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Reigniting growth
Advanced Materials Systems

Global Manufacturing Industry group
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Purpose

The development of functional solutions to address current global unmet needs and wants is opening unique opportunities to deliver growth and profitability to shareholders and to differentiate against competition with new, unique, and protectable offerings.[1] This comes at a time when the materials and chemicals industries are in need of approaches to reignite growth after some decades of volatile returns.

This report describes a new approach for manufacturing sectors to pursue opportunities in large markets, enabled by materials technologies, wherein innovation moves beyond the frontier of new molecules and materials. This approach, called Advanced Materials Systems, or AMS, has the potential to enable growth, value creation, and innovation renewal by delivering *functional solutions* to markets and customers that desire or require those solutions. The AMS framework calls for leveraging inventive combinations of materials, process technologies, business models, partnerships, and collaborations. The key insight is that global megatrends have opened up significant opportunities to capture value in new markets through functional solutions and that these solutions are achievable through systems-level engineering versus discovery of new molecules and materials. This study is a call to action for players in the AMS ecosystem, across a variety of industries and points along the value chain, to create and capture value in a complex, evolving landscape.

[1] For this report, "functional solutions" refers to physical systems enabled by the specific performance properties of materials, whether according to conventional classifications (e.g., polymers, metals, ceramics, composites, and semiconductors) or newer categorizations (e.g., specialty monomers, polymers and polymer materials, hybrid-material systems, nanostructured materials, biobased polymeric materials, and bio-inspired systems).

Overview

Most chemical and materials companies encounter periodic struggles to create and capture value, particularly using traditional approaches of supplying product to market. Practical challenges associated with the business model of selling products by volume have been increasingly apparent in overall industry performance for the last two decades, particularly in recent years.[2] During this time, loss of momentum in new-materials invention was clear, due in part to fundamental limitations on what could be done at the molecular level.[3] The resulting slowdown of innovation and reduction in research and development (R&D) yield has led to a series of structural changes in basic and applied research, and reduced corporate innovation further constrained materials innovation and growth. There was limited tolerance for trial and error development with no clear market opportunity, as generations of stage-gate processes were implemented to gain incremental efficiencies.[4] Basic and applied research ceased to be the domain of many companies and was dramatically reduced to that of a dedicated few. Meanwhile, competition became more global as manufacturing asset investments were made all over the world to pursue new customers and lower labor costs. Materials and chemical manufacturers endured commoditization and were polarized toward a focus of price over value, which largely defines the situation today.[5]

A unique opportunity exists to develop new functional solutions from engineered materials to meet a large and growing number of unmet market demands

Countering this is the AMS approach to innovation and growth, which is gaining traction in many industry segments that utilize materials to meet the needs of their customers and markets. Convincing evidence suggests that what started as a small cross-section of companies delivering functional solutions to the marketplace is growing, and data indicates these companies are outpacing traditional materials and component makers in value growth.[6] Across virtually all manufacturing industries, the Deloitte Touche Tohmatsu Limited (DTTL) Global Manufacturing Industry group has observed specific cases of success in growth and innovation, success in bringing functional solutions to market using creative materials design, and a simultaneous struggle with legacy assets and business models. The importance of traditional manufacturing is not to be minimized; nor is the end of purveying products by volume anticipated. Yet it is noteworthy that those worlds are both mature and ever more competitive. This observation may also explain why leaders of several manufacturing industries are exploring new frontiers of innovation enabled by materials and process technology and systems-level engineering and are targeting specific unmet market needs, versus adopting a "build it and they will come" mentality.

In fact, the DTTL Global Manufacturing Industry group has identified an elite group of manufacturing companies, including traditional stalwarts in chemicals and materials, looking to break away from conventional norms. These companies have increasingly found differentiation and growth to be possible through solutions based on systems-level design. These leading manufacturers are learning and benefiting by

[2] Deloitte Touche Tohmatsu Limited (DTTL) Global Manufacturing Industry group, *The chemical multiverse: Preparing for quantum changes in the global chemical industry*, 16 November 2010, www.deloitte.com/thechemicalmultiverse; DTTL Global Manufacturing Industry group, *The decade ahead: Preparing for an unpredictable future in the global chemical industry*, 10 December 2009, www.deloitte.com/thedecadeahead; World Economic Forum in collaboration with DTTL Global Manufacturing Industry group, *Future of Manufacturing: Opportunities to drive economic growth*, 24 April 2012, www.deloitte.com/futureofmanufacturing.

[3] Based on the number of bonds an atom can make (e.g., carbon can make only four) and the fundamental relationship between how matter is structured (the organization of atoms) and its properties (how it behaves), there are clear physical limits to inventing new compositions of matter that also have unique properties.

[4] DTTL Global Manufacturing Industry group, *The chemical multiverse: Preparing for quantum changes in the global chemical industry*, 16 November 2010, www.deloitte.com/thechemicalmultiverse; DTTL Global Manufacturing Industry group, *The decade ahead: Preparing for an unpredictable future in the global chemical industry*, 10 December 2009, www.deloitte.com/thedecadeahead; World Economic Forum in collaboration with DTTL Global Manufacturing Industry group, *Future of Manufacturing: Opportunities to drive economic growth*, 24 April 2012, www.deloitte.com/futureofmanufacturing.

[5] Observation by the DTTL Global Manufacturing Industry group through the various discussions with chemicals and material manufacturers, February 2012 to October 2012.

[6] Observation by the DTTL Global Manufacturing Industry group through the various discussions with chemicals and material manufacturers, February 2012 to October 2012. DTTL compiled a database of information on Advanced Materials Systems that was used to formulate the analysis for this paper.

engineering important properties into already discovered and available materials and new process technologies to create functional solutions designed to address specific needs in global markets.

Twenty-first century market drivers differ from those of the past century. New constraints have become evident, while others remain. For example, there are finite limitations on the ability of any player to invent new compositions of matter at previous, historical rates, especially as required for current product cycles and growth rates expected by shareholders. In the late 20th century, this limitation first posed a struggle, and then came to be accepted by many (but not all) as a given, which hampered companies in many industries from inventing and commercializing new materials with their former vigor.

Yet there is a growing group of emerging industry leaders in the 21st century who have acknowledged the reality of finite invention at the molecular level and are focusing on a different approach — an approach defined in this paper as Advanced Materials Systems.[7]

Fundamentals of Advanced Materials Systems

The AMS framework outlines how to utilize, engineer, and market innovative combinations of materials, process technologies, business models, partnerships, and collaborations, across a variety of industries, leveraging points along the value chain to create and capture value in an evolving landscape. The framework also urges players to determine how various entities in the ecosystem are performing relative to the broader industry and identify areas where changes in business and operating models may open future opportunities.

