World Economic Forum

COMMITTED TO IMPROVING THE STATE OF THE WORLD

Industry Agenda

Advanced Materials Systems
Chemistry and Advanced Materials

In Collaboration with Deloitte Touche Tohmatsu Limited

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Contents

Foreword

As the planet faces a growing array of challenges, the need for chemistry and advanced materials has never been greater. Future requirements for energy and water, communications and transportation, health and nutrition, and environmental stewardship are all on the rise due to population growth and improving standards of living. Solutions created in the last century often no longer apply to the problems of today. To meet every one of these challenges, the world will need new chemicals and materials.

And yet today, the state of global enterprise for chemistry and advanced materials is marked by turbulence. Feedstocks for manufacturing chemicals are changing due to availability, economics, regulations, and government policies. The innovation paradigm that served the industry so well during the 20th-century no longer applies. Customer product life cycles are shortening. Investor demands have increased and their tactics are far more aggressive. The industry is having difficulty attracting the next generation of top talent.

As in the past, innovation is key to overcoming these obstacles and essential to the industry's future. But what will this innovation look like?

The Advanced Materials Systems (AMS) Framework for Collaborative Innovation helps companies frame the questions and find the answers to help them find their proper place in the industry's global ecosystem. These questions include:

– With feedstock volatility leading to extreme pressure for more efficient, cost competitive solutions, and greater use of natural resources, how can companies use their feedstocks more intelligently, using less (or new, renewable feedstocks) to achieve more?
– Collaborative innovation shortens timelines and reduces costs but can add complexity if the expectations of all stakeholders are not well aligned. How can companies identify and manage the right partners in industry, government, and academia to play meaningful roles in advanced materials innovation?
– As customer product lifecycles are shortening, can cycle times for product development shorten to keep pace with this trend?
– As selling an advanced material as an ingredient is a less powerful business model than selling materials as part of systems, how are value chains analysed to optimize value capture?
– The future of advanced materials depends on the ability to attract talented newcomers to the enterprise. How does the industry share its excitement for innovation to capture young people who might otherwise land in healthcare, IT, financial services, or other fields?

To succeed in these areas, the industry will have to understand and address the needs of the marketplace. This can likely be achieved through the concept of "seeds and needs". While 'needs' in the marketplace will require innovative ideas, new disruptions produced by the industry can also serve as 'seeds' for broader changes to society. They, in turn, create brand new needs. Both of these approaches will likely require a deep connection to the market place to understand and anticipate needs and to share the disruptive potential of new innovations.

Capable team members representing leading institutions and companies in advanced materials have participated in this study. Their work was supported by World Economic Forum staff and by Deloitte Global. I thank them all for their outstanding efforts. Their product is not just a compelling, insightful study but can also serve as a roadmap for the future of innovation in our industry.

Thomas M. Connelly,
Executive Director and Chief Executive Officer,
American Chemical Society (ACS), USA

Executive Summary

Changing business ecosystems and the declining viability of traditional materials research and development (R&D) are creating an irresistible impetus for dramatic evolution among companies in the chemicals and advanced materials industry (or chemical industry).

Sluggish development cycles increase time to market, heighten the risk to innovation, and create disconnect between supply and demand of materials. Global megatrends, including feedstock volatility and a push for sustainability, are placing new pressures on the industry. Specialty and commodity chemicals businesses are growing increasingly segregated, imposing strains on existing product portfolios and creating the need for new sources of innovation. The enormous library of existing materials is complicated both to understand and to use, but within that library is the potential for a near endless number of new chemical combinations. Taken together, these factors create a compelling case for new approaches to materials innovation.

The Advanced Materials Systems (AMS) framework for collaborative innovation is an example of this approach. AMS calls for materials innovation that uses combinations of existing materials to develop systems-level solutions to address unmet needs. These solutions will be brought to the marketplace via novel business models and by engaging new categories of stakeholders. AMS may potentially accelerate the development of materials solutions across a variety of end markets, including agriculture, construction, electronics, energy, healthcare, and mobility.

While AMS may create significant value for an organization, deploying AMS presents a number of challenges. Cultural inertia is a well-known and remains the most difficult impediment to transformational change within companies. At the same time, traditional methods of capturing value through intellectual property (IP) protections are becoming less relevant. Technical and human capabilities within an organization can be insufficient to undertake systems-level design while an ageing workforce and skills gap can create talent barriers. Working with other organizations will be essential to overcoming these challenges, but this poses its own set of hurdles.

These challenges may seem daunting, but actionable solutions to overcome them means unlocking significant value and reigniting growth within the industry. This report looks to explore these themes and will dive into how AMS can drive collaborative innovation in companies to the benefit of all stakeholders.

For quick reference, Figure 1 showcases the various topics, insights and recommendations explored in further detail. This report is also a continuation of a previous research publication, *Reigniting Growth: Advanced Materials Systems*, published in 2012 by Deloitte Touche Tohmatsu Limited (Deloitte Global), which was an integral starting point for this body of work.

Figure 1. AMS report structure: Context and challenges, insights and recommendations

Topic	Project insight	Recommendation
The need for new approaches to innovation		
Declining viability from traditional materials research and development (R&D)	Innovation models are evolving from pipelines to platforms	Create well-functioning innovation platforms
Long cycle times for materials R&D	Risk and fragmented value chains unnecessarily increase time to market	Integrate end-user needs into development and innovation processes
Emerging global megatrends	Trends towards sustainable feedstocks and products will impact industry profitability	Engage directly with end users to increase awareness of the benefits of sustainable materials
New sources of innovation	Divergence economics of specialty versus commodity chemical companies are leading to new business models	Adapt to changing industry economics by forming the right partnerships
Extensive inventory of existing materials	Access to materials databases will enhance materials innovation efforts	Expand access to materials databases
Current challenges to deploying an Advanced Materials Systems (AMS) framework		
Hardwired internal cultures	Frontline employees can be empowered to drive change within organizations	Designate a project manager for transformational change efforts
Inability to capture value from innovation	Differentiated capabilities and ecosystem positioning will be key to capturing value	Pursue innovative ways to capture value
Lack of systems-level engineering capabilities	The Fourth Industrial Revolution can enable accelerated materials innovation	Develop the right technical assets
Talent challenges	The C&AM industry will need to make itself attractive to millennials to address an ageing workforce	Develop the proper talent
Successfully managing collaborative innovation	Strategies for managing collaborative innovation will be crucial to implementing AMS	Adopt a prepare, partner, pioneer model

Collaborative Innovation in the Global Chemical Industry

Evolution of collaborative innovation in the global chemical industry

The scale and complexity of the largest challenges facing society make them impossible for any actor to address alone. Making progress on these challenges will require both collaboration and innovation. Taken together these words form the powerful idea of collaborative innovation, where trusted partners come together to share ideas, information, and work to achieve a common goal. Working in groups is often a difficult proposition, but the payoffs can be substantial. As Bruce Mau, author of the *Incomplete Manifesto for Growth* says, "The space between people working together is filled with conflict, friction, strife, exhilaration, delight and vast creative potential."[1] Companies around the world are orienting their organizations towards innovation. According to the Deloitte United States (Deloitte University Press) *2015 Global Chief Investment Officer (CIO) Survey*, 45% of CIOs put innovation at the top of their business agendas.[2]

The World Economic Forum has been working to promote collaborative innovation within the global chemical industry over the past several years through initiatives such as Innovation and Entrepreneuring, Biotechnology Ecosphere, Energy Harnessing, and most recently AMS. Specialists from industry, government, and academia are consistently and strategically working towards advancing these fields.

The Forum has used these platforms to convene industry leaders at private sessions during the annual meeting in Davos and the annual meeting of the New Champions, as well as action-focused conferences in North America, South America, and Asia. Insights from all project activities have been captured, disseminated through reports, and used to create tangible results for the global chemical industry, such as government policy reforms.

Partners have indicated that collaborative innovation is becoming an important part of their businesses. A survey of the Forum's Global Agenda Council on Chemistry and Advanced Materials showed that 75% of member organizations already employ collaborative innovation to a meaningful degree.[3]

The objective of the project, which is called Collaborative Innovation and Emerging Technologies, is to refine the AMS framework for collaborative materials innovation and R&D. This report, the primary output of the project, identifies and characterizes the essential components of the AMS framework, assesses the barriers to its fast implementation, and proposes actionable strategies to overcome them.

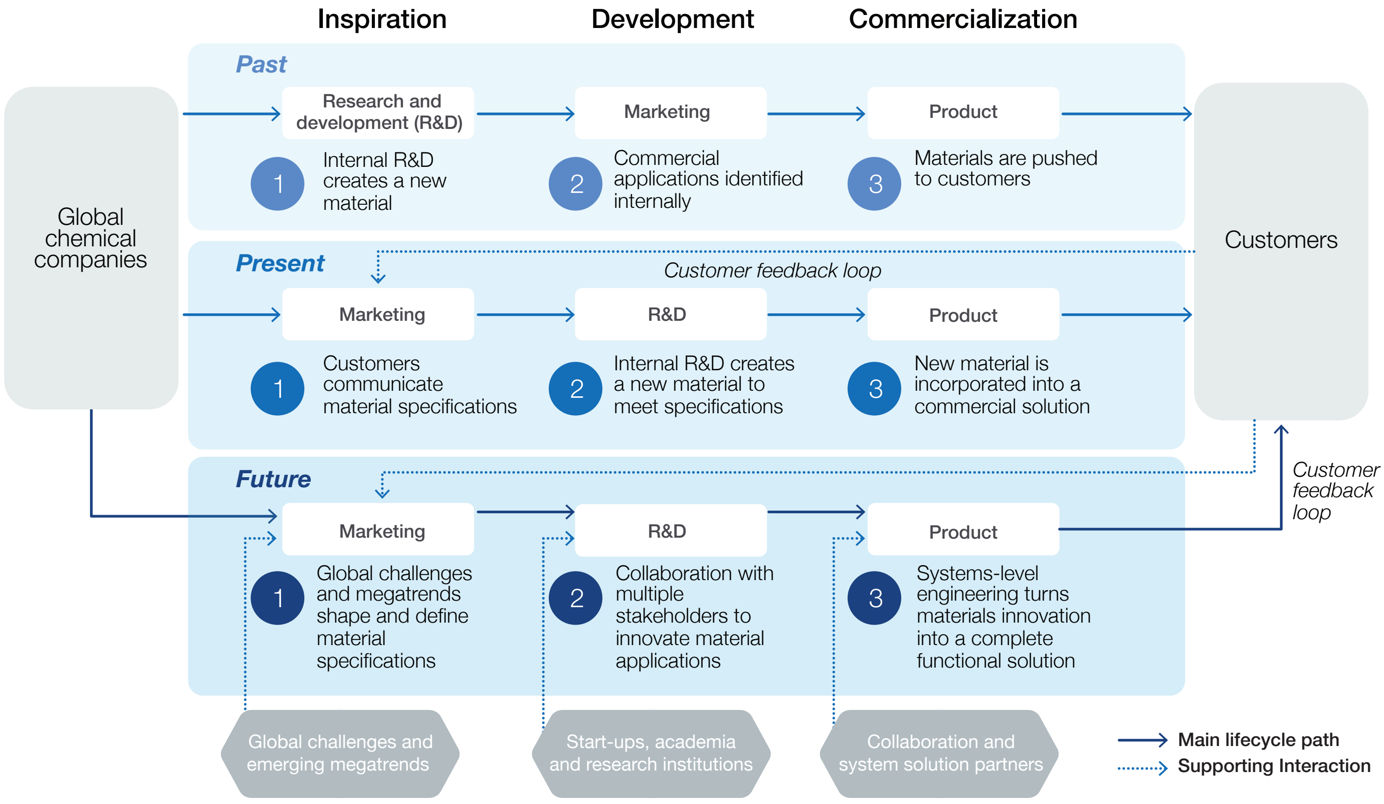
A framework is needed to help companies improve internal R&D efforts and to drive positive business outcomes. It will also direct efforts towards market needs resulting from current and future global challenges. The AMS framework may potentially redesign the industries' R&D efforts, improve a company's ability to innovate, and increase the value it captures from these innovation efforts.

