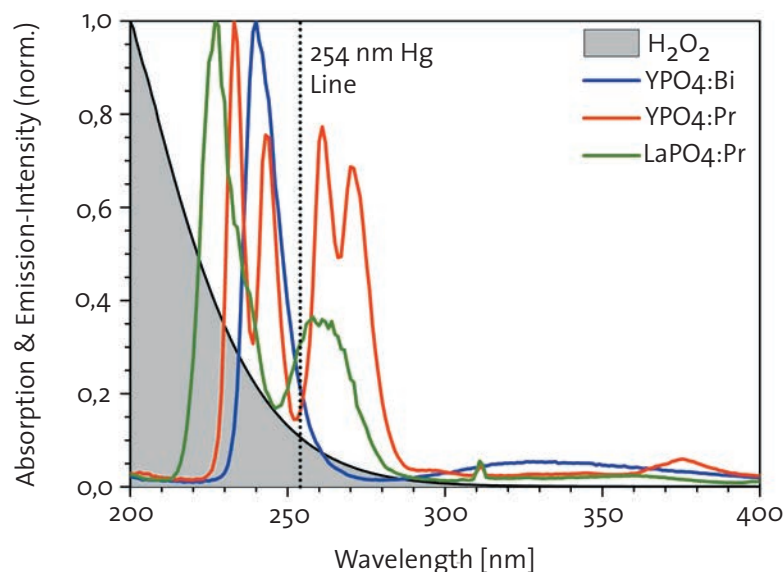
As mentioned in chapter 5.1.1. the article's scope does not address a certain yet commercialized product solution including a phosphor converted Xe excimer lamp. A detailed evaluation of the quality of a certain product can thus neither be objective here. What appears reasonable is to address a set of quality criteria or definitions, which are applicable to describe a variety of products build on the basic technology of Xe excimer lamps utilizing wavelength conversion by phosphors. In this context, the authors decided to choose the quality of implementation, performance and stability as suitable metrics for the evaluation of the product quality level.

Focusing on the possible quality of the implementation and performance of phosphor converted Xe excimer lamp for the treatment of water in order to perform a cleaning from persistent organic pollutants (POP) or germicidal treatments, those lamps may comprise a higher extent of quality in terms of functionality.

Current products that are related on excimer lamps already prove that Xe excimer lamps can be manufactured as electrically efficient emitters of 172 nm radiation. A suitable example is given by Osram, which has several VUV emitting Xe excimer lamps in stock. Referring to publicly available data, lamps of the type Osram XERADEx (L40/120/SB-S46/85) exhibit a wall plug efficacy of around 30% as 20 W of electrical power are converted into 0.04  $\text{W}/\text{cm}^2$  irradiance at 172 nm (Osram, 2017). A further on going development may push that efficacy even further. A second setscrew in terms of the device wall-plug efficacy of phosphor converted excimer lamps is given by the external quantum yield of the applied phosphor material itself. The external quantum yield is thereby defined as the number of emitted photons divided by the number of initially absorbed photons at specific excitation energy. Unfortunately, this value is rather difficult to measure for VUV excited and UV-C emitting phosphors and is therefore an often untouched issue. Nevertheless, researchers try to solve this by a performance measurement of a completely assembled lamp. A rough assumption, which is supported by high temperatures for thermal quenching of certain  $\text{LnPO}_4$  based phosphors leads to a quantum yield of approx. 80% for a phosphor like  $\text{YPO}_4:\text{Bi}$  (under 160 nm excitation) (Jüstel et al., 2004).

A very promising feature that promotes prod-

Figure 4 H<sub>2</sub>O<sub>2</sub> absorption and YPO<sub>4</sub>:Pr, LaPO<sub>4</sub>:Pr, YPO<sub>4</sub>:Bi emission spectra (source: own representation).



uct quality in terms of performance is the fact that the radiation output may be tailored spectrally according to the respective process demands. Exemplary, the efficacy of a POP cleavage process using H<sub>2</sub>O<sub>2</sub> as auxiliary chemical could be completed faster and more energy efficient using for example YPO<sub>4</sub>:Bi<sup>3+</sup> or YPO<sub>4</sub>:Pr<sup>3+</sup> converted Xe excimer lamp compared to a Hg low pressure lamp (Nietsch and Jung, 2017; Nietsch, 2017; Broxtermann et al., 2017). This is due to a higher spectral overlap of the excimer lamp emission and the H<sub>2</sub>O<sub>2</sub> absorption curve. Figure 4 shows the respective absorption and a couple of idealized emission spectra exhibited by different phosphor converted Xe excimer lamps as well as a Hg low pressure lamp.