Application of the AMS framework also raises essential inherent concepts and questions:

- R&D with clear market direction: *What market problem are we solving? Can we define the need in terms of a functional solution? Do we know the difference between "good enough" and "overshoot"?*
- Conscious understanding of what it takes to meet a need: *Is a "science project" (i.e., new molecule discovery) the only answer, or will a "materials and systems engineering" approach (using already known materials) work just as well or be "good enough" to meet the need? Can we imagine the evolution of the functional solution once we have gained a foothold?*
- Finding leverage in an open innovation network (i.e., pursuing innovation both internally and with external sources, partners, or collaborators). As previously reported by the DTTL Manufacturing Industry group, many companies have cut R&D budgets for various reasons related to cost and yield.[8] *Is it possible to meet a need alone? Is it plausible to find, introduce, and sustain an optimal functional solution without extending beyond the company's domain? Is it possible to syndicate the risk of this investment and reduce time to market with partners? Can exclusive partnerships complement the intellectual property (IP) strategy and enhance differentiation?*
- Understanding of scaling principles and infrastructure choices: *Are there options to consider related to scale and investment? Can solutions be manufactured in a distributed and decentralized fashion, and would such a solution enable faster scaling? How would a business model work in this context? Could it differentiate the supply chain and make capital more efficient?*
- Stretching the boundaries of value: *Is it possible to operate effectively in value domains that are new and unfamiliar? Is it possible to develop and deliver a functional solution without operating in an extended ecosystem? Or can we compete effectively beyond our traditional borders?*

The DTTL Global Manufacturing Industry group's research identified several companies across a spectrum of manufacturing and process industries that are significantly altering their approaches in this space. An understanding is thus taking shape, of how to find new growth frontiers and

[7] For this report, "Advanced Material Solutions" (AMS) refers both to the technology/platforms in which materials are innovatively integrated into whole solutions to address specific market needs, as well as the overall commercial development framework (including business models, partnerships, and intellectual property (IP) strategies) in which such solutions are brought to market.

[8] DTTL Global Manufacturing Industry group, *The chemical multiverse: Preparing for quantum changes in the global chemical industry*, 16 November 2010, www.deloitte.com/thechemicalmultiverse; DTTL Global Manufacturing Industry group, *The decade ahead: Preparing for an unpredictable future in the global chemical industry*, 10 December 2009, www.deloitte.com/thedecadeahead.

exploit them using a combination of materials engineering and sharper marketing. In addition, an increasing number of companies are staking out roles in relatively new and evolving open innovation networks (see **Decommoditizing the business model: Unleashing the value of Advanced Materials Systems**) to access breakthroughs in materials and process technology originating in basic and applied research labs.[9] As noted, the last 20 to 30 years have seen something of a structural re-sorting of R&D in corporations and among universities, private venture-capital-funded start-ups, and government laboratories. This restructuring has enabled certain emerging industry leaders to invest in developing systems-level design and integration capabilities to play heretofore unorthodox roles in value chains and ecosystems.[10] In essence, these leaders are raising the bar on themselves and disrupting their own customer relationships, their approach to marketing, and their own tried-and-true business models. Trends toward open innovation and expanded value chain partnerships are undeniable; and while such actions reintroduce the risk of trial and error into players' managerial frames, they also hold the promise of growth. Meanwhile, a revolution in materials engineering is also taking hold in the start-up world.

Because the AMS approach is about creating functional solutions to satisfy specific market needs and maximizing value across an ecosystem, a practitioner of this approach can bank on facing the challenges of changing how materials are developed and processed, how business models are defined, executed, and refined, and how advantage is established. Success can often be found in a culture characterized as having unique capabilities; one that acknowledges and appreciates the need for a multidisciplinary approach. Because success in an AMS environment calls for pushing beyond comfortable value chain boundaries and redefining the very competitive positions companies wish to protect and fortify, practitioners should be prepared to be intrepid enough to disrupt themselves.[11]

Such requirements are likely to put stress on conventional management and operating methods. Applying an AMS approach to think and act differently can be decisive in delivering functional solutions that global markets need and want, but it is not for the faint of heart. Capturing value will require companies to fill gaps in critical skill sets and to overcome their own legacy (in both assets and culture). Yet those who make the leap can open themselves to an unprecedented and growing number of potential market opportunities that benefit society and business.

Historical context for AMS

In the early 20th century, growth in the materials industry was largely driven by the drop-in substitution of natural materials with synthetic ones (e.g., lead pipes replaced by polyvinyl chloride; leather seats, by vinyl; wooden and ceramic countertops, with Formica®).[12] This period of substitution, which lasted from the 1920s through the 1960s, enabled value creation and capture by materials companies and the formation of important materials-based industries. The 1970s through 1990s were a period of transition, from a focus on substitution, to the creation of custom materials that provide tailored functionality (for example, the development of polycarbonate[13] enabled the invention of compact discs and the widespread use of optical storage media).

The promise of drop-in substitution is not the juggernaut it once was and, in many cases, no longer seems to be a viable demand driver. Today, materials are chosen based on their ability to perform in sustainable systems designed

[9] Observation by the DTTL Global Manufacturing Industry group through the various discussions with chemicals and material manufacturers, February 2012 to October 2012.

[10] See, for example, Solvay Live, Special issue: *Solvay Innovation Trophy 2009, The Future, A question of innovation*, July 2009, www.solvay.com/EN/NewsPress/Solvaygroupmagazine/Archives/Documents/SL257_Magazine_EN.pdf; Ford News Center, "Ford and Dow Team Up to Bring Low-Cost, High-Volume Carbon Fiber Composites to Next-Generation Vehicles," 12 April 2012, http://corporate.ford.com/news-center/press-releases-detail/pr-ford-and-dow-team-up-to-bring-36330; BASF, "BASF and three top European universities team up on functional materials research," 6 December 2011, www.basf.com/group/pressrelease/P-11-515.

[11] Observation by the DTTL Global Manufacturing Industry group through the various discussions with chemicals and material manufacturers, February 2012 to October 2012.

[12] PVC Europe, "The history of PVC," accessed on 29 October 2012, www.pvc.org/en/p/history; Haartz website, Glossary, definition of "Vinyl," accessed on 29 October 2012, www.haartz.com/en/consumer_info/glossary/glossary.asp#V; The Vinyl Institute, "History of Vinyl: From Accidental Discovery to Worldwide Acceptance," accessed on 29 October 2012, www.vinylinfo.org/vinyl-info/about-vinyl/history-of-vinyl/; Formica website, "The Fifties: The Formica® Brand Comes of Age," accessed on 29 October 2012, www.formica.com/en/home/ContentPage.aspx?code=PAG_OURLEGACY_1950/.