Declining viability from traditional materials research and development

In the early 20th century, growth in the materials industry was largely driven by the substitution of natural materials with synthetic ones.[4] Through the 1970s and 1990s, the focus shifted from substitution to the creation of custom materials, which provided tailored functionality.[5] The innovation model during these decades was relatively simple: R&D departments would create materials and the sales and marketing teams would find applications for the new products and market them to customers.

The industry's present innovation model has evolved to include greater customer feedback. Customers often dictate specifications for materials, which are then developed and produced. Currently, customers choose materials based on their ability to perform in sustainable systems. As a result, the more promising and disruptive opportunities are enabled by materials optimized for a total solution.

Figure 2. The evolution of materials research, development and innovation



A new era is taking shape in the engineering and the advancement of the function of materials and represents a large opportunity for value creation. In a systems-level design, existing materials can be engineered using advanced manufacturing and process technologies to enable functional solutions that perform well enough or better than those dependent on wholly new materials. Figure 2 illustrates this evolution. The new Development and Innovation (D&I) model to which companies should aspire involves:

– A market-facing approach to R&D where global megatrends are taken into account
– Collaboration and partnerships with a variety of external stakeholders to incorporate diverse perspectives
– Systems-level engineering to provide a functional solution to a given challenge or need

Some companies have already begun to incorporate co-design elements or partnerships within their R&D cycle. Early examples have shown favourable results, as presented in the "End Markets with Most Potential for AMS Solutions" section of this report via case studies. section of this report. The challenge remains, however, to establish this methodology as the norm, rather than as an experiment or exceptional example.

To assess the financial viability of these different R&D models, Deloitte conducted a study of over 1,300 companies from 2004 to 2014.[6] Companies were separated into providers of commoditized materials and systems integrators (those who ultimately made and delivered solutions to the end market). The companies come from a range of manufacturing industries, each engaged in, or relevant to, the development and use of functional solutions. This evidence suggests that companies focused on creating systems-level solutions are able to translate their more robust D&I capabilities into differentiated financial performance. Figure 3 shows that systems integrators had a consistently higher return on capital than commodity materials companies, with systems integrators averaging 11% higher annual returns between 2004 and 2014.[7]

Figure 3: Return on capital for systems integrators and commodity materials providers (2004 to 2014)[8]

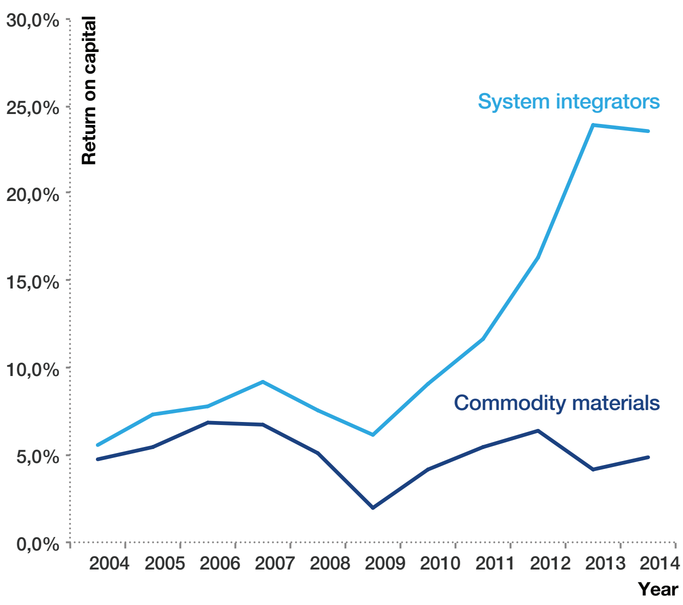
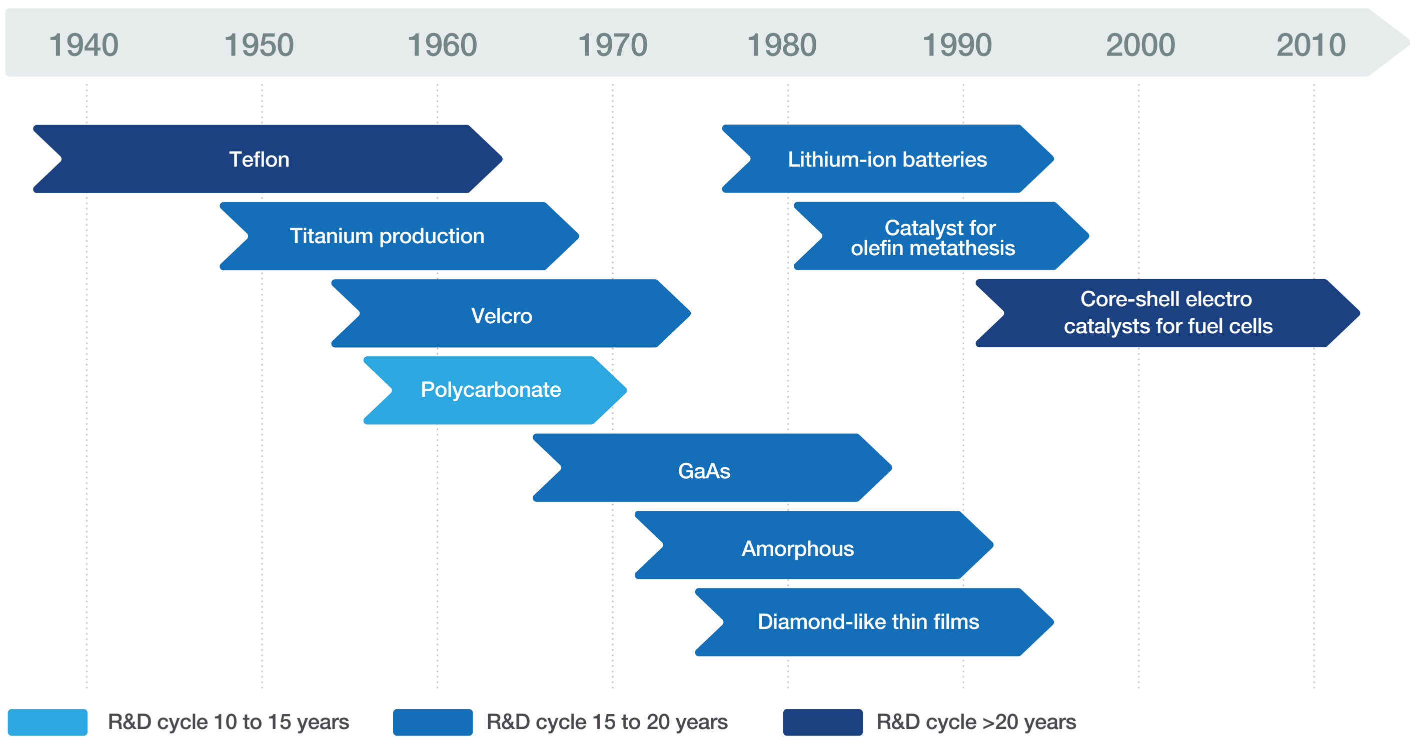


Figure 4: R&D lifecycles for selected 20th century materials innovations[9]



Long cycle times for materials research and development

While the global chemical industry has spent much of the past century shaping society through materials development, the time from discovery in the lab to deployment in the marketplace has remained frustratingly long, generally 10 to 20 years. This is illustrated across a number of examples in Figure 4.

A number of factors can lengthen the duration of R&D lifecycles, including a lack of transparency into end-market needs, a focus on developing entirely new molecules, internally oriented development processes, and insufficient technical capabilities. Technical equipment is costly and may only serve a single purpose. The advanced equipment required to confirm a hypothesis may only be available in a national laboratory. Furthermore, inadequate financial modelling may not justify the investments in development and high turnover among middle and high-level management leads to inconsistent decision-making."

Collaborations decrease R&D timing by providing access to the required advanced technical equipment and most knowledgeable experts. With shorter R&D lifecycles, management can oversee a project from start to finish and be more confident of the return on R&D.

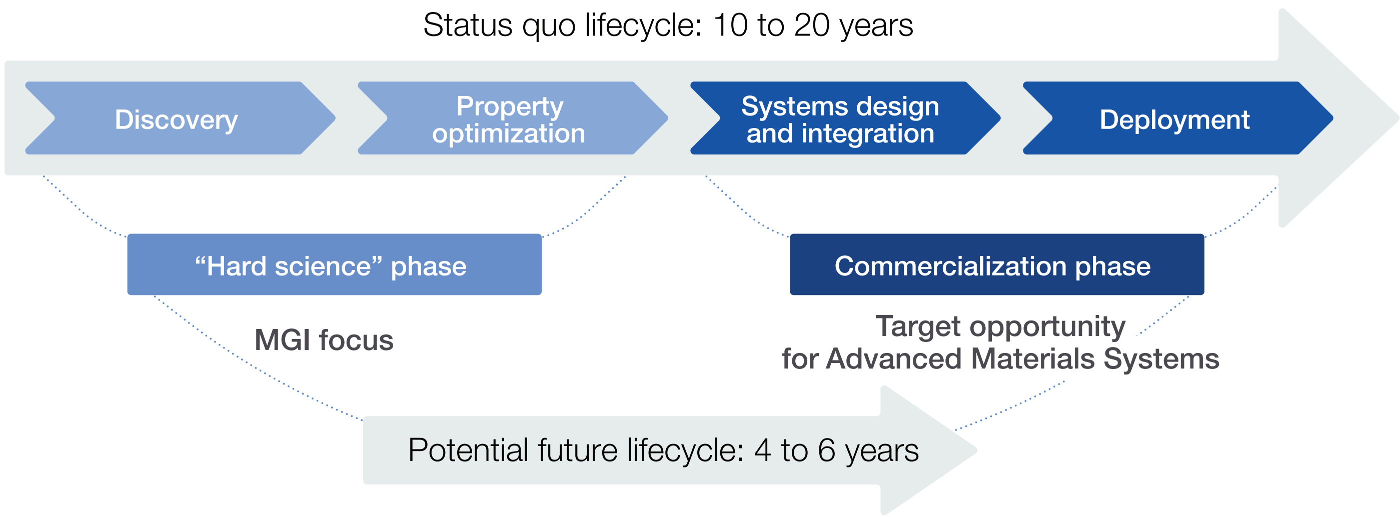
Programs such as the Materials Genome Initiative (MGI), seek to decrease the time to market by providing researchers access to vast quantities of data on material properties and the computational tools to analyse the data.[10] While the MGI seeks to improve data transparency throughout the materials lifecycle process, its efforts are mostly geared towards improving efficiency in the early stages of the process.