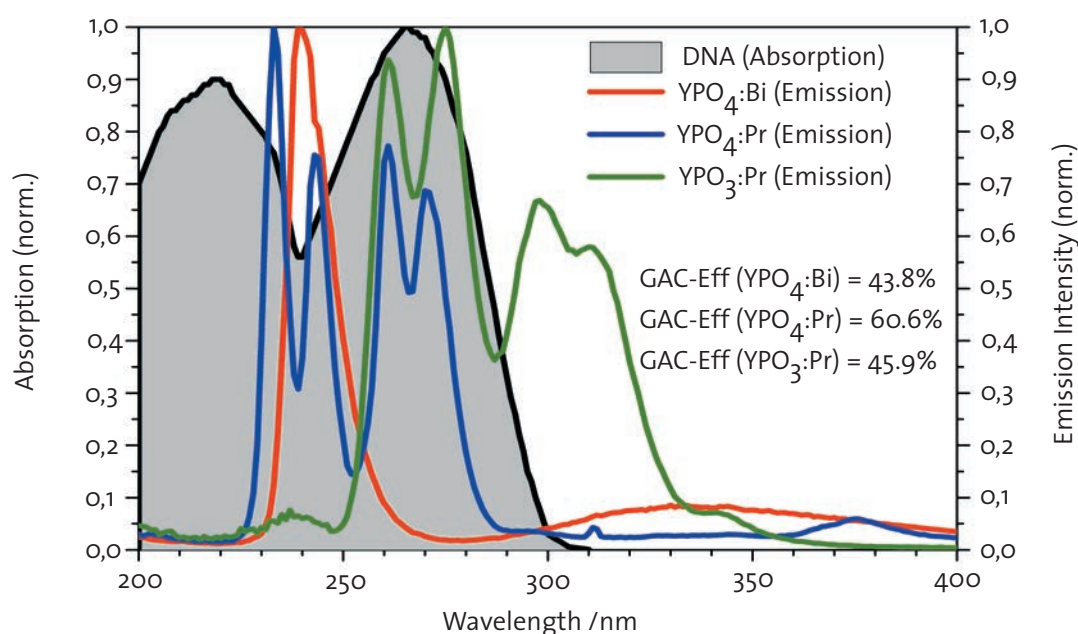
Beyond that the high energetic radiation < 250 nm leads to a further enhancement in POP cleavage, as recent findings demonstrate that even without H<sub>2</sub>O<sub>2</sub> addition, a solutions' TOC (total organic carbon) content may be significantly decreased (Nietsch and Jung, 2017; Nietsch, 2017; Broxtermann et al., 2017). It was thereby proven that both phosphor converted Xe excimer lamps are more energy efficient in the photo oxidative depletion (H<sub>2</sub>O<sub>2</sub> addition) as well as the bear photolysis (no addition of reactant) of an POP (Sulfamethoxazole) than an analogously tested Hg low pressure lamp (Hg amalgam). The DLR (Deutsches Zentrum für Luft- und Raumfahrt) used respective measurements to calculate a reduction of CO<sub>2</sub> emission due to the consumption of electrical power of up to 95% for

the direct photolysis and a reduction for 85% for the photooxidative treatments, when suitable tested YPO<sub>4</sub>:Bi or YPO<sub>4</sub>:Pr comprising lamps were compared to the Hg antagonist (Nietsch and Jung, 2017; Nietsch, 2017). This simple example indicates the tremendous prospect that task-specifically tailored phosphor converted excimer lamps may comprise treatment time, energy efficacy and a reduction of CO<sub>2</sub> emission in terms of AOP clarification treatments.

The above mentioned spectral adaptability of the phosphor converted excimer lamps is as well interesting, since the performance of germicidal treatments can be influenced by the lamps' output e.g. by an adjustment the absorption spectrum of the targeted bacterium. A commonly used tool to evaluate the germicidal efficacy of a certain phosphor converted lamp is to weight the emission spectrum of the applied phosphor for the function of the spectral inactivation efficacy exhibited by a certain germ. Figure 5 gives an example involving the absorption spectrum of DNA over the UV region as well as the emission spectra of a selection of UV-C emitting phosphors.