[13] Plastics Europe, *The Plastics Portal*, "The history of Polycarbonate," accessed on 29 October 2012, www.plasticseurope.org/what-is-plastic/types-of-plastics/polycarbonate/the-history-of-polycarbonate.aspx.

within a complete functional solution. As a result, the more promising — and disruptive — opportunities are enabled by materials optimized into a total solution; e.g., going from solar photovoltaic (PV) cells (material-optimized) to solar window systems (a whole-solution approach; see sidebar, **Case study — Solar window technology**). A new era of *engineering and advancing the function of existing materials* is taking shape, and it 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. Working with existing versus newly invented materials can likely also shorten development times, lower development costs, and help mitigate risk. Further, existing materials can be chosen and engineered not only for their performance and economic characteristics but for their cradle-to-cradle environmental sustainability profile.

The power of megatrends

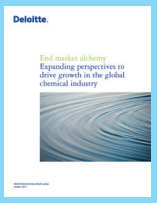
Global societal changes reflected in demographic shifts and changing patterns of income — frequently classified as megatrends — indicate the emergence of a growing number of unmet needs and desires, which this study defines as market opportunities. These market opportunities exist geopolitically, in companies, and for individuals worldwide; examples include energy security, affordable and environmentally efficient housing, mobility, information connectivity and exchange, and increasing demands for water, nutrition, and health care. There will be extreme pressure on companies not only to provide more-efficient and cost-competitive solutions than conventional products but also to best utilize limited feedstocks and resources. Yet even with efficiency gains, meeting new market needs and wants will further increase the already significant demand-and-supply pressures on natural resources.

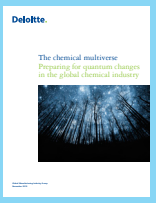
Despite the often fleeting nature of market opportunities, certain solutions (such as environmental sustainability, health care, and energy) arguably warrant pursuit for the sake of humanity; however, capital has become fickle and less patient, especially when the technology experience base has not fully evolved and other critical competencies are still surfacing. The long-held creative tension between addressing environmental and humane concerns and generating positive returns demands a new approach.

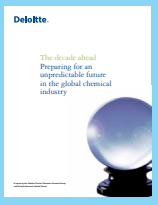
Core to many of these megatrend-influenced needs and wants are new functional solutions — again, advanced physical systems enabled by specific performance properties of materials. Many companies in industries such as energy, health care, transportation, and manufacturing that are naturally positioned to address these abundant opportunities are, however, finding themselves in need of new approaches to do so. How will they expand their capabilities to develop different *systems* (not just an adaptation of the legacy and not just the raw materials or components), accelerate time to market, and reduce their risks for development? What forces could compel certain companies to think differently about innovation of products and business models? What makes the learning curve to protect and strengthen a competitive position in an open innovation environment worth it? While neither posing easy questions nor offering responses without inherent risk, the AMS framework offers a means of growing value by claiming the edge in developing and commercializing functional solutions.

Chem2020 report series

A recent series of DTTL Global Manufacturing Industry group reports, titled *Chem2020*, examined the state of the global chemical and materials industry as it headed into the second decade of the 21st century. These studies showed that chemicals and materials companies are struggling to create and capture value. Specialty and commodity suppliers are no longer differentiated in terms of resistance to cyclicality, and return on capital; 30 percent of the 200-plus companies included in the study did not show returns greater than the cost of capital. But while there are significant challenges to the industry, some leading companies are pressing their financial position and know-how to break away from their competition.







Source: DTTL Global Manufacturing Industry group, *End market alchemy: Expanding perspectives to drive growth in the global chemical industry*, 19 October 2011, www.deloitte.com/endmarketalchemy; DTTL Global Manufacturing Industry group, *The chemical multiverse: Preparing for quantum changes in the global chemical industry*, 16 November 2010, www.deloitte.com/thechemicalmultiverse; DTTL Global Manufacturing Industry group, *The decade ahead: Preparing for an unpredictable future in the global chemical industry*, 10 December 2009, www.deloitte.com/thedecadeahead.

Introduction: The Advanced Materials Systems landscape

Why change?

The fundamental role of materials in providing functional solutions has changed, and industries that are enabled by chemical and materials-based technologies are particularly well poised to capture value in current 21st century global markets. From a recent series of studies of the global chemical industry by the DTTL Global Manufacturing Industry group titled *Chem2020*,[14] it is evident that much of the chemical industry is caught up in the struggle to overcome cyclicality, legacy assets, and hardwired cultures. In many cases, this survival mode is inhibiting the industry's ability to rise to the challenge of value creation with AMS, despite companies' being well positioned to contribute and lead (see sidebar, ***Chem2020* report series**).

At the same time, the broader manufacturing industries seem to be hitting the limits of their ability to consistently grow and create value in accordance with the demands of their shareholders. A study by the World Economic Forum in collaboration with DTTL, titled *Future of Manufacturing: Opportunities to drive economic growth*[15] (see sidebar, ***Future of Manufacturing***), showed that long-term trends in asset profitability in all but two sectors of the manufacturing industry (consumer products, and aerospace and defense) have seen significant rates of erosion in their performance. Furthermore, increased spending on R&D is not an absolute indicator of growth; investments in broader strategies for innovation are required to grow revenue, net income, and market cap.[16]

Future of Manufacturing

The study titled *Future of Manufacturing: Opportunities to drive economic growth*, developed by the World Economic Forum in collaboration with the DTTL Global Manufacturing Industry group, highlighted some of the challenges facing the manufacturing industry. An analysis comparing top innovators to research and development spenders showed that the top 10 innovators in manufacturing significantly outperformed the top R&D spenders (as a percentage of revenue) in terms of growth in revenue, net income, and market cap for the five years ending in 2010. This study also showed a 45-year trended decline of return on assets (ROA) for the metals and mining (30 percent), chemicals (49 percent), paper and wood (75 percent), and automotive (92 percent) sectors from 1965 to 2010. The ROA increased for the consumer products sector (6.7 percent) and aerospace and defense (25 percent) over the same period of time.

Source: World Economic Forum in collaboration with DTTL Global Manufacturing Industry group, *Future of Manufacturing: Opportunities to drive economic growth*, 24 April 2012, www.deloitte.com/futureofmanufacturing.

[14] DTTL Global Manufacturing Industry group, *End market alchemy: Expanding perspectives to drive growth in the global chemical industry*, 19 October 2011, www.deloitte.com/endmarketalchemy; DTTL Global Manufacturing Industry group, *The chemical multiverse: Preparing for quantum changes in the global chemical industry*, 16 November 2010, www.deloitte.com/thechemicalmultiverse; DTTL Global Manufacturing Industry group, *The decade ahead: Preparing for an unpredictable future in the global chemical industry*, 10 December 2009, www.deloitte.com/thedecadeahead.