The AMS framework can also play a significant role in reducing cycle times at the systems design and integration and deployment stages. The AMS framework positions companies to understand how materials innovations can be used as part of a complete system to meet the needs of end users. It also shows how innovations can be more efficiently deployed in the marketplace through novel business models. By taking advantage of frameworks (which establish gains to the hard science phase) and adding efficiencies to the commercialization phase, the AMS framework can potentially reduce these times even further, from as much as 10 to 20 years to 4 to 6 years.[11] The impact of these initiatives and the AMS framework on the innovation lifecycle can be seen in Figure 5.

When materials first enter the market, they are often not used to their full potential. For example, lithium ion batteries were initially developed in the mid-1970s and then entered into the market at scale in the mid-to-late 1990s, but they have only recently been fully integrated into electric vehicles.[13] A framework such as AMS helps accelerate feedback loops by bringing the actors closer and more aligned to the system's objectives, and not their own. Integrating additional elements, such as end user needs and business models, stands to multiply this impact.

There is already evidence of the use of process technologies and systems-level design to accelerate advanced materials development. The US National Research Council's Integrated Computational Materials Engineering (ICME) program is promoting integration of computational processes into materials development to optimize material properties and systems design.[14] While it has only been deployed on a small scale so far, ICME has already showed tangible impact by helping to reduce development times of aluminium castings in the automotive sector by 15-25%. The same program helped reduce costs by $120 million.[15]

Figure 5: Present and potential future materials innovation lifecycle[12]



Emerging global megatrends

Societal changes, frequently classified as megatrends, indicate the emergence of a growing number of unmet needs which the AMS framework views as market opportunities. Opportunities to address global issues exist at the level of individuals, companies, and countries. Examples include energy security, information connectivity and exchange, demand for water, etc. This report focuses on feedstock volatility and consumer demands for sustainable products as two critical, interdependent megatrends of special interest to chemical companies.

In recent decades, the price of feedstocks has oscillated wildly, from \$80 per barrel in 2010, to \$120 per barrel in 2012, to less than \$30 per barrel in January 2016.[16] This volatility can compromise a manufacturer's and customer's ability to commit to joint efforts due to uncertain profitability and possible low (or negative) return on investment (ROI). Feedstock volatility puts extreme pressure on companies, not only to provide more efficient and cost competitive solutions but also to limit the use of feedstocks and natural resources.

At the same time, consumers are demanding sustainably-made products to protect the environment and to limit the use of non-renewable natural resources. Fifty-five per cent of global online consumers across 60 countries say they are willing to pay more for products and services provided by companies that are committed to positive social and environmental impact.[17] Integrating sustainability into the materials development process creates a clear opportunity to address a pressing global challenge while creating and capturing business value.

New sources of innovation

The ways the global chemicals industry generates innovation has shifted. For most of its history, the largest players have also been the primary sources of innovation. These companies often had broad portfolios and were able to reinvest their earnings from steady commodity revenues. In the last five years, the economics of specialty and commodity chemicals have diverged. Corporations with broad portfolios are being driven by investors to split into separate companies focused on either specialties or commodities. This is disrupting the traditional method of funding D&I, as is the result of the pending Dow–DuPont merger.

As investors and executive management become increasingly impatient with plateauing margins and slow rates of innovation, the effectiveness of current innovation approaches and investments with longer-term returns are being challenged. New and more nimble sources of innovative material solutions from leading universities and public sector institutions have emerged to fill this gap. Start-up companies have also become an essential part of the innovation landscape. Their small size, ambition, and appetite for higher risk lead them to pursue game-changing innovations.[18]

While large companies are no longer the primary sources of innovation, they can still play an important role and capture value in this new landscape. In the past, companies have mostly approached D&I from within their own organizations (closed innovation). Now there are opportunities to fuel additional growth through collaborative innovation partnerships. This would allow larger companies to access novel ideas from different stakeholders and smaller players to access industry experience and the operational infrastructure needed to scale solutions. However, large companies have traditionally been difficult to penetrate for both small start-ups and academics with new ideas. A mechanism and communication plan should be integrated into companies' innovation centres to ease access to large company development teams by smaller outside organizations.

Extensive inventory of existing materials

The industry's historical focus on developing and commercializing new materials with unique properties has led to a vast inventory of existing materials available to manufacturers. The inventory of existing chemical substances maintained by the US Environmental Protection Agency boasts more than 84,000 existing chemicals as of January 2015[19] and the Chemical Abstracts Service had over 100 million substances documented in November 2015.[20] This array of materials represents a significant opportunity to explore novel combinations of known materials. Existing materials can serve as building blocks for potential new solutions and not merely individual commodities. This enables companies to reallocate resources from developing new materials to combining existing materials into a holistic solution. Adopting this approach also places a new emphasis on end customer needs, developing a solution with the end user in mind from the outset.

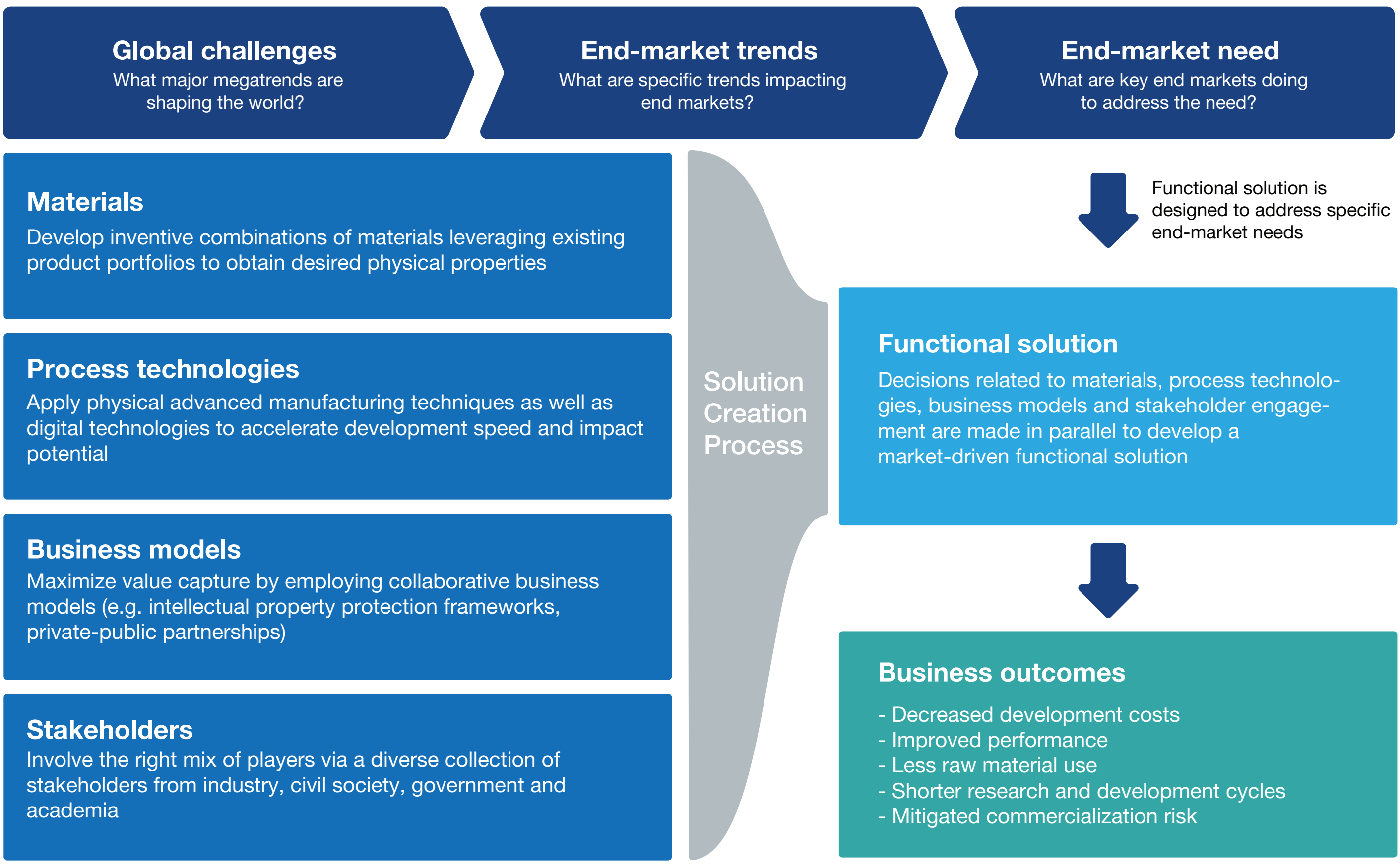
AMS: An Approach to Collaborative Innovation

The Advanced Materials Systems (AMS) framework is an approach for capturing value from global megatrends and unmet needs through functional solutions that focus on systems-level engineering over the creation of new materials. Put more simply, the framework prescribes looking at the unmet needs of customers and developing system solutions which utilize available materials and technologies. Such an approach requires players to collaborate across industries and value chains while developing new business models.

By considering end-market demand and ecosystem positioning at early stages of development, AMS can potentially decrease time to market and reduce innovation risk for materials providers. At the same time, using new business models could create value for a variety of stakeholders not traditionally engaged by the global chemical industry. For these reasons, pursuing materials innovation through an AMS approach has the potential to create significant value for materials providers, their customers, and society at large.

Collaborative innovation is enhanced via the AMS framework in two ways. First, different stakeholders bring different views, experience and understanding of the issues. AMS is modular by definition, which allows it to realize the potential contributions of these stakeholders. When the system is distributed, the possibilities for the system to work efficiently alone are reduced. The AMS framework, illustrated in Figure 6, brings structure and productivity to collaboration efforts. Second, more parties may benefit. The results (knowledge, market intelligence, problem-solving skills, etc.) and outputs (product sales, intellectual property, etc.) of the collaboration are more effectively shared.

Figure 6: The Advanced Materials Systems framework



Elements of the Advanced Materials Systems framework

Global challenges and end-market trends and needs

AMS urges companies to continuously identify ways to maximize value and to address pressing market needs. These requirements often flow from larger global challenges and megatrends, trends that manifest themselves as specific end-user needs in local markets. D&I should have a clear market direction by identifying which problems they are solving and defining this need in terms of a functional business solution. Priority should be placed on finding solutions that appropriately meet the need.

D&I departments should also have a conscious understanding of the appropriateness of a solution. Is a discovering a new molecule the best answer, or will a materials and systems engineering approach achieve a better result when taking into account socioeconomic factors? Once companies understand the market needs, performance requirements and value capture opportunities, they should then begin the development and innovation process.

Materials

The industry's extensive inventory of existing materials presents an opportunity to move from a pure chemistry approach (i.e. inventing entirely new compounds with unique properties to address a need) to a systems-level engineering approach (i.e. utilizing existing compounds to create a system to address a need). By approaching innovation in this way, existing materials can serve as building blocks for potential new solutions rather than as individual commodities.