A suitable metric, the so called GAC (germicidal action curve) overlap or germicidal efficacy may then be calculated as given by equation 1, where  $I_{\lambda, \text{Sample}}$  stands for the emission spectrum of the phosphor sample (counts vs. wavelength) and  $\text{Abs}_{\text{Rel, DNA}}$  for the relative absorption exhibited by isolated DNA. We thereby assume a direct cell core

Figure 5 DNA (UV absorption) and photoluminescence emission spectra of the UV-C emitting phosphors  $\text{YPO}_4\text{:Bi}$  and  $\text{YPO}_4\text{:Pr}$  (160 nm excitation) (source: own representation).



damage due to the absorption of UV-C irradiation by DNA.

In spite of the huge implementation and performance related benefits of phosphor converted excimer lamps, they currently bear an unneglectable disadvantage. This disadvantage is related to stability as metric for quality and is typified by a short device lifetime due to aging effects. Current research projects, as currently worked on by the Muenster University of Applied Sciences (BMBF Project "Fluoro UV, funding no. 01LY1303B) follow this issue by trying to understand and prevent the pronounced aging effects. Recent research has proven that the aging effects, exhibited by phosphor converted Xe excimer lamps originate from a pronounced aging or degradation of the applied phosphor itself upon contact to the Xe plasma discharge (Broxtermann and Jüstel, 2017). Aging prevention will be a key to a significant improvement of product quality in terms of stability as well as a key factor for a realization and success of any com-

mercial product. Furthermore, it will include direct protection methods like particle coating, as well as certain arrangements regarding product geometry and design to effectively reduce phosphor aging to a minimum extent (Broxtermann and Jüstel, 2016).

Summed up we are facing rather low product quality in terms of long-term stability which contradicts a high level of task specific efficiency and adaptability.

### 5.1.3. Degree of Product Concentration vs. Diversification

The technology of phosphor converted excimer lamps exhibits a certain potential for diversification by itself. A basic carrier technology, namely Xe comprising excimer DBD discharge lamps, emitting 172 nm VUV radiation, is combined with the wavelength conversion potential given by VUV excitable photoluminescent phosphors. A first lever

Equation 1 (source: own representation).

$$\frac{\int_{200}^{320} (I_{\lambda, \text{Sample}} * \text{Eff}_{\lambda, \text{GAC}})}{\int_{200}^{320} (I_{\lambda, \text{Sample}})}$$

enabling diversification is given by the used lamp geometry. This also includes the implementation of an electrode exterior to the discharge vessel (Kogelschatz, 2000). For the application in conductive media, like water, there is no need for any exterior electrode as the conductive media can be contacted directly. Besides if a lamp is used for the treatment of gases or the treatment of solid surfaces, there must be a conductive material attached to the outer wall of the discharge vessel dielectric, acting as electrode. However, the general technology of Xe DBD lamps offers the opportunity to address liquid and gaseous media as well as the surface of solid media (Oppenländer, 2003).

As sketched earlier, the choice of the phosphor or phosphor blends offers additional and distinct potential for diversification, because this determines the kind of targeted application, e.g. germicidal treatments or clarification from POP. If there is once an established well working concept yielding a long term stable phosphor converted excimer lamp, it appears feasible to target different applications. These may range from small scaled point-of-use consumer applications, over medium sized commercial up to large scale industrial solutions. A well-established portfolio of phosphor converted lamps is thus suitable to address more than just one market in a diverse approach.

#### 5.1.4. Product type, e.g. customnes

Excimer lamps offer a wide variation in terms of the construction shape scalability. With respect to a tubular design, as sketched in Figure 3, those lamps may be constructed with sizes from a few centimetres in length and a diameter of barely a centimetre up to lamps with a length larger than one meter and exhibiting a diameter of several centimetres. This variability as well holds for the desired electrical lamp power, which is technically in direct correlation to the power output of UV radiation. The consumption of electrical power can be adjusted from just a few  $mW_{El}$  per cm length up to values up to several  $W_{El}$  per cm lamp length. This degree of freedom thus enables application in small point-of-use devices with just a few  $mJ/m^2$  (alike the mentioned Philips product Instant Trust). Also, large scale industrial solutions which require short treatments times for huge volumes and therefore high UV doses in the range of several hundred  $J/m^2$ , as the German Association of Manufacturers of Equipment for Water Treatment (FIGAWA) has published within one of their recommendations in 1987, are possible to realize.