[15] World Economic Forum in collaboration with DTTL Global Manufacturing Industry group, *Future of Manufacturing: Opportunities to drive economic growth*, 24 April 2012, www.deloitte.com/futureofmanufacturing.

[16] Ibid.

Figure 1: Return on net assets (2003 to 2011)

Performance divergence between materials and systems…

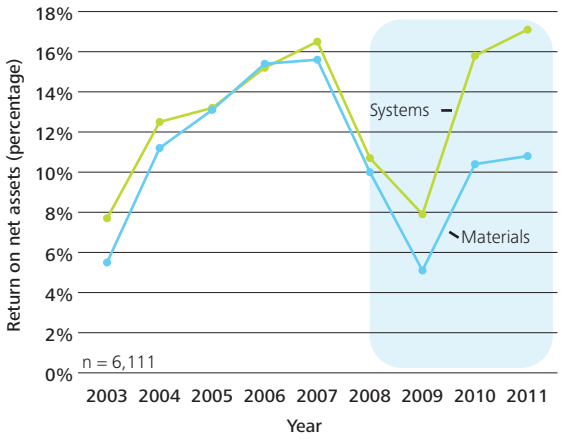
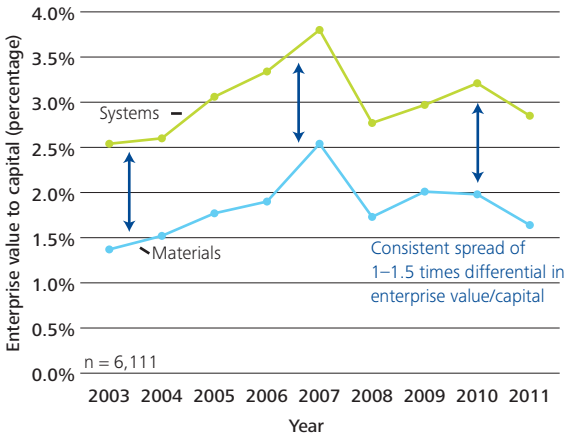


Figure 2: Enterprise value to capital (2003 to 2011)

…while market consistently rewards systems players



Note: There were 6,111 companies included in the analysis that either made materials or were systems integrators that design solutions enabled by materials.

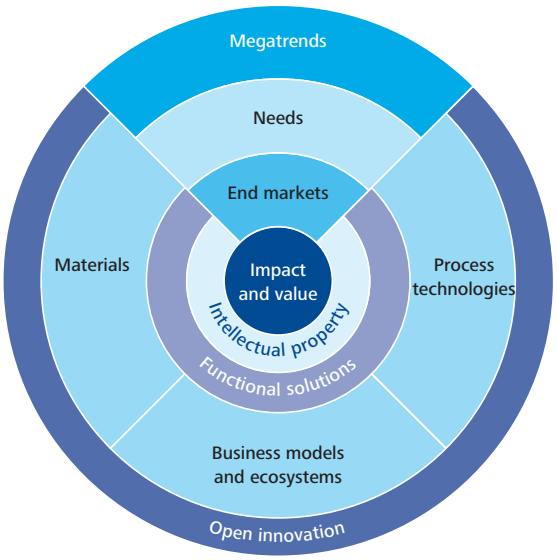
Source: DTTL Global Manufacturing Industry group, October 2012 and data from Capital IQ accessed on 29 September 2012.

For this study, DTTL analyzed the financial performance and role (as a provider either of materials or of systems) of over 6,000 companies, from 2003 to 2011, from a range of manufacturing industries engaged in or relevant to the development and use of functional solutions. This analysis reveals that value (using return on net assets as a proxy) favors companies with explicit strategies in systems-level integration (see Figure 1). Makers of materials had lower returns on net assets than did the systems integrators (i.e., those who ultimately made the solution that went into the end market and to whom materials are supplied); the system integrators were more valued by the market by a consistent ratio of one to one-and-a-half times the material providers. Also, from this analysis, the market consistently rewards systems integrators over materials providers: stakeholders saw a greater return on net assets for investments in solutions than in the creation of materials themselves, particularly in the last few years (using enterprise value to capital as the proxy; see Figure 2). Regardless of prevailing products or business models, most, if not all of the companies analyzed need to either grow or sustain value.

Beyond a shift in focus from material compositions to systems-integrated solutions, innovation itself should be reconsidered. A fundamental evolution has occurred in materials science and engineering innovation, previously achieved mainly by the large corporate R&D labs of the mid-20th century and then in the academic materials science and engineering departments of the late 20th century.[17] Today, novel developments are increasingly the purview of interdisciplinary institutes emphasizing systems-level engineering (many as public-private partnerships) and of start-ups efficiently bridging the gap between technology and markets.

[17] Observation by the DTTL Global Manufacturing Industry group, October 2012.

Figure 3: The Advanced Materials Systems framework to support new approaches for innovation and growth



Source: DTTL Global Manufacturing Industry group, October 2012.

AMS framework provides a structured way to approach …

- Designing solutions around megatrends and unmet needs that can have a significant impact on the market
- Developing functional solutions that best fit the market requirements and are built from the optimal combination of materials and process technologies to maximize value creation potential
- Delivering for parallel structure, new solutions to the market with protectable business models and partnerships that improve success rates and minimize risk

The Advanced Materials Systems framework

The AMS framework (see Figure 3) outlines an approach to develop, commercialize, and manage innovative combinations of materials, process technologies, business models, partnerships, and collaborations to ultimately grow new businesses. This report is meant to rally players in the AMS ecosystem, across a variety of industries and points along the value chain, to engage in the evolving landscape and to learn and pioneer new approaches to value growth.

This study will address three main purposes:

1. Review cases of how an AMS approach is used today to create and capture value
2. Develop an understanding of the AMS ecosystem and describe the unique process of going from market needs (issues) to functional solutions (impact)
3. Outline a process for creating value in specific end markets that are shaped by pertinent global trends

This report proposes that an AMS framework is an attractive alternative to variations on conventional business models, and thereby enables evaluation of how current players in the ecosystem are performing relative to the broader industry to identify areas where changes in business and operating models may open future opportunities.