Companies will require the infrastructure and technical competencies to search through existing chemicals for those that have the properties they need. Investment in these capabilities will enhance existing development and innovation efforts as companies can explore opportunities to combine existing building blocks to achieve better results than by developing new chemicals. Materials are presented here as an input to the solution creation process but they are also part of the output or functional solution. This is a complicating factor when building solutions for customers, but one which global chemical companies must overcome. As a result of the AMS framework, the use of materials will evolve from kilograms of elements to an integral part of a functional solution.

Process/digital technologies

The rise of process and digital technologies is transforming the global economy, and the materials industry is no exception.

Advanced supercomputing and data analytics technologies are pairing with digital modelling technologies to create mechanisms which can quickly design and create customized products by using a combination of existing materials. Cloud-based software is enabling collaboration and allowing companies to tap into resources beyond their own internal research and development teams. Finally, new digitally enabled production techniques, such as Additive Manufacturing, are changing how companies think about their business models and allowing for new channels to deliver products to customers.

Industry leaders recognize the importance of these technologies, but have yet to invest in them adequately. According to the *2015 Global CIO Survey* conducted by Deloitte United States (Deloitte University Press), 77% of manufacturing CIOs believe analytics and business intelligence will significantly impact their business in the next two years, but only 48% indicate a high level of investment in these capabilities.[21]

Business models

AMS expands the idea of collaborative innovation arrangements into commercialization and calls for the business models themselves to be re-evaluated. Within this context, business models are defined as mechanisms to better develop and deliver solutions to market, recognizing both internal and external partner capabilities. Given the need to tailor business models to solutions, companies will likely need to consider a variety of dimensions. These dimensions include product and market focus, competitive positioning, location and scale of production, identification and acquisition of customers, and development of distribution networks.

Business models also should be responsive to both internal and environmental triggers and be able to adopt dynamic strategies. These triggers can constitute factors such as technological hurdles, market conditions, or changes in regulation and may shift the strategic considerations of a particular project.

Stakeholders

The development of new materials solutions will also be enhanced and accelerated through collaboration between different groups of stakeholders, including groups which may not traditionally interact with each other. Other sources of innovation, such as academia and start-ups, can help to supplement innovation efforts at large companies by providing access to new ideas, talent and speed. Governments and civil society will also play an important role through shaping public policy that supports innovation efforts and by serving as a facilitator of collaboration.

Companies can also benefit from collaborating with broader initiatives created by national and regional governments to promote research and commercialization. Examples of this type of platform include the Environmental Defense Fund in the United States[22] and the BioBuild project in the European Union.[23]

Idea for inspiration

Inspiration: Reducing CO_2 emissions to curtail the causes of human-made climate change is a major global challenge of the 21st century. The transportation sector is second only to the power sector when comparing contributors to US CO_2 emissions. Aircraft account for nearly 3% of total US carbon dioxide emissions. The Solar Impulse project sought to address this challenge by creating an airplane that could circumnavigate the world without using any fuel.

Diverse stakeholder engagement: The Solar Impulse project involved the collaboration between a multidisciplinary team of 50 engineers and technical specialists from six countries assisted by 80 technological partners, among whom Solvay was the first main partner and 100 advisors and suppliers. It is financed by private individuals, companies and the Swiss government. The diverse pool of actors allowed the project to leverage the best talent and technologies to achieve its goal.

Result: A long-range experimental aircraft to circumnavigate the earth by a fixed-wing aircraft using only solar power. The aircraft is currently mid-journey, having conducted a record breaking trip from Japan to Hawaii. It will resume its journey in the Spring of 2016.

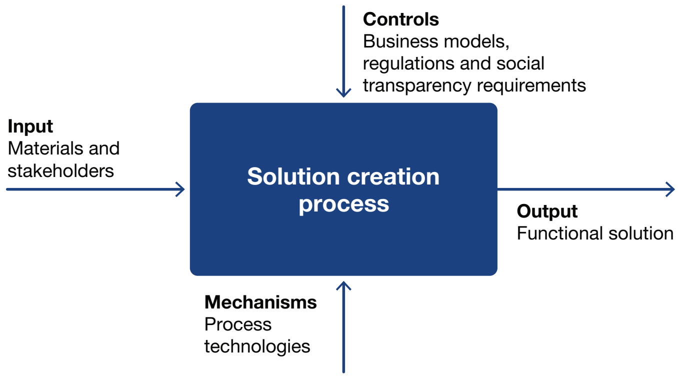
Solution creation process

In the AMS framework, materials, process technologies, business models, and stakeholder engagement come together to form a functional solution that addresses a specific need. This input and output model is a traditional method to view and understand manufacturing functions, development, or engineering processes.

The new and exciting aspects of this process are the complex ways in which these inputs, controls, and mechanisms are coming together to form more tailored and higher performing outputs. Furthermore, each input itself is becoming more complex.

As the complexity increases, highly skilled process managers are in greater demand. These managers should have an understanding of the market needs, material science, the network of stakeholders, cutting-edge process technologies, and the controls which regulate this ecosystem. This ideal manager may be very difficult if not impossible to find and, as a result, this process may have to be managed by a team of specialists depending on complexity. The solution creation process within the AMS framework is illustrated below in Figure 7.

Figure 7: Solution creation process diagram



Functional solutions

Materials, process technologies, business models and stakeholder engagement come together to form a functional solution that addresses a specific end user need in the AMS framework. Functional solutions are market driven rather than materials driven. They make use of existing materials to create a solution that appropriately address a particular need.

As materials providers begin to adopt a solutions-oriented approach, customer engagement will need to evolve beyond a simple sales and feedback process. Companies can use continuous interaction with the marketplace to anticipate emerging end user needs and develop new solutions. Finally, companies should seize opportunities to apply solutions in areas other than those for which the solution was designed.

Business outcomes

With the AMS approach, companies can potentially create significant value for themselves, their customers, and their society. By bringing end-user needs and ecosystem positioning into the development process at an early stage, AMS will likely decrease time to market and reduce innovation risk by determining that there is a demand for the solution and that there is value to capture. By focusing efforts on developing marketable solutions and avoiding wasted research efforts and expenditure, AMS can also significantly decrease development costs. Customers will also benefit from improved performance, as the functional solution will by definition meet their requirements. Finally, as opportunities arise for applying functional solutions towards addressing challenges at a global level, society at large stands to benefit.

Supporting considerations in an AMS ecosystem

Beyond the core elements of the framework, there are also several additional trends that companies will need to consider when implementing AMS. These will impact the processes through which companies develop and deploy solutions, collaborate with other players in their ecosystem and capture value from their innovation efforts.

Rapid testing and prototyping techniques

Emerging process technologies, such as Additive Manufacturing, can enable new forms of rapid testing and prototyping. Historically, new product ideas and designs required various cycles of prototyping and development. This significantly increased development times and slowed innovation. Additive Manufacturing enables rapid fabrication of a scale model using three-dimensional computer-aided designs. This allows for greater ability to test innovations, thereby reducing time to market. Rapid prototyping technologies also enable decentralized business models. New designs can be sent to local 3D printers, desktop CNC (computer numerical control) routers, or prototyping specialists, removing the need for centralized manufacturing and processing.

Open innovation

Traditionally, companies have pursued innovations using closed innovation strategies, relying primarily on their internal knowledge and existing technology. Open innovation frameworks broaden this scope, as companies source external capabilities, ideas, and resources from other players in their ecosystem.

These types of open networks can increase rates of innovation and identify additional applications for a wide variety of technologies. Organizations have also used crowdsourcing competitions to solicit innovative designs from the public. This can also be paired with emerging technologies as companies and public sector organizations have successfully crowdsourced new designs that use 3D printing to reduce cost and material use. Tapping external resources and ideas can allow companies to design functional solutions that more efficiently use existing materials to meet end user needs.

New partnership structures and intellectual property

When collaborating across the value chain, proactively managing IP is a crucial consideration. That being said, companies should be cautious to avoid treating IP as an end goal in partnerships. Rigorous IP negotiations between potential collaborators before a project even starts can be costly and time consuming and may erode trust.

Companies that have been successful using IP as a facilitator of open innovation and commercialization have adopted a light-touch approach with mutually beneficial IP arrangements involving joint ownership and licensing. This can take the form of a system where partners can share IP that arises from collaborative projects and preserve their ability to transfer lessons learned to other non-competing applications.[24]

A robust IP framework, along with differentiated capabilities, can create barriers to entry that could increase value capture. In many cases, IP positions will dictate the optimal nature of the partnership (i.e. joint venture versus acquisition). This is particularly relevant when larger companies work with smaller start-ups and inventors. Existing patents owned by smaller companies can serve as a signalling device to the larger partner, provide an easy means of transferring ownership of the idea, and protect the rights of the smaller partner.[25]

End Markets with Most Potential for AMS Solutions

As the AMS framework begins with a market or customer need, it is beneficial to understand some of the global challenges which are shaping these needs. The World Economic Forum is committed to providing an impartial and trusted space for top-level, public-private collaboration to advance the agenda on the world's most pressing issues. The following case studies illustrate how AMS solutions can be used successfully.

Agriculture

The global population is expected to grow to 9.5 billion people by 2050, which would increase global food demand by 60%.[26] Much of this growth will come from developing markets with Africa expected to double its population from 1 to 2 billion people by 2050.[27]

Meeting these challenges will require increased productivity, particularly in the developing world, and improved sustainability. Developing countries will need to increase food production 77% by 2020 to meet rising demand, requiring higher crop yields and more efficient planting.[28] As production increases to meet this demand, the industry will need to simultaneously reduce water use and greenhouse gas as 70% of water withdrawal and 29% of global greenhouse gas emissions currently come from the agricultural sector.[29,30]

New advancements in agricultural biotech, digital technology and data analytics are poised to transform agriculture. Precision farming in developed markets are helping improve productivity while small farmers are benefitting from new value chain links to materials-enabled input technologies. Potential AMS solutions to agricultural challenges include more efficient water use systems (desalination, purification, waste management, and irrigation) and advanced technologies to improve food preservation and transport.

Monsanto (The Climate Corporation) – Digital Agriculture

End-market trends → End-market needs

The global population is expected to reach 9.5 billion people by 2050, increasing global food demand by 60%. At the same time, the amount of farmland per person will be less than one-third of an acre. Materials have traditionally helped to improve agricultural productivity through yield enhancing inputs. Given the scope of the challenge, however, farmers will need likely new ways to improve their decision-making ability to increase the amount of food that they produce while minimizing resource use.

Materials

Plant biotechnology allows for the transfer of genetic information that produces beneficial traits in crops. Monsanto provides a variety of biotechnology solutions to improve productivity for farmers including insect and weed protection chemicals, drought tolerant corn and higher yielding seeds.

Process technologies

Many aspects of agriculture are being digitized from seed genetics, environmental conditions and the remote sensing of plots of land. Remote-sensing systems in equipment enable real-time monitoring of actual field conditions. More precise weather observations from satellites and weather stations also allow for a deeper understanding of atmospheric conditions.