## 5.2. Nature of Technology (Production & Development) used

### 5.2.1. Technology fit or synergy with the firm

As phosphor converted excimer lamps embody an on-going development originating from its phosphor free predecessor, it appears very reasonable to assume that the development of commercial products would strongly benefit from a detailed know-how as well as a strong and reliable infrastructure regarding classical discharge lamp technology and excimer discharge technology in particular. Therefore it seems very likely that through sophisticated research and development can be best accomplished by already established players on the market. Know-how, originating from the assembly of classical Hg discharge lamps may be very useful for the implementation of phosphor converted Xe excimer DBD lamps. Furthermore, could existing distributions channels ease a possible market entrance for those products. As those phosphor converted Xe lamps could be used to aim for a substitution of Hg containing products in the future, it appears even more comprehensible that a current supplier of Hg related products could prefer to push the development of such mercury free alternatives themselves rather than leaving this field open to competitors on the market. If a company is able to provide additional knowledge, abilities and potential market share for UV products used in disinfection or other clarification applications, the resulting synergistic effect could be a significant advantage.

### 5.2.2. Maturity of technology. e.g. state-of-the-art vs. "old" technology

Phosphor converted Xe excimer lamps do not represent a matured well-established technology with respective to hold a share on the market of UV products. The technology is in a rather early state and a successful broad commercialization of related products is yet hindered by a significant lack of quality on terms of stability, namely long-term stability (see 5.1.2.). For the many different applications that have been addressed in more detail within the prior chapters, phosphor converted Xe excimer lamps do not embody a state-of-the-art technology. In most cases it appears suitable to describe them as a possible challenger of the current state-of-the-art technology represented by Hg containing discharge lamps or in case of a new application sought as a development technology. The earlier chapters dealing with the technical background of Hg and Xe excimer lamps, with and without conversion by phosphors, are supposed to give

a broad background regarding the certain features and possible drawbacks of each technology. At this point it is adequate to point out that Xe DBD discharge lamps involving energy conversion via inorganic phosphors pose a challenger technology on a rather early, still pre-commercial status with only one available small scale product on the market called Philips instant trust.

### 5.3. Type of New Product Markets Sought

#### 5.3.1. Market size growth and potential

According to a McKinsey study from 2012 the general lighting market is a very dynamic one, which steadily increased over the last years. Although a decrease of the GDP was predicted by McKinsey, between 2011 and 2012, the lighting business was prognosticated to grow even further. An analogous trend was observed for the UV radiation business as well. From 2011 to 2015 the market for UV disinfection equipment has risen from 885 million USD up to 1.4 Billion USD (Hanft, 2011). This is an increase of 58% within 4 years and moreover a compound annual growth rate of 14.6% is expected from 2015 to 2020 (Ramamurthy, 2015). Since the technical development in this sector is only of incremental nature and based on old-fashioned discharge lamps, this increase is mainly due to an increased market pull. Since the current innovations within this sector have only been incremental innovations, the development and commercialization of phosphor converted excimer lamps might be a game changer on this rapidly growing market offering several technical advantages as mentioned in 5.1.2. Moreover a development of new sub markets within the market of water disinfection is expected. Due to the spectral tenability of phosphor converted excimer lamps this market will certainly experience a significant diversification, wherein each specialized on a certain emission range especially aiming for certain bacteria, microorganism or virus.

#### 5.3.2. Competitive situation

The market for UV emitting luminaires appears to be a very competitive market, which is in Europe mainly dominated by big companies like Heraeus, Osram, Narva and Xylem (Van Der Meer et al., 2015). In this market, success is strongly governed by product prizes and cost efficacy, especially in a situation in which a new uprising technology like phosphor converted Xe excimer lamps aim to challenge well-established state-of-the-art technology like Hg discharge lamps. This is very perceptible if we draw parallels to the market developments for general lighting over the recent years. This market,

which in 2011 amounted to 140 Billion USD €/a experienced serious changes over the last decades (McKinsey&Company, 2012). These changes went along with the development and commercialization of LED related luminaires and products. The ascent of LED in general lighting stood in strong correlation to serious scientific progress in semiconductor production, especially at a large scale, which made LED related products affordable and available in large numbers, providing sufficient product lifetime, and high performance (Cho et al., 2017).