Manufacturing industries, including chemicals and materials, face significant hurdles to take this course

The growing portfolio of unmet needs with limited resolution indicates that prevailing approaches (i.e., products made and sold by the chemicals and materials industries) are inadequate as compared to solutions designed to meet specific needs and wants. The current translation of unmet needs to specific market opportunities, while promising, is still embryonic: to date, many investments in the development of these solutions have effected only minor improvements.[18]

[18] Observation by the DTTL Global Manufacturing Industry group, October 2012.

If it is true, as growing evidence seems to suggest (see Figures 1, 2), that value derived is likely to be higher for companies that provide solutions via systems-level integration than it is for materials providers, then where is the inflection point for a company to participate? It is instructive to begin by examining current models; there are four potential key reasons behind the lower growth and innovation performance of a materials-centric focus. First, current approaches are often inefficient, with development activities occurring in isolation among different players in the value chain and supporting ecosystem; this sometimes results in mismatches between market requirements and the performance of solutions and their economics (e.g., solutions that are too heavy, too inflexible, or too expensive to be competitive), leading thereby to increased risk of commercial failure. For example, early attempts to develop commercial airplanes out of fiber-reinforced plastics failed because they did not take advantage of the unique performance and design characteristics of these engineered materials.[19] Second, markets defined by these needs have diverse demographics: customers are no longer represented by one homogeneous target market with pervasively similar requirements. Third, the engineering capabilities (tools, techniques, and skill sets) needed for development of solutions to problems are increasing in sophistication and call for systems-level innovation. Fourth, the benefits to value capture of providing a solution continue to accrue further down the value chain, closer to customers and away from the enabling technologies such as materials science and engineering.[20]

Manufacturing sectors — defined as manufacturing goods and services related to transportation, aerospace and defense, construction material and equipment, machinery, electronics, fine and specialty chemicals, pharmaceuticals, textiles and garments, food and beverage, and personal care — are challenged with the demands of meeting short-term financial goals, which often take precedence over longer-term market initiatives and growth strategies. Data indicates that innovating companies in the manufacturing sector have a potential advantage over their competition (see sidebar, ***Future of Manufacturing***). However, growth through innovation for the manufacturing industry are sparse, making these benefits difficult to realize.[21]

[19] It has been reported, for instance, that the Beech Starship composite airplane failed because it did not leverage the performance potential of composite materials; *Air & Space* magazine, "Beached Starship," September 2004, www.airspacemag.com/military-aviation/starship.html?c=y&page=1.

[20] Observation by the DTTL Global Manufacturing Industry group, October 2012.

[21] World Economic Forum in collaboration with DTTL Global Manufacturing Industry group, *Future of Manufacturing: Opportunities to drive economic growth*, 24 April 2012, www.deloitte.com/futureofmanufacturing.

This report identifies four central challenges to innovation in the manufacturing industry:

1. Some companies have traditionally taken a more closed approach to innovation; that is, they have focused their efforts on solving problems from within, or intra-organizationally. Yet, by R&D spending as a proxy for investment in innovation, it appears that the closed innovation approach does not correlate well with growth in revenue, income, or market capitalization (see sidebar, ***Future of Manufacturing***).[22] Furthermore, closed innovation by its nature forgoes seeking the best available solutions with the most viable technology, in favor of only of the best solutions in-house (and thereby potentially suboptimal).
2. Innovation cycles take too long. The industry-common product development cycles of 20-plus years are no longer viable in current markets.[23] In the United States, the time from consumer availability to 10 percent market penetration was 30 years for electricity and 25 years for the telephone; slowly, technologies such as the television and mobile phone began to reduce that time to just over 10 years, but not until smartphones and tablets did this begin to change dramatically:[24] smartphone manufacturing cycles reached 6.7 months in 2011,[25] illustrating that, for big innovations, a more rapid cycle time to commercialization is becoming the norm.
3. The chemical and materials industries may be skewed toward selling products and bulk materials; companies may therefore have few or limited systems-engineering and integration capabilities, which are critical to developing solutions beyond bulk materials alone. The capability to engage in systems-level development of solutions may increase speed to market and often be a strategic enabler for new and unique business models, but the structure and culture of materials and chemical companies sometimes disrupt this direction.
4. The benefits of traditional mass-volume production, i.e., through owning and operating large, centralized assets, are being challenged. It is becoming harder to compete globally with this approach, as it is often too expensive to continue to grow these assets. As demonstrated in *The chemical multiverse r*eport, 46 percent of chemical companies have limited means to reposition themselves in the next decade.[26] At the same time, companies may be understandably hesitant to make changes that put at risk the tremendous investments already made in the types of capabilities (people) and assets (plants and equipment) that have been the cornerstones of their success to date — however much new opportunity may beckon.

The challenges are significant, and the path forward for all industries to achieve these objectives is not always clear, especially to product-by-volume suppliers like process, industrial products, and other manufacturing sectors. New systematic approaches are therefore needed that consider the entire market ecosystem from start to finish, access the full breadth of capabilities to develop complete solutions, accelerate time to market, and reduce development risk.

[22] Ibid.

[23] DTTL Global Manufacturing Industry group, *The chemical multiverse: Preparing for quantum changes in the global chemical industry,* 16 November 2010, www.deloitte.com/thechemicalmultiverse; DTTL Global Manufacturing Industry group, *The decade ahead: Preparing for an unpredictable future in the global chemical industry,* 10 December 2009, www.deloitte.com/thedecadeahead.

[24] *MIT Technology Review*, "Are Smartphones Spreading Faster than Any Technology in Human History?" 9 May 2012, www.technologyreview.com/news/427787/are-smart-phones-spreading-faster-than-any/, with data sources including International Telecommunication Union, *New York Times*, Pew Research Center, *Wall Street Journal*, U.S. Census Bureau.

[25] Money.cnn.com, "Your new smartphone is already a dinosaur," 3 February 2011, http://money.cnn.com/2011/01/31/technology/new_smartphone/index.htm.

[26] DTTL Global Manufacturing Industry group, *The chemical multiverse: Preparing for quantum changes in the global chemical industry*, 16 November 2010, www.deloitte.com/thechemicalmultiverse.

Transformational impact of Advanced Materials Systems

The opportunities and challenges in Advanced Materials Systems are clear; but how to answer the challenge requires articulation. Many of the players that could effectively enable functional solutions are currently suppliers of materials and process technologies, and most will face a need to do things differently. This section explores how the AMS framework unites materials and process technologies through systems-level design and integration to render AMS solutions that align with end market needs.

As proposed herein, value capture and increased speed to market with AMS will largely come from combining and reusing existing materials in innovative process technologies rather than creating new materials to address specific targeted needs. This perspective implies that the universe of materials currently available is largely sufficient for many solutions to emerging market demands, when shaped and combined through novel processes and brought to market through new business models and interactions. Such process developments and open innovation approaches stand to reduce risk and time to market against developing solutions based on totally new materials, which must yet demonstrate compliance, safety, scalability, competitiveness, and end-user acceptance.