Business models

Monsanto uses six strategic retail partnerships with close ties to customers to expand its commercial reach. Joint ventures, such as a recent connectivity agreement between The Climate Corporation and John Deere, also further integrate services for farmers by connecting near real-time data connectivity from The Climate Corporation's Climate FieldView™ digital platform into certain John Deere farm equipment.

Stakeholders

Monsanto works closely with regulators to ensure that their products are safe for humans, animals and the environment. Efficiency improvements will also benefit society at large by increasing yields to address evolving food demand. Sustainability benefits of current and future products will play a large role in meeting Monsanto's pledge of net zero carbon emissions by 2021.

Solution Creation Process

Functional solution

The Climate FieldView™ platform provides farmers with one connected suite of digital tools. Using real-time and historical crop and weather data, the platform delivers customized insights that help farmers make better decisions to optimize materials use and maximize yields.

Business outcomes

Climate FieldView™ can help to address large efficiency gaps, such as the $1 billion opportunity to improve productivity for US corn. By complimenting existing Monsanto biotechnology materials and creating new opportunities for cross selling, the platform is also creating business growth and is currently used on over 75 million acres across the US.

Building, construction, and infrastructure

Large demographic shifts have led to increased urbanization, particularly in developing countries. Currently, more than 50% of the world's population live in cities, with this figure expected to rise to 66% by 2050.[31] This increase will result in another 2.5 billion new urban residents, with 90% of this increase coming in Asia and Africa.[32]

This rapid urbanization will increasingly lead to the growth megacities (10 million inhabitants or more) from the current 28 to 41 by 2030.[33.34]

Materials innovation will be crucial in shaping these cities so that they can grow in an efficient and sustainable way.

New lightweight construction materials will be essential to minimize resource use and the costs of expansion. Smart city technologies that more efficiently monitor and distribute utility resources, like water and electricity, will be empowered by new materials innovation.

Effectively developing and implementing all of these technologies will require collaboration between a number of players across the private and public sectors, including municipal governments, non-government organizations (NGOs), materials providers, utilities, and technology companies. Using AMS solutions to drive sustainable growth will be an important part of determining how cities use resources effectively and improve the standards of living of their inhabitants.

Arup and GXN Collaboration – BioBuild Project

End-market trends → End-market needs

Currently, more than 50% of the world's population live in cities with this amount expected to rise to 66% by 2050. This rapid urbanization will increasingly lead to the emergence of megacities or cities with more than 10 million inhabitants. These megacities will create unprecedented challenges for environmental sustainability and resource use. Given the large role buildings play in consuming energy and other resources, sustainable building materials will be needed to decrease energy consumption and improve resource efficiency while supporting an ever growing urban population.

Materials

Biocomposites, which are composed of fibres such as flax, hemp, jute and resins, can be converted into lightweight and durable building materials. Arup and GXN Innovation have utilized biocomposites to develop sustainable façade panels, which are constructed using biocomposite outer shells, made of flax fabric and bio derived resin, with a central layer of insulation material.

Process technologies

BioBuild uses modular systems designs and pre-fabrication technologies to reduce construction costs and improve building times. Modular panels constructed from biocomposites can be delivered to construction sites fully fabricated and quickly assembled into a façade system.

Business models

The use of sustainable biocomposites enables a circular economy model for building materials, demanded by clients of Arup and GXN. At the end of the building lifecycle, all biocomposite parts can be detached from the façade system and recycled or reused, allowing for "cradle to cradle" sustainability.

Stakeholders

Arup and GXN worked with 13 organizations from 7 countries through the BioBuild Project funded by the 7th Framework Programme for Research and Technological Development by the European Commission. The programme brought together public and private organizations from across the construction value chain to develop new materials built from rapidly renewable resources.

Solution Creation Process

Functional solution

Arup and GXN Innovation have developed the first self-supporting façade system for building construction made of biocomposites. By utilizing renewable inputs and advanced techniques, the system significantly reduces building energy consumption, while retaining high performance and commercial competitiveness.

Business outcomes

The biofacade system can reduce embodied energy in façade systems by up to 50%, compared to conventional materials with no increase in cost. It also positions Arup and GXN as leaders in green building materials consultancy which is expected to grow 13% annually over the next 5 years.

Electronics

Sustainability concerns are an increasing concern for the consumer electronics industry as 41.8 million tonnes of electronic equipment is discarded globally.[35] The discarded material poses significant health risks, as its disposal can expose the people involved to health-threatening toxins. Unsustainable and potentially harmful materials such as halogens and red phosphorous have traditionally been used in electronic manufacturing.[36] This wasted material represents a significant economic opportunity of $52 billion in potentially reusable resources.[37]

If companies are able to design consumer electronics with halogen-free materials that meet the same performance requirements, then recyclable electronics can likely become a reality. These new materials will also need to be integrated into systems level solutions using process technologies such as laser direct structuring and surface mount technology. This will allow for the creation of lightweight and sustainable electronic components, including miniature circuit boards, terminal blocks and compact antennas. These new solutions will enable electronics companies to drive connectivity with more functionality and faster data transfer while focusing on miniaturization, productivity, safety, and environmental impact.

Royal DSM – Greener Electronics

End-market trends → End-market needs

The market is faced with challenges regarding increased consumer awareness and stricter regulations with regard to the use of substances of hazardous concern (like halogenated flame retardants and PVC), e-waste and recycling. Simultaneously, electronics companies drive next generations with improved connectivity, more functionality, faster data transfer and cloud computing while focusing on miniaturization and productivity. The challenge is thus to develop high performance halogen free materials for the electronics industry that meet safety and performance requirements without compromising freedom of design.

Materials

DSM has drawn on its understanding of the mechanisms that give halogens their flame-retardant nature to develop new halogen-free high-temperature plastics, such as Stanyl, ForTii, and Arnitel for connectors, sockets, cables and structural components. These materials meet the flame-resistance requirements, allow designers flexibility in component structure and tooling, design and support miniaturization while keeping high mechanical properties.

Process technologies

New process technology capabilities supported by CAE (Computer Aided Engineering), mold-flow analysis and colouring allow for optimal molding conditions and surface aesthetics, whereas secondary processing technologies like plating and laser-direct-structuring drive functionality.

Business models

To integrate the new technologies into its materials, DSM is collaborating with ecosystem partners such as raw material and hardware suppliers, brand owner, and universities.

Stakeholders

DSM engaged in an extended ecosphere including non-government organizations, regulators, and academia and works to ensure its materials meet and surpass sustainability standards defined for the electronics industry, such as RoHS (Restriction of Hazardous Substances) and the Waste Electrical and Electronic Equipment (WEEE) directive in the European Union.

Solution Creation Process

Functional solution

Building on its unique portfolio of high temperature resistant materials with high flow like Stanyl, ForTii and Arnitel, DSM developed in-house technologies on halogen free flame retardants and solutions for lead-free soldering with improved mechanical properties.

Business outcomes

Engineering plastics allow the electronics industry to develop devices with more functionality, more speed, more light weight designs, more safety and a reduced environmental impact. DSM is contributing over €500 million sales into the electrical and electronics market leveraging its Bright Science to create brighter living.

Energy/biofuels

Reducing carbon dioxide emissions and manmade climate change is certainly a priority for the 21st century. Biofuels could reduce carbon dioxide emissions by 20-50% relative to gasoline as an energy source. However, growth of biofuels has been impeded by uncompetitive economics.[38]

While many renewable sources of energy are beginning to become competitive on their own, materials innovations and systems-level design can help to accelerate this process. For example, companies are exploring ways to embed solar panels into windows.

New materials innovation and process technologies can lead to more efficient energy generation systems. For example, advanced materials can enable more energy efficient computer chips for solar and wind installations.

Biofuels will also benefit from materials and systems innovations. Public support for biofuels has decreased on concerns that the crops they require, known as first generation feedstocks, are competing with land that could be used for food. A new functional solution, called "waste to fuels", uses novel technologies and business models to create low carbon biofuels. While non-recyclable wastes have traditionally been either incinerated or dumped into landfills, new materials technologies and catalytic processes allow them to be transformed into sustainable feedstocks.

The waste to fuels model also uses a novel circular economy approach to engage a variety of players who would not otherwise collaborate. In this model, a waste generator (such as a city) will send its waste biomass to a manufacturer, who will use it as an input for creating end products which can then be returned to the city for use by consumers. For example, lithium-ion battery technology developed for consumer electronics has been reapplied to e-mobility (electric vehicles) and for stationary energy storage (smart grid and smart building applications).

Johnson Controls – Distributed Energy Storage

End-market trends → End-market needs

Renewable energy has long been viewed as a way to reduce emissions and improve sustainability. While renewables have been gaining traction in recent years, providing 40% of new power generation in the US in 2013, they still faces challenges associated with intermittent and variable generation. At the same time, a growing population and rapid demographic shift toward urbanization will require new approaches for cities and buildings to minimize their use of key resources, particularly energy.

Materials

Johnson Controls is a leading provider of lithium-ion batteries, which are currently used for applications in the automotive industry. Hybrid vehicle batteries comprise a high-voltage battery system that enables improved driving range and fuel savings of 20% over a conventional vehicle.

Process technologies

Johnson Controls offers advanced building efficiency technologies to enable smart buildings that reduce energy usage and lower operational costs. The Metasys platform connects systems such as HVAC, lighting and security onto a single platform and uses analytics to support better decision-making.

Business models

Johnson Controls uses existing business partnerships, such as with the Merchandise Mart in Chicago, to launch its new distributed energy storage platform. These initial partnerships will demonstrate proof of concept and tangible results to enable expansion of energy storage.

Stakeholders

Johnson Controls has launched a partnership with the US Department of Energy's Joint Center for Energy Storage Research. They are part of a consortium of researchers, entrepreneurs, and commercial partners from across industries exploring energy storage applications for mobility and the electric grid.

Solution Creation Process

Functional solution

Johnson Controls' distributed energy storage systems combine lithium-ion battery technology, building efficiency expertise and intelligent controls to optimize building energy performance. They use adaptive algorithms and advanced battery compositions minimizes total energy lifecycle costs.

Business outcomes

Johnson Controls' distributed energy storage systems have the potential to reduce annual electricity spend for facilities by up to 35%. It will also allow for growth for to expand in the nascent but growing market for building energy storage, which is projected to reach $16 billion in size by 2024.

Healthcare/nutrition

The world is ageing and healthcare needs are increasingly becoming more complex. Healthcare spending in North America is projected to grow by 4.9% annually from 2014 to 2018.[39] One important driver of growth will be improvements in personalization. Technological advancements, combined with the increasing availability of health data and understanding of the human genome, have led to the advent of personalized medicine. Personalization stands to drive significant change in the way healthcare is delivered through reducing misdiagnoses, better predicting how treatments will impact individual patients, and improving the quality of care.

Coupled with enabling emerging technologies, materials innovations are poised to serve as a major driver of change in the personalization in healthcare. New materials that can be used in conjunction with 3D printers allow for customized therapies that address a variety of issues. New materials that evolve over time are being combined into solutions and used to create new customized "4D" medical implants. These implants adapt to the changing conditions of the bodies of young children, allowing diseases previously thought untreatable to be treated.