For those applications and related markets where converted Xe excimer lamps enter as competitors challenging well-developed, quite cost-efficient and qualitatively sophisticated products like Hg low pressure lamps, they will have to prove a clear benefit to the customer in order to outplay the established technology. Along with the most striking benefit presented by the needlessness of Hg, the further advantages arise by the spectral output adaptability throughout wavelength conversion via certain phosphor species as well as the instant-on operation mode. The unique features may offer significant economic and ecological benefits. Concluding one could state that although the UV lighting market is strongly cost driven and mature the phosphor converted excimer lamp offers several benefits which makes it a superior technology regarding its applications.

#### 5.3.3. Stage of the product life cycle

To this point in time it is actually not possible to describe phosphor comprising Xe excimer lamps and related products in terms of a product life cycle. The fundamental technology dealing with the excimer discharge is broadly researched, as numerous scientific articles and reviews to some extent as well used as literature for this article indicate. Furthermore, Xe DBD related products have already found application e.g. in surface treatment, ozone generation and televisions (see chapter 2). However, as already scratched earlier, phosphor converted Xe DBD lamps are still a piece of research as they have not found a broader application beyond laboratory scale, except for Instant Trust by Philips. Basically, this technology has currently no commercial relevance due to the fact that possible product realizations like Instant Trust by Philips more or less represent niche products with a market volume that probably vanishes upon comparison to the overall market for UV products for clarification treatments. At the moment this product has probably not the potential for a wider introduction of phosphor converted excimer related products as the current limitation to poor lifetimes and the current lack for a feasible solutions would clearly hin-



der success on the market.

#### 5.4. Orientation and Commitment to the new Product Program

##### 5.4.1. Whether the program is defensive or offensive in nature

In subchapter 5.2.1. possible synergistic effects that might take effect upon the realization of a product portfolio based on phosphor converted excimer lamps by a company or organization that is already experienced in the assembly and distribution of discharge lamps were discussed. Furthermore, subchapter 5.1.3. describes the benefits of a rather diversified product strategy. Thus it appears as a logical deduction to present a potential product program as rather balanced. A focussed, straight forward product program comprising a sharply focused marketing strategy appears very useful for those excimer products comprising phosphor conversion that tackle novel application areas in which phosphor converted excimer lamps succeed due to their unique selling points. Respective application areas could be e.g. nitrate/nitrite depletion from strongly contaminated ground water or regarding the solution point-of-devices for disinfection and AOP cleavage. Wherever phosphor converted excimer lamps are sought to be a competitor for existing technology, it appears as either feasible to excel established products distributed by a competitor on the market or to foster the own product portfolio through a step-by-step substitution by the new superior product development. The latter case would clearly demand for a defensive strategy whereas the first case strongly demands for an offensive product program.

##### 5.4.2. Whether the R&D effort is pure research vs. applied

The research and development (R&D) effort which is necessary for the realization of sophisticated commercially distributable solutions comprising phosphor converted Xe excimer lamps for any targeted application (water treatment, AOP, germicidal treatments, photochemistry, and so on) will be of truly applied nature. The target of this R&D will clearly aim at a maximum for the so called wall-plug efficacy and lifetime. For an UV-C emitting lamp, the wall-plug efficacy is yielded by calculating the emitted UV-C energy as fraction of the total electric energy consumption. The main goals for applied research aiming for an optimization of the phosphor converted Xe excimer lamp are the optimization of Xe excimer generation, phosphor quantum yield as well as an effective coupling of

the emitted radiation into a respective reaction vessel or medium to be addressed in a treatment. The issue of pronounced lamp aging poses a very, if not the most important challenge to pass. In our opinion, it is probably the key problem that needs to be solved in order to enable broad success.

##### 5.4.3. Political and social drivers

There are two central points which highlight the development of phosphor converted Xe excimer lamps in terms of the so-called trend of "Neo-Ecology" combining economy, ecology, and social responsibility. These points are embodied by the abstinence of mercury or other heavy metal components due to the Xenon based discharge technology and the possibility to perform energy efficient clarifying treatments, in which a task specifically manufactured luminaire reduces energy consumption, thus shrinking the correlated emission of CO<sub>2</sub>.