Specific global and market trends define AMS opportunities

The World Economic Forum identified nine global trends (megatrends) poised to define many global unmet needs of the 21st century[27] (see Figure 4) that are tractable to AMS solutions. Companies that address these needs stand to accrue significant value. Assessing similar needs, the European Commission Directorate-General for Research and Innovation quantified market opportunities across five major sectors of the global economy — energy, transport, environment, health, and information and communication technology[28] (see Figure 5). That analysis estimated the size of potential end markets at roughly US$2 trillion, or 3 percent of global gross domestic product — with US$150 billion specifically as an opportunity for material providers, or 20 percent of today's global specialty chemicals market.[29]

Twenty-first century factors driving manufacturing growth include political mandates for carbon-emission restrictions, climate-change and environmental sustainability, increased global competition for limited natural resources and feedstocks, ever growing demand for energy, demographic shifts such as expanding middle-class incomes and manufacturing power in developing regions like India and China, increased mobility and migration into cities (urbanization) placing demands on infrastructure and construction, and, given an exponentially growing world population,[30] unprecedented market demand for food, clean water, and health care.

Key evolutions in global markets

Present-day materials R&D and commercialization exhibit important common themes: flexibility of resource use (to accommodate recycling and reuse of materials driven by either supply scarcity or challenges in accessibility), incorporation of renewable feedstocks into production streams, deploying products and systems in a decentralized fashion, systems-level innovation, increased customization (to maximize competitiveness through differentiation in an increasingly full market space), and pressure to reduce product-development timelines and increase the speed to market. In particular, three evolutions in global markets appear to be defining challenges and opportunities and call for companies to fundamentally change how material solutions are manufactured and deployed:

Carbon-source-agnostic fuels and chemical feedstocks: With concerns over energy costs and energy security, active pursuit of alternatives to crude oil is seeing government and investment-capital support worldwide. Primary feedstocks are transitioning from petroleum to a range of

[27] DTTL Global Manufacturing Industry group analysis of World Economic Forum (The Forum) data included in a presentation deck for a monthly Project Board guidance "WELCOM" virtual meeting and Chief Innovation Officers of World Economic Forum Partner Organizations and bilateral discussions at The Forum in a slide titled "Nine global trends selected for discussion," (as developed by the Community of Chief Innovation officers at The Forum) on 21 July 2009, www3.weforum.org/docs/IP/2012/CH/WEF_CH_GlobalTrends_InnovationNeeds.pdf.

[28] European Commission, *Technology and market perspective for future Value Added Materials*, Final Report from Oxford Research AS, February 2012, http://ec.europa.eu/research/industrial_technologies/pdf/technology-market-perspective_en.pdf.

[29] Ibid.

[30] The world's population passed the seven-billion mark during 2011 to 2012 and, according to the United Nations Population Division, will increase to 9 billion by 2050. "World population will increase by 2.5 billion by 2050; People over 60 to increase by more than 1 billion," United Nations Department of Public Information press release, 13 March 2007, www.un.org/News/Press/docs//2007/pop952.doc.htm.

Figure 4: Unmet needs spurred by global trends addressed through Advanced Materials Systems innovation

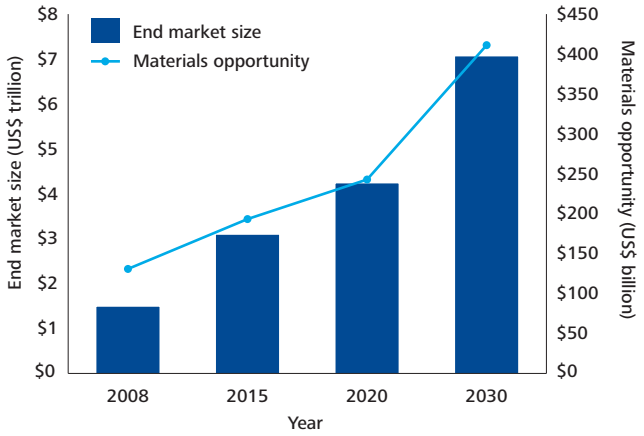
AMS innovation	Global trends
Alternative sources of carbon-based materials (alternatives to oil: biobased molecules, biomass, and biofuels)	
Alternative fuel and propulsion systems (adsorbed natural gas, hybrid vehicles, and fuel cells)	
Alternative vehicle frame design and construction to reduce weight and downsize vehicles (reduce CO_2 emissions, improve fuel-efficiency, and reduce energy for manufacturing)	
Improved systems to manage energy flow in buildings (insulation, active and passive solar, and airflow)	
New energy storage and transport systems (e.g., supercapacitors, batteries, power management electronics, and superconductors)	
New technologies to increase resource productivity and efficiency and reduce consumption	
New technologies and solutions for recycling and reusing materials, components, and devices	
New technologies to scale up renewable energy solutions and reduced dependencies on strategic materials (e.g., rare earth elements)	
Better technologies to extract resources and raw materials economically (e.g., shale gas)	
More-efficient systems for use of water in agriculture, industry, and households (desalination, purification, waste management, and irrigation)	
Advanced technologies to improve food preservation and transport (often in the absence of a cold chain).	
Breakthrough technologies in diagnostics, monitoring, therapeutic administration, and medical devices to provide high quality healthcare outside hospital settings	
Technologies that enable more targeted and localized solutions (for energy, telecommunications, etc.)	
New materials to build larger "mega cities" such as lighter and fast-drying materials	
New electronic systems for advanced manufacturing (e.g., new, high-performance semiconductor technology, robotics, interactive applications, artificial intelligence, smarter solutions that use external information to make judgments, and use sensing technologies to provide feedback)	
Information technology and media solutions to enable more targeted and localized connectivity	
New interfaces between humans and electronics — tactile, auditory, and optical stimulation and feedback	

Source: DTTL Global Manufacturing Industry group analysis of World Economic Forum (The Forum) data included in a presentation deck for a monthly Project Board guidance "WELCOM" virtual meeting and Chief Innovation Officers of World Economic Forum Partner Organizations and bilateral discussions at The Forum in a slide titled "Nine global trends selected for discussion," (as developed by the Community of Chief Innovation officers at The Forum) on 21 July 2009, www3.weforum.org/docs/IP/2012/CH/WEF_CH_GlobalTrends_InnovationNeeds.pdf.