Bio-based printers are also being developed to print human tissues and open a variety of new avenues for areas of healthcare such as drug testing.

Organovo – Bioprinting Human Tissue

End-market trends → End-market needs

Developing cures for new diseases can be a long (typically greater than 10 year) and costly (typically greater than $1.2 billion per launched product) process. The bulk of the cost is in late stage clinical trials. When drugs fail late in the process, the direct cost of failure can be several hundred million dollars. Between 1990 to 2010 alone, over 160 drugs failed in phase III clinical trials or after product launch. To enable safer, more effective drugs to come to market faster and at a lower cost, the industry needs much more predictive human tissue models for drug safety and efficacy testing.

Materials

Organovo uses a proprietary 3D bio-printer and specially crafted "bio-inks" of human cells to create 3D, functional, fully human tissue models that mimic the architecture and functionality of real human tissues. This provides far more clinically relevant models of bodily tissues.

Process technologies

Organovo has built an in-house hardware engineering team to design and build printers with several different modes of depositing human cells, and also to create flow systems and maturation conditions that will replicate the native tissue environment.

Business models

Organovo has collaborated extensively with drug developers to develop customized bioprinted tissues for use in drug discovery and preclinical trial modelling. They have also partnered with academic researchers to combine their specific therapeutic expertise with Organovo's bioprinting capabilities.

Stakeholders

Organovo's primary customers are pharmaceutical companies and drug developers. However, their stakeholders also extend down the value chain to patients, health systems which bear the burden of the high cost of drug failure, and regulators who have been pushing drug companies to predict efficacy or safety concerns far earlier in the development process.

Solution Creation Process

Functional solution

Organovo has developed 3D human liver and other tissue models for preclinical drug modelling. These solutions allow more advanced and realistic testing conditions such as human metabolic behaviours and drug toxicity levels. As a result, pharmaceutical companies can begin identifying the effects of new treatments on humans much earlier in the drug development process.

Business outcomes

By allowing drug developers to identify safety and efficacy issues much earlier on, Organovo can save these companies years of research and billions of US dollars, while significantly accelerating the time to market for drugs that may save millions of lives.

Mobility

As part of the push to meet fuel efficiency standards, mobility manufacturers are striving to make their cars, airplanes, and ships lighter while still meeting performance requirements. Existing materials such as carbon fibre meet these criteria; however, the high costs and slow processing times have prevented wide adoption. To unlock the full potential in these materials, systems-level innovations will be needed in their manufacturing and commercialization processes.[40]

Collaborative innovation and new business models will play an important role in developing and commercializing these new technologies and designs. Given the complexity of the challenges, organizations that have been successful have leveraged various methods of collaboration. Companies have launched joint ventures across industries and with governments to develop more efficient processes. For example, several chemical companies, including Mitsubishi Rayon and Toray, have collaborated with Japan's New Energy and Industrial Technology Development Organization and the University of Tokyo to develop a carbon fibre reinforced thermoplastic that can not only reduce the weight of an automotive chassis by 30% but is also suitable for mass production.[41]

Companies have also tapped into the well of ideas and talent that is available in the public through the use of crowdsourcing competitions that solicit new component part designs for the automotive and airline industries. For example, GE used a crowdsourcing initiative to generate new ideas for jet engine design that used 3D printing to reduce the weight of key parts by up to 84%.[42]

Caterpillar – Remanufacturing ("Cat® Reman")

End-market trends > End-market needs

Sustainability concerns have arisen across advanced machinery value chains, from the materials use and greenhouse gas emissions related to new parts manufacturing to the large quantities of waste generated when parts are disposed. At the same time, end markets for heavy machinery, particularly resources and energy industries, are being challenged by volatile commodities prices. Together, these forces are creating the need for new machinery manufacturing solutions that improve sustainability while reducing costs.

Materials

The remanufacturing process is taken into consideration during the design of new parts, as more durable materials for new parts can facilitate Reman in the future. For example, thin film coatings can make parts more resistant to corrosion, allowing Caterpillar to only need to remanufacture the surface of the part.

Process technologies

Caterpillar has developed advanced salvage technologies, such as hard recasting, thermal cutting, shock wave cleaning and metal deposition, which allow them to return otherwise unusable parts at the end of their lifecycle to "same-as-when-new" conditions. During the product design phase, the remanufacturing process is taken into consideration to maximize the effectiveness.

Business models

A circular economy model, known as the Reman Cycle, has been developed to allow customers to return end-of-service-life parts to Caterpillar before failure. These products can then be salvaged, remanufactured, tested and re-entered into the supply chain.

Stakeholders

Reman allows Caterpillar to work collaboratively with customers across the construction, resource and energy industries. Caterpillar is also working with regulators to develop supportive policies for Reman products, such as clearly defined standards, removal of trade barriers, and incentives for sustainability.

Solution Creation Process

Functional solution

Reman is the process of returning end-of- service-life products to the same-as-when-new condition or better at a fraction-of-new costs using state-of-the-art remanufacturing technologies and production processes, all while reducing the impact on the environment.

Business outcomes

Caterpillar's global remanufacturing business employs more than 4200 employees today across 17 facilities in North America, South America, Europe and Asia. Cat Reman makes sustainable progress possible every day by reducing waste, lowering greenhouse gas emissions and minimizing the need for raw materials to produce new parts. Over the last 10 years our global remanufacturing facilities have returned more than 500,000 tons of end-of-service-life materials to productive use. Through remanufacturing, we make one of the greatest contributions to sustainable development - keeping renewable resources in circulation for multiple lives.

Lockheed Martin – Advanced Polymer Engineered for the Extreme

End-market trends → End-market needs

The aerospace industry is increasingly demanding product designs suited for extreme environmental conditions while challenging suppliers for cost and fuel efficiencies through lighter materials. Aerospace engineers and scientists have been working towards the time when they could affordably replace machined aluminium parts with a lighter weight, more producible material without sacrificing the strength, performance, and reliability of aluminium solutions.

Materials

Lockheed Martin's Advanced Polymer Engineered for the Extreme (APEX) is a multi-scale reinforced thermoplastic nanocomposite structural material that rivals aerospace grade aluminum, carbon fibre reinforced thermoset polymers and other engineered materials. APEX is designed to replace machined aluminum parts in aerospace platforms, resulting in lower manufacturing costs, greater performance and reduced lead times.

Process technologies

APEX product solutions embrace a multidisciplinary approach to product development that considers materials design and manufacturing in parallel. It relies on Lockheed Martin's extensive capabilities in sophisticated engineering, modelling and simulation, manufacturing, testing and analysis, and systems validation.

Business models

APEX combines improved affordability, performance, weight and production rates to provide programme managers, design engineers and production leads increased flexibility. Costs are reduced using a robust supply chain for raw materials and molding parts.

Stakeholders

APEX originated at Lockheed Martin R&D departments and grew to include customer line of business advocates to satisfy an unmet manufacturing need. Currently, Lockheed Martin engages with the National Network of Manufacturing Innovation to identify additional applications for APEX and other advanced materials.

Solution Creation Process

Functional solution

When an end-use application demands rigorous requirements of three or more key performance metrics, APEX offers material advantages and versatility. The APEX Forward Destruct Bracket replaced the 6061-T6 aluminium original with a 30% weight and 93% cost reduction. APEX is a tailored balance of properties, processing, economics and environmental performance.

Business outcomes

The APEX material was initially designed for aerospace environments. It is now being widely applied to a number of different applications across the space and defense industries and opening up new markets for Lockheed Martin.

Challenges to Deploying an AMS Framework

Despite the benefits to the D&I process provided by an AMS framework, companies will inevitably face an array of issues when attempting to implement any new system of innovation. They will be numerous and possibly derive from unexpected places, but the likeliest will fall under five categories:

1. Hardwired internal cultures
2. Inability to capture significant value from innovation
3. Lack of systems-level engineering capabilities
4. Talent challenges
5. Successfully managing collaborative innovation

Hardwired internal cultures

A company's internal culture may pose the greatest obstacle to implementing a new system like AMS. It is an inherently disruptive process and will likely result in pushback from those invested in current systems. Adherents to traditional mass-volume production, the benefits of which are being challenged, may resist change.

It is becoming harder to compete globally with this approach, as it is often too expensive to continue to grow these assets or rearrange the use of expensive capital equipment. For example, 46% of global chemical companies have limited means to reposition their capital investments in the next decade, which will lead to a limited willingness to drastically change business models.[43]

Change management will also be an essential component of implementing AMS-style thinking. Particularly within large organizations, R&D functions may be more aligned with processes designed for new material creation, rather than the systems-level development of solutions required by AMS. Ensuring success in this new environment will require sufficient training. New skills will be required and day-to-day activities will be refocused towards collaboration and systems-level design. Support from senior leadership will also be essential to successfully adopting AMS ideas, as executives will communicate these new ideas to the broader pool of stakeholders and leading the drive for change within the organization.

Inability to capture significant value from innovation

Even if companies overcome the obstacles innovation creation, they should also ensure that they reap the benefits by capturing value commensurate to the solution. Value capture continues to accrue further down the value chain, closer to customers and away from the enabling technologies, such as materials science and engineering. Creative IP protections and developing differentiation strategies are two methods companies can pursue to capture more value from innovation.

Traditionally, companies have focused on developing strong IP protections as the primary means of capturing and protecting value. Players have focused on protecting their positions early in the R&D cycle and not just when the product reaches the market. Companies should identify ways to capture value not only from product development, but also from other innovative areas in which that product can provide solutions to other market needs. An effective IP strategy can provide a good defense to value and can become a key component a strategy for new market entry. In addition, an effective IP strategy within an AMS context incorporates shared value and requires players to effectively manoeuvre IP concerns with all stakeholders involved in the collaboration. Strategic positioning through partnerships may prove even more protective than IP, as it is more difficult to replicate collaborations than a single production technique.

Another consideration for value capture with systems-level engineering is shifting mindsets towards new methods of differentiation. Given the different aspects of the AMS framework, there are several new avenues for differentiation, such as developing collaborative partnerships, creating proprietary logistics capabilities, or filling in a unique role within an ecosystem. Given the complexity of AMS ecosystems, this new line of thinking also means that in many cases the physical dimension of an AMS solution could be commoditized but not the process that creates this product. These processes, along with software and digital technologies that enable them, are becoming the tools through which companies capture value. They will be seen as the true means of differentiation.