The complete absence of the toxic heavy metal mercury poses a striking ecologically advantage, especially where mercury containing discharge lamps are substituted by excimer driven alternatives. While people are increasingly aware of man-made mercury pollution of nature due to mining, energy generation and mainly from fossil fuels (Hylander and Goodsite, 2006). Industrial sectors like chemical industry increasingly refrained from the use of mercury for in synthesis, purification or analysis over the recent decades (Hylander and Meili., 2005). In that given context, it appears quite interesting, that Hg driven discharge lamps embody the last large scale application for Hg. The large scale is truly not given by a certain lamp, which's mercury content was constantly decreased alongside the technological development, but by the huge number of lamp bodies, still sold and used. By today, even politics address that topic more drastically as legislative programs like MINAMATA (Minamata Convention on Mercury), aiming for a prohibition of the use of Hg in lighting and UV luminaire construction, recently demonstrate (United Nations, 2013). A simple model calculation, assuming a fictional annual sales volume of 1 mill. Hg low pressure lamps, each comprising an estimated amount of 1.5 mg Hg leads to an overall application of 1.5 kg Hg entering the free market for industrial, laboratory and household application (Freie Universität Berlin). If we then assume a rate of 1 in 100 lamps to experience breakage and thereby causing uncontrolled Hg emission into the environment, we would end up at a total annual amount of Hg released into nature of 15 kg. This dramatic impression would even intensify the use of mercury medium pressure lamps, exhibiting a significantly higher amount of Hg would be taken into account. In industrial

application Hg containing lamps are a risk factor which is handled by professionals. In contrast to that, applications involving individual private customers, namely application in household and in portable point of use systems, are influenced by individual emotions and concerns when it comes to the handling of toxic material and the private agenda regarding ecologically friendly technology. Taking this into account makes the phosphor converted excimer lamp, in terms of chemical risk or danger, to an absolutely harmless alternative, which is especially beneficial for the implementation of products in the private sector.

Last to be mentioned here, the special innate benefit of instant-on operation renders UV luminaires based on Xe excimer emission perfectly suitable for the discontinuous operation in small scaled point of use applications, e.g. in household. Since Hg lamps need up to 10 minutes to reach their full light output, a lot of energy is wasted. In that case, the absence of mercury results also in a synergistic benefiting, simplifying shipping, storage, handling and disposal for private users. Summarizing, the phosphor converted Xe excimer benefits from a significant CO<sub>2</sub> reduction, because of its increased efficacy and the political desire to ban Hg in public applications. Moreover, the socialized fear from Hg containing products will additionally support its popularity.

#### 5.4.4. Risk level of projects

Although the technology for phosphor converted Xe excimer lamps is known for decades by now, there is currently no broad product portfolio on the market. This fact already implies that the risk level which comes along with a respective development and implementation of this technology cannot be neglected and has to be ranked as rather high. The success of product based on Xe excimer technology and involving phosphor coating stands and falls with the long-term stability, or product life-time as critical quality criterion (also see 5.1.2.). The short device lifetime, which is according to recent results (see chapter 4) caused by a rapid aging of the applied phosphors upon contact to the Xe plasma discharge, is an ongoing issue of intensive research. This poses a strong boundary towards commercialization that has to be taken in order to enable commercial success, especially when cost intensive applications like industrial scale water treatment are targeted. Due to the high potential of phosphor converted Xe DBD lamps, it appears as strongly justified to spend R&D effort on the implementation of lifetime prolonging protective measures, which are thought to be realizable through a thoughtful choice of stable phosphor materials as well as protective

particle coatings and a lamp's construction layout itself.

## 6 Conclusions

Phosphor converted Xe excimer lamps pose themselves to be an emergent technology for applications in which task specifically tailored UV spectra are demanded. Such applications involve e.g. germicidal treatments of water, gaseous media and surfaces, cleavage of POPs from wastewater through AOPs, NO<sub>x</sub> reduction, and surface treatments of polymers and the promotion of photochemical or photobiological processes. They combine the inherent advantages of Xe excimer lamps such as instant on and -off operation, pulsed operation as well as a high efficacy with the various possibilities of spectral tuning given by the use of suitable inorganic phosphors. An intensified use of such lamps instead of established lamps usually based on mercury discharge lead to an improved energy balance for certain processes due to the application of a task specific spectral output as well as to a reduction of mercury involved in UV radiation related products and thus a reduction of mercury exposure to the environment. However, Xe excimer lamps are on the market for a set of applications for quite a time, there is not more than one product relying on a phosphor converted Xe excimer lamp available on the market by now. That is due to the fact that application of phosphor conversion in combination with Xe excimer discharge implies a set of distinct challenges that have to be overcome through sophisticated R&D efforts. The largest problem that has to be solved is given by the fast aging of the involved phosphor materials due to direct contact to the Xe excimer discharge. The phosphor converted Xe excimer lamp is thus evaluated as a promising developing technology bearing a lot of potential for implementation in a variety of future application areas.

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