Global trends
Climate change, environment, and sustainability
Rapidly growing demand for energy
Limited resources*
Increasing scarcity and unequal distribution of water
Growing demand for food, nutrition, and health
Demographics, including shifting populations and mobility
Shifting centers of economic activity
Social life in a technological world
Corporate global citizenship

* Note: Resource demand rapidly outpaces supply (oil, gas, coal, water, biomass, and other raw materials), price volatility.

Figure 5: Growth opportunity for Advanced Materials Systems within applicable end markets



Source: European Commission, Technology and market perspective for future Value Added Materials, Final Report from Oxford Research AS, February 2012, http://ec.europa.eu/research/industrial_technologies/pdf/technology-market-perspective_en.pdf.

carbon sources, including natural gas, coal, and biomass. Beyond cost management, alternative carbon sources may permit flexible production of materials from local feedstocks, potentially reducing dependency on foreign supply while decoupling production costs from volatile fuel markets.

Biofuels are a prime example. The U.S. Energy Independence and Security Act of 2007 increased the renewable-fuel requirement to be blended into transportation fuel in the United States, from 9 billion gallons in 2008, to 36 billion gallons by 2022.[31] The amended Renewable Fuel Standard (dubbed RFS2) distinguished four separate categories of renewable fuel (cellulosic biofuel; biomass-based diesel; advanced biofuel, i.e., any renewable fuel except corn-starch ethanol; and renewable biofuel, which subsumes all biofuels, including corn ethanol), each meeting specific greenhouse gas-emission reduction requirements.[32] Of the 36 billion gallons of renewable fuel mandated by RFS2 by 2020, 21 billion gallons must be represented by advanced biofuels (non-corn ethanol, non-petroleum);[33] that is, true "next-generation" technologies are required, which opens enormous opportunities for industrial biotechnology and other AMS approaches in markets from agriculture, to chemicals and enzymes, to infrastructure. With advanced biofuel production yet lagging, adoption of the AMS approach may prove advantageous to overcome the many technical and business challenges to commercializing these next-generation fuels, given the differential between cellulosic biomass feedstock availability[34] and the limited market-scale production capabilities demonstrated to date.[35]

Sustainability as a potential profitable driver of opportunity: Carbon-source-agnostic feedstocks inherently recognize sustainability as an equally important business imperative. As resources like precious metals

[31] U.S. Environmental Protection Agency (EPA), "Renewable Fuel Standard (RFS)," accessed on 24 October 2012, www.epa.gov/otaq/fuels/renewablefuels/index.htm.

[32] U.S. EPA Office of Transportation and Air Quality, National Renewable Fuel Standard Program Overview, 14–15 April 2010, www.epa.gov/oms/fuels/renewablefuels/compliancehelp/rfs2-workshop-overview.pdf.

[33] Ibid.

[34] U.S. Department of Energy (DOE), U.S. Billion-ton Update, Biomass Supply for a Bioenergy and Bioproducts Industry, August 2011, www1.eere.energy.gov/biomass/pdfs/billion_ton_update.pdf.

[35] National Research Council of the National Academies Board on Agriculture and Natural Resources, *Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy*, National Academies Press: Washington, DC, 2001, www.nap.edu/openbook.php?record_id=13105&page=R1; Kelsi Bracmort, *Congressional Research Service Report for Congress, Meeting the Renewable Fuel Standard (RFS) Mandate for Cellulosic Biofuels: Questions and Answers*, 11 January 2012, www.fas.org/sgp/crs/misc/R41106.pdf.

(used for electronics and catalysts) and rare-earth elements (for electric motors and generators) become scarce[36] or less accessible[37] (whether from depleting resources or intractable harvesting), economic opportunities emerge in the strategic recovery of these materials. Industrial design of AMS solutions may likely include end-of-life considerations for reuse and recycling to dramatically increase the sustainability of these systems.

Decentralized production and distribution: Solutions for emerging high-growth markets will likely be deployable in a decentralized fashion, as many of these markets will not be based in traditional city-centers.[38] Decentralization may reduce capital costs by obviating capital-intensive centralized development projects. An added benefit is the enabling of solutions customized for local conditions and of deployment among distributed populations that may lack extensive infrastructure. Decentralized deployment may also reduce risks of loss of service from natural disasters and other disruptive forces such as war or acts of terrorism, given the absence of centralized systems to be debilitated.

The rapid spread of wireless communications in sub-Saharan Africa shows how decentralized deployment can leapfrog customary forms of technology (landlines) that may be less effective in rural and decentralized regions. Full landline networks can be prohibitively expensive, especially in countries with poor roads, vast distances, and low population densities. Mobile phone coverage in sub-Saharan Africa, by contrast, is primarily provided via a network of specialized base stations that provide service to a 5- to 10-kilometer radius — a limited but effective service area for the target region.[39] Solutions thus deployed can eclipse conventional alternatives: landlines were initially rolled out in places like Kenya to stagnate at only 3.1 subscriptions per 100 people, but mobile phone penetration grew to 22 per 100 individuals in the first decade of the 21st century.[40] Sub-Saharan Africa, despite including 34 of the world's 50 poorest countries, is now the fastest-growing wireless market worldwide.[41]

20th century materials development: A rich legacy

The manufacturing industries are well situated to meet the market needs emerging in the 21st century by creatively drawing from a rich existing inventory of building blocks for commercial product development. Traditional materials development over the 20th century yielded a vast number of available materials. A sampling from one of the major U.S. suppliers is illustrative: Sigma-Aldrich's catalogue lists over 5,000 different compositions of matter[42] across the standard categories of industrial materials, namely, polymers, metals, ceramics, and semiconductors or electronic materials.

The current inventory of available building blocks resulted largely from the manufacturing industry's previous focus on developing fundamentally new materials — completely novel molecules and compositions of matter, including plastics (synthetic polymers) and semiconductor materials doped with precise chemical elements to favorably alter their electronic properties. Primary drivers of manufacturing growth in the 20th century were World War and reconstruction, the Cold War and space race, the growth of the U.S. and European middle classes and greater disposable income, and supplies of cheap petroleum that spurred new product streams (from large-scale agriculture to mass processed-food production, to new consumer and household products). One theme in the development of these materials was replacement of natural options (e.g., wood, leather, metal, glass) with synthetics that were cheaper, lighter, and functional enough to be adopted over natural counterparts (i.e., "good enough"). Another theme was new functionality; for example, advanced microelectronics products like personal computers and

[36] U.S. DOE, *Critical Materials Strategy*, December 2011.

[37] See, for example, Rech, Barbara K. and TE Graedel, "Challenges in Metal Recycling," *Science*, Vol 337 pp 690–695, 10 August 2012.

[38] World Economic Forum in collaboration with DTTL Global Manufacturing Industry group, *Future of Manufacturing: Opportunities to drive economic growth*, 24 April 2012, www.deloitte.com/futureofmanufacturing.