Lack of systems-level engineering capabilities

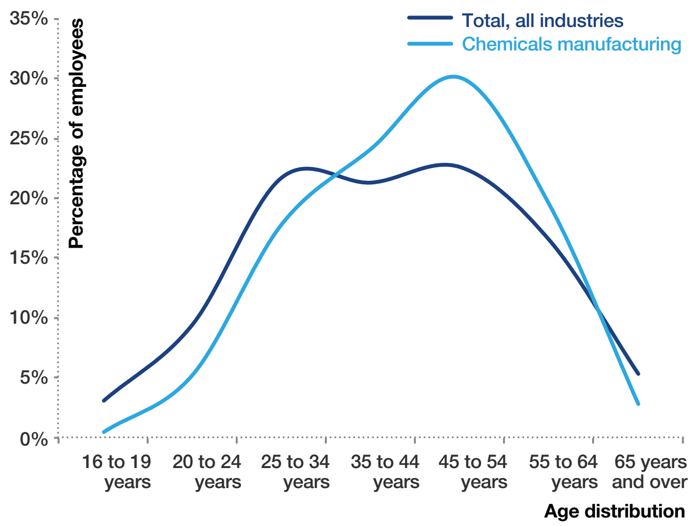
When looking at their D&I portfolios, companies often focus on creating innovation as opposed to creating value. This is driven by companies that don't use explicit strategies to prioritize end market needs. Development in isolation among different players in the value chain results in mismatches between market requirements, the performance of solutions, and their economics (e.g. solutions that are too heavy, too inflexible, or too expensive to be competitive). As a result, isolated development increases the risk of commercial failure. For example, early attempts by the aerospace industry to develop commercial airplanes out of fibre-reinforced plastics failed because they did not take advantage of the unique performance and design characteristics of these engineered materials. It has been reported, for instance, that the Beech Starship composite airplane failed because it did not leverage the performance potential of composite materials.[44]

Systems-level engineering shifts the focus from discovery and development of new compositions of matter to innovation using existing materials. The present collection of available materials comprises building blocks, with well-understood physical and chemical properties that, together with innovations in process technologies and systems-level design, can enable new functional solutions. In prioritizing systems-level design, the AMS solution brought to market may or may not contain materials that the company owns. Systems-level engineering can also increase opportunities for value capture by allowing companies to price their solutions based on the value they create for the system, rather than just placing a margin on top of the cost of inputs.

Talent challenges

A number of factors are intersecting to create a talent crisis in the global chemical industry that will affect the implementation of AMS solutions. One major area of concern within the industry is an ageing workforce. As seen in Figure 8, the median age of 45.3 years for US chemicals employees is older than many other industries; 23% of the workforce will be eligible for retirement within the next 10 years. What's more, the age distribution of employees means that there is likely not a large segment of younger workers poised to replace their retiring colleagues.

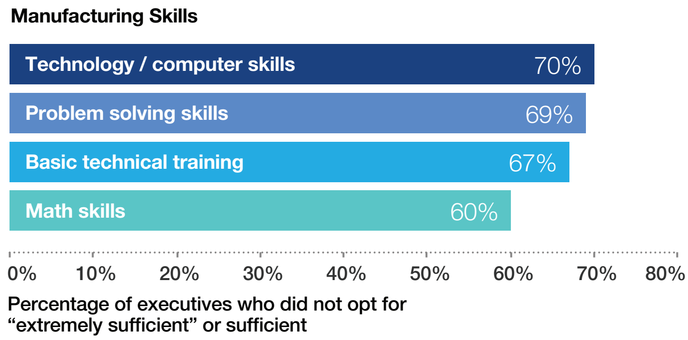
Figure 8: Workforce age distribution for the US chemical industry compared to all industries[45]



This ageing workforce calls for a new infusion of talent, but a pronounced skills gap and a negative public perception of the sector will make this difficult. Sector leaders have long lamented the lack of science, technology, engineering and math skills in university graduates. As seen in Figure 9, new insights reveal that this skills gap goes beyond specific technical skills and into more general skills needed to be successful in an AMS context, including general problem-solving and math skills.

Compounding this skills gap among younger employees is a negative perception of the sector. A recent survey designed to determine in which industry people would want to start their career revealed that manufacturing was fifth of seven among the overall population and dead last among respondents between 19 and 33 years old.[46]

Figure 9: Skills gap for US manufacturing employees[47]



These broader talent challenges related to an ageing workforce, lack of math and technology skills, and negative public perception of the sector will be particularly pronounced within an AMS context. Employee skillsets that can leverage the enabling capabilities of digital technologies, as well as a general need for entrepreneurial thinking and openness to change, will be required for AMS to thrive.

Successfully managing collaborative innovation

Engaging in collaborative innovation through AMS can potentially create significant value for all parties involved, particularly when younger and more established firms share complimentary resources. Younger, more dynamic firms are often focused on the development of novel solutions, while more established firms have deep market knowledge and established business channels. Collaboration complements both as established firms can gain access to disruptive new ideas and younger firms can more efficiently bring their solutions to market.

Managing this collaboration can be challenging as each player within the ecosystem will want to protect their own interests. This is further complicated by the fact that the requirements for each partnership are shaped by the different circumstances of each partner.[48]

While the specific nature of these partnering issues can vary, research by the World Economic Forum found that they tend to fit into three general categories:

1. Inadequate preparation
2. Misaligned partnership structures
3. Inability to adapt to evolving circumstances

Many potential collaborators fail to adequately prepare themselves as they enter into a new partnership and companies should first establish their own clear objectives. Once companies have decided to enter into a partnership, they will also need to ensure that the formal parameters of their agreement align with the business cases for both organizations. Companies will need to find the appropriate balance between each party's desires for control.

Finally, the circumstances for many partnerships will evolve over time due to both changing market conditions and the changing organizational priorities of the partners. This evolution can threaten the commitment and resource allocation if the players do not have adequate change management policies.

Conclusions and Recommendations

Insights and recommendations for the need for new approaches to innovation

The following conclusions and recommendations have been developed in consultation with senior executives and other global leaders of the project steering and advisory committees, as well as through private sessions at World Economic Forum events, such as the Annual Meeting of the New Champions, the Industry Strategy Meeting and the Annual Meetings in Davos. A number of these insights were further validated by members of the Global Agenda Council on Chemistry and Advanced Materials, with broad agreement among surveyed participants as to the validity of the insights.[49]

1. Declining viability from traditional materials research and development

Insight: Innovation models are evolving from pipelines to platforms

Materials R&D is moving from a largely linear model to a more complex platform model in which end-user needs are paramount. In addition, downstream companies have begun to develop internal materials development capabilities that are directly competing with global chemical companies.

Recommendation: Create well-functioning innovation platforms

Integrate new, outside stakeholders into the innovation process so that customers, suppliers, regulators and other stakeholders have formal channels to influence the innovation cycle. Start the innovation process with a defined problem that needs to be solved and invite a collection of companies to partner in finding the solution that leverages each of their distinct capabilities.

Several elements will combine to create a platform that achieves the goals of its constituent partners. An important prerequisite is a governance structure that determines the roles of all participants, the types of interactions they will have, and how potential conflicts will be resolved.

The platform can also be structured to facilitate interactions between different players depending upon the project's needs. If a central player is coordinating efforts to design one particular solution, they can engage with each participant individually through a hub and spoke model. Other more open ended projects with a less concrete end goal may call for more fluid interaction between all players, requiring a more open platform structure.[50]

While there are mechanisms in place in most countries to provide financing during the non-competitive phase of research, future innovation platforms may go a step further. Procurement-inspired practices, which utilize public bids both for performing the research and for buying the output, will give companies more control and flexibility.

2. Long cycle times for materials research and development

Insight: Risk and fragmented value chains unnecessarily increase time to market

R&D activities that are disconnected from the business operations of a company can mean taking longer to commercialize new solutions and an increased risk of failure. Additionally, a lack of honest communication between materials providers and customers can create barriers to developing new solutions that will address a clear need and meet a market demand.

Recommendation: Integrate end-user needs into development and innovation processes

Bring knowledge of end-user needs and the business ecosystem into development and innovation efforts at an early stage. Increase communication and collaboration between business and technical functions within an organization to help ensure that development efforts are solving a business issue before significant resources are invested into a project. This can decrease time to market and reduce innovation risk by ensuring that there is a market demand for the solution and that a company can maximize value capture.

Within an organization's innovation hub, an incubator (a small, multi-functional team) can help accelerate commercialization of technology and products. The team is focused on speed, fidelity and iteration – launch, learn, iterate and relaunch. Usually, the team is composed of a unique blend of financial, business, technical, and entrepreneurial-minded people.

Beyond improving the financial viability of individual projects, reducing time to market can also create additional benefits that allow companies to improve their competitive positioning. Bringing a solution to the market means first mover advantage and relationships with customers. Reducing development times also allows companies to match the products lifecycles of their customers, particularly in industries such as technology with its rapid product turnover. The voice of the customer is critical and prototypes in customers' hands are imperative – early in the process – before the product is ready for commercialization.

3. Emerging global megatrends

Insight: Trends towards sustainable feedstocks and products will impact industry profitability

Feedstock price volatility can compromise commitments to joint efforts and inhibit collaborative innovation. It will be difficult for companies to incorporate more sustainable and more expensive feedstocks as consumers are unlikely to pay an eco-premium for sustainable materials, which are part of a complex value chain where environmental savings are difficult to understand. The trend towards circular economy models is also reducing demand for new input materials.

Recommendation: Engage directly with end users to increase awareness of the benefits of sustainable materials

Raise awareness about the environmental benefits of sustainable materials innovations to increase market pull demand. When an innovation is integrated into a complex system, it can be difficult for end users to understand the benefits. A way to address this problem is to engage directly with end users to help them better understand the value that the material innovation creates. If end users appreciate this value, they may be more likely to request products that involve that solution.

This will be particularly relevant for sustainable materials, as consumers may be willing to pay an eco-premium for sustainable materials that are part of a complex value chain if they understand the environmental benefits. Increasing awareness can also improve the materials providers' ability to price their solutions; they can set the price based on the value created, rather than the cost of feedstocks. Decoupling pricing from inputs can allow companies to maintain profitability, despite volatile fluctuations in feedstock costs.

4. New sources of innovation

Insight: Diverging economics of specialty versus commodity chemical companies are leading to new business models

Diverging economics are causing companies with broader portfolios to split into more specialized units focused on either specialty or commodity chemicals. An evolution of industry business models is taking place as companies tap into new sources of innovation (such as start-ups and academia) to help supplement their corporate innovation portfolios.

Recommendation: Adapt to changing industry economics by forming the right partnerships

Develop a strategic approach to forming collaborative partnerships to supplement internal D&I capabilities. Strategic partnerships are becoming increasingly important for the industry as the separations of specialty and commodity chemicals businesses reduce the availability of internal resources. Although prioritizing optimal solutions over in-house isolationism seems logical and practical, it can prove difficult when an organization has imbedded-capital and dedicated organizational resources. Nonetheless, external experience and resources are often available to access technical knowledge and capabilities. This includes government entities, universities and NGOs. As such, AMS partnering networks are not only worthy of consideration, but often the source themselves of differentiation and protection. Special attention should be given to the increased involvement of supernational, national, or trade associations. They are particularly useful for asymmetric relationships, such as between a start-up and a multi-billion company. Two multi-billion companies in relationship will likely continue to interact directly through traditional channels.

The AMS approach summons companies to think very differently about risk and exposure, both in terms of cash and invested capital. A large global chemical company, for instance, may come to market with a new solution but may not, in the end, be the principle manufacturer of the materials if another company has a more cost-effective production platform. This point may be of particular relevance to big process companies. Healthy humility and goal-focused intelligence will best guide partnership strategies to create new value streams which reduce the need for massive capital investments, yet generate continued returns.

5. Extensive inventory of existing materials

Insight: Access to materials databases will enhance materials innovation efforts

When creating systems-level solutions, it is imperative to have the right materials regardless of the producer. Access to internal and external materials databases will provide a competitive advantage as it will enable the best systems solution.

Recommendation: Expand access to materials databases

Create an exhaustive internal database of materials developed by the organization, including their properties. This database, combined with analytical tools designed to quickly find materials or combinations of materials with given properties, will enable internal innovation teams to fully harness existing materials. Once a robust internal database has been established, the organization should link up with country and industry wide databases (such as the MGI and ICME) to gain visibility into materials in the marketplace that are not currently available internally. Global chemical companies can do a number of activities to take advantage of materials databases to enhance or implement an AMS system within their organization, such as:

- Leverage advanced digital tools that empower companies to analyse their existing materials databases
- Participate in the $25 million multi-stakeholder NIST (National Institute of Science and Technology) Center of Excellence, which focuses on a number of leading sectors within the chemical industry, to foster collaborative innovation[51]
- Apply for direct funding to support D&I initiatives; the MGI has supported more than 500 research scientists across 200 companies, universities, and national labs.[52]

Insights and recommendations for current challenges to deploying an AMS framework

1. Hardwired internal cultures

Insight: Frontline employees can be empowered to drive change within organizations

Frontline employees and local managers are often best positioned to develop new solutions in an AMS context given their deep understanding of the needs of local markets. They also stand to benefit from increased focus on meeting their customers' needs. They can be empowered as change agents to support the cultural shift required for transformational efforts such as AMS.

Recommendation: Designate a project manager for transformational change efforts

Dedicate a specific and qualified project manager to organize the efforts of collaborative innovation. They should be experienced at managing talent and cultural attitudes within organizations when attempting to implement new innovation approaches like AMS. This manager will play an important role both in directing the resources needed to complete the transition most efficiently and communicating the value to senior executives. This will be critical step in obtaining and maintaining endorsement from senior management. The person chosen as project manager must have both the technical knowledge to understand the materials development implications and the interpersonal skills to effectively manage the cultural change. Reward, recognition, and incentives are all important to transform and instil lasting change in this area.

2. Inability to capture value from innovation

Insight: Differentiated capabilities and ecosystem positioning will be important to capturing value

The traditional model of seeking value capture by patenting everything possible is less relevant under collaborative innovation. Value capture will increasingly come from non-traditional methods of differentiation, such as logistics, partnerships, systems, or occupying a unique place in an ecosystem.

Recommendation: Capture value in innovative ways

Seek to identify ways to capture value not only from product development, but also from other aspects of the solution. Companies ultimately need to redesign their go to market strategy to focus on the value it delivers to customers. This can be achieved in a number of ways:

– Develop a comprehensive innovation strategy with mutually reinforcing policies or behaviours that promote alignment among diverse groups within an organization, clarify objectives and priorities, and help focus efforts[53]
– Create a market niche by forming strategic partnerships with other companies that are uniquely positioned to provide both the product and a suite of accompanying services
– Develop a pricing and marketing strategy derived from the value created from solving a customer's problem, as opposed to a pricing strategy based on a margin above raw material cost
– Offer complementary products, capabilities, or services (both physical and virtual) that complement or enhance the real world product portfolio and prevent customers from defecting to rivals

3. Lack of systems-level engineering capabilities

Insight: The Fourth Industrial Revolution can enable accelerated materials innovation

The rate at which new materials are being discovered has declined and development cycles remain long. In response, initiatives such as the Materials Genome Initiative in the US and the Materials Innovation Institute in the Netherlands are exploring ways to accelerate materials solutions development.[54,55] This acceleration is enabled by the increased data availability and computing power available through the Fourth Industrial Revolution.

Recommendation: Develop the right technical assets

Employees will need the appropriate set of tools to maximize the output in any collaborative innovation system. These tools include the right mix of software that complement the technical capabilities of employees and enhance AMS principles, including:

– **Computational and analytical software:** Obtain analytical software which is able to select the most appropriate material from a large database given desired properties. Materials innovation will likely involve significant analysis of diverse data points like functional requirements, material properties, costs, supply chain factors, etc.
– **Flexible enterprise technologies:** Upgrade enterprise software to a version which enables adaptable business models. Successful implementation of an AMS system will require organizations to implement quick changes to systems and processes in order to adapt to the rapidly changing customer environment.
– **Cybersecurity:** Secure the information among partners and instil confidence. AMS systems necessitate the formation of strategic partnerships. Organizations will require the technology to share and store data with these partners safely and securely.

4. Talent challenges

Insight: The global chemical industry will need to make itself attractive to millennials to address an ageing workforce

The millennials needed to replace the chemical industry's ageing workforce value working for companies that create a positive impact on society and develop individuals, traits which they do not associate with the global chemicals industry.

Recommendation: Develop the proper talent

To maximize the value from an AMS framework, attaining the right talent is paramount. An open and inclusive culture breeds innovation when the right people are brought together. Looking at best practices among creative start-ups, certain strategies stand out that will allow AMS players to emulate these creative and agile cultures. These best practices include:

– **Selective recruitment**: Search for candidates with a mix of strong business skills, social personality traits and the ability to tolerate ambiguity. Identify, motivate and incentivize self-starters who can work without a lot of direction or structure and who independently identify business needs.
– **Flat-lattice hierarchy**: Adopt flexible teaming structures that encourage peer accountability and allow staff members to take on a variety of leadership roles. Individuals within this development concept are given freedom to explore their ideas or initiate product development within a healthy, intra-organizational competitive environment.
– **Contribution-based development**: Reward employees for completing trainings and experimenting with ideas that contribute to their teams. Contribution-based evaluations focus on employees' capacity to make long-term impact rather than solely on short-term profit.[56]

5. Successfully managing collaborative innovation

Insight: Strategies for managing collaborative innovation will be crucial to implementing AMS

Collaborative innovation relationships are highly sensitive to the unique situation of each participating company and stakeholder. Inadequate preparation, misaligned partnership structures, and the inability to adapt to evolving circumstances can create hurdles to implementing collaboration.

Recommendation: Adopt a prepare, partner, pioneer model for managing collaborative innovation

Adopt a prepare, partner, pioneer model to help proactively manage challenges that arise from inadequate preparation, misaligned partnership structures, and the inability to adapt to evolving circumstances.

– **Prepare**: Clearly articulate objectives for the partnership, build organizational and cultural readiness to ensure internal support, and leverage networks to identify and engage with the appropriate partners.
– **Partner**: Create an agreement that is based on mutual trust by ensuring that it is aligned to the objectives of all partners, embraces uncertainty and proactively defines how IP will be used and protected through the partnership.
– **Pioneer:** Monitor evolving circumstances to identify whether changing organizational priorities threaten the partnership, as well as whether there are opportunities to introduce new partners, resources, or ideas to enhance the collaboration.

Avenues for further research

While this report presents a number of opportunities for using the AMS framework to drive change on global challenges, several additional avenues of exploration were identified:

– **Policy recommendations:** National and regional government policies have a significant role to play in supporting elements of the AMS framework. These policies will likely take a number of forms and could potentially include innovation support such as loan guarantees, incentives for incorporating sustainable materials into end products, and initiatives to address the technical skills gap. For example, royalty opportunities for government researchers to financially benefit from discoveries that are commercialized.
– **Additional end markets that are amenable to AMS solutions**: The end markets discussed in this report were recognized as the markets with the most potential for AMS solutions, but the AMS framework could likely be applied across a number of additional markets given the wide availability of materials.
– **Opportunities for public-private partnerships**: Initiatives were identified in the report, such as the Materials Genome Initiative in the US,[57] which show significant potential for public-private partnerships. Given the important role that materials innovation can play in improving economic competitiveness, there are likely many opportunities to collaborate within the public-private ecosphere on developing AMS solutions. Non-profit leadership is essential as it will likely raise fewer concerns about antitrust and encourage more openness to share data.
– **Impact of AMS on development and innovation lifecycles**: This report has begun to estimate the impact that AMS can have on decreasing the time to market for new materials discoveries. Additional research could help to refine these estimates and identify new ways in which collaboration can improve the materials development and innovation process.
– **Protecting IP within collaborative innovation ecosystems**: Competing interests in IP is a significant issue when collaborating between multiple companies. It becomes more difficult when multi-national companies are involved because of the different views on IP rights (and enforcement of those rights). Within a collaborative innovation ecosystem, the traditional IP model of protecting everything through patents is becoming less important. Companies can adapt to this by shifting their mindset towards new methods of differentiation. Given the different aspects of the AMS framework, there are several new avenues for differentiation, such as through developing collaborative partnerships, creating proprietary logistics capabilities, or filling in a unique role within an ecosystem. Additional research can uncover applicable IP frameworks to supplement the AMS collaborative innovation framework.

Appendix

Glossary

- **Advanced Materials Systems (AMS):** An approach for materials innovation that uses new combinations of existing materials, process technologies, and novel business models to develop and commercialize systems level solutions that address global challenges and emerging megatrends.
- **Chemistry & Advanced Materials (C&AM):** The global chemical industry uses chemical reactions to turn raw materials into higher value added products, which form the building blocks of numerous manufacturing processes. The industry provides a variety of products and services including commodity materials, specialty materials, and systems integration.
- **Collaboration**: Multiple organizations agreeing to work together to design or commercialize new products and services.
- **Collaborative innovation:** An innovation process in which members of a group or community share ideas, information and work to achieve common goals. The members aim to innovate through a continuous sharing of ideas, knowledge and resources, which involves strong linkages and high level of trust.
- **Development & Innovation (D&I):** A new way to view the development of products and services in the global chemical industry that prioritizes developing innovative solutions for customers over the creation of new materials. D&I efforts tend to be more focused on ecosystems, with a view of end market needs and collaboration across the value chain.
- **Digital technologies**: Advances in computing that are making the ability to work with data and the ability to collaborate across borders both more powerful and more accessible. Examples of digital technologies include, but are not limited to advanced analytics, cloud computing and crowdsourcing.
- **Functional solution**: A product or service that is designed by a company to address a specific need of an end user. This end-user need is considered from the outset of the design process and shapes how the product or service is developed.
- **Innovation:** The introduction of a new method, idea, device, or solution that improves outcomes for businesses, customers and society.
- **Invention**: Act of discovery or creation of new product for the first time.
- **Materials:** Compounds created at the molecular and/or atomic scale for the purpose of advancing technology, developing more efficient products, creating new manufacturing technologies, or improving the human experience.[58]
- **Megatrends:** Global, sustained and macro-economic forces of development that impacts business, economy, society, cultures and personal lives, thereby defining the future world and its increasing pace of change.
- **Non-government organization (NGO)**: A non-governmental organization (NGO) is an organization that is neither a part of a government nor a conventional for-profit business. Usually set up by ordinary citizens, NGOs may be funded by governments, foundations, businesses, or private persons.
- **Open innovation**: The use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for external use of innovation, respectively.
- **Process technologies**: Machines, equipment and devices that contribute to business operations.
- **System-level engineering**: An approach and means to enable the realization of successful systems. It forces on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem.[59]
- **Research and development (R&D):** The historical approach to developing new products in the chemical industry, involving investments by a firm in discovering new materials, and applying those discoveries to create new products. R&D tends to be more focused on internal capabilities and the creation of new materials.

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