[39] Aker, Jenny C, and Isaac M Mbiti, "Mobile Phones and Economic Development in Africa," *Journal of Economic Perspectives*, Vol 24 No 3 pp 207–232, Summer 2010, http://sites.tufts.edu/jennyaker/files/2010/09/aker_mobileafrica.pdf.

[40] Sherry, Justine Marie, "Unlocking the potential of cell phones," in *Task Force 2009: From the Bottom Up: Rethinking U.S. Development Assistance*, pp 303–326, accessed on 24 October 2012, https://digital.lib.washington.edu/researchworks/bitstream/handle/1773/4634/TF_SIS495G_2009.pdf?sequence=1.

[41] IEEE Spectrum, "Africa Calling," May 2006, http://spectrum.ieee.org/telecom/wireless/africa-calling.

[42] Sigma-Aldrich website, www.sigmaaldrich.com/sigma-aldrich/home.html, accessed on 24 October 2012.

mobile phones were enabled by the novel properties of new semiconductor materials.

The fundamental creators of value in the 20th century were development of new materials and molecules and large-volume scale-up of production of these materials. The basic materials industry[43] grew from this foundation and has been highly profitable (for instance, the Dow Jones U.S. Basic Materials Index℠ has been up more than two times the Dow Jones Industrial Average over the last 10 years).[44]

21st century materials innovation: Systems-level solutions and design

Creating new molecules or compositions of matter is no longer enough to capture differentiable value in the market. The newest and most efficient materials for converting solar energy to electricity, for example, have not proven competitive against less efficient materials that offer lower total electricity costs (mainly through lower up-front installation outlays).[45] The solar AMS ecosystem was initially enabled by adapting existing materials to an unmet need but has yet to be optimized to create and successfully capture value. Thermoplastics illustrates this further: polycarbonate, developed in the 1960s,[46] initially captured a market premium. By the 1990s, these materials were already commoditized, eroding margins for manufacturers.[47] Thermoplastics still have properties that make them of potential value in functional solutions but for them to surpass commodity status, new strategies will be needed.[48]

[43] For example, as catalogued by the 560 companies that make up the Dow Jones U.S. Basic Materials Industry sector, http://bigcharts.marketwatch.com/industry/bigcharts-com/stocklist.asp?Symb=DJUSBM&startingIndex=0.

[44] Variations in the Dow Jones U.S. Basic Materials Index, however, show this increase characterized by more rapid upturns and dropping more rapidly in downturns.

[45] *MIT Technology Review*, "The Dog Days of Solar," 26 July 2012,www.technologyreview.com/news/428583/the-dog-days-of-solar.

[46] The Plastics Portal (Plastics Europe), "The history of polycarbonate," www.plasticseurope.org/what-is-plastic/types-of-plastics/polycarbonate/the-history-of-polycarbonate.aspx, accessed on 29 October 2012.

[47] ICIS Chemical Business, "Polycarbonate may gain increased share of engineering plastics market," 15 April 2011, www.icis.com/Articles/2011/04/15/9453128/polycarbonate-may-gain-increased-share-of-engineering-plastics.html.

[48] Ibid.

Emerging innovations in materials

This is not to suggest that innovation of materials development is extinct but rather that it is being done differently than in the past century. The organization Joint Research Network on Advanced Materials and Systems, dubbed JONAS, exemplifies current materials innovation in the AMS approach.[49] Incorporated by BASF SE in 2011, JONAS includes three European academic partners: the ISIS Institute at Strasbourg University, Freiberg University, and ETH Zurich.[50] Founded to extend the scientific basis and understanding of future materials and systems, JONAS revised industry classification schemes to describe emerging materials, in a way that recognizes the importance of innovation with existing materials. JONAS's classification identifies specialty monomers (used as cross-linkers and in coatings), polymers and polymer materials (including both natural and synthetic materials), hybrid-material systems (composites of two constituent compounds at the molecular or nanometer level), nanostructured materials (structural elements in the 1–100 nanometer range), biobased polymeric materials (bioengineered polymers), and bio-inspired systems (including biomimetics, both of biohybrid and "purely" synthetic materials).[51]

Inventive combinations of existing materials within an AMS framework may provide stakeholders a particularly efficient means of leveraging these materials and material combinations into functional solutions, as demonstrated by several case studies, described below.

Stretchable electronics: The processing of existing semiconductor materials (typically rigid and brittle) into extremely thin forms is allowing the creation of conformal electronics (see sidebar, **Case study — Wearable electronics**). By embedding the ultrathin microchips that these materials enable, into films produced from existing, rubbery elastomeric materials, and by connecting them with metal spring-like wires, electronic devices become possible with similar flexibility properties as temporary tattoos worn easily on the skin. One application of such

[49] Joint Research Network on Advanced Material Systems (JONAS) website, accessed on 24 October 2012, www.jonas-research.net/index.php/en/.

[50] Ibid.

[51] Ibid.

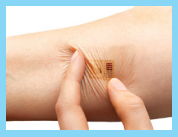
technology is in high-efficiency solar arrays that may be integrated into combat clothing, packs, and tents to provide portable personal power for military use. Another usage is in wearable electronic monitors that measure vital conditions of athletes and soldiers, for peak performance and to provide preemptive warnings against potential pending injury.[52]

Bioabsorbable composites: Novel combinations of existing biodegradable polymers are being designed into implants mimicking the mechanical properties of various human tissues, to replace diseased or damaged tissues. Once implanted in the body, these bioabsorbable composites support local tissue as it heals, before dissolving into the body once their function has been served. First applications of these materials are being demonstrated in scaffolds for treating diseased arteries (see sidebar, **Case study — Medical device innovation**).[53]

Self-assembled materials: Self-assembly as relevant to AMS refers to the harnessing of natural forces between different materials or molecules to guide their inherent formation into an intentional structure. An easily understood macroscale parallel is the inherent pull of opposite magnetic poles (and repulsion of like poles). At the molecular scale, in the biophysical sphere, proteins, lipids, and other biomolecules aggregate to form cells and tissues in a living organism. Materials science is marshaling such processes of self-assembly to build materials systems and composites through a "bottom-up" approach — very different from traditional "top-down" materials processing, which typically starts with actual chunks of material that are cut, ground, melted, or molded into a final shape. Self-assembly is one strategy for producing biomimetic nanocomposites. It is also being explored as an alternative means of making nanoscale electronic systems

[52] MC10 website, "Reebok-CCM and MC10 to Launch Revolutionary Sports Impact Indicator," accessed on 29 October 2012, http://mc10inc.com/news/2012/reebok-ccm-and-mc10-to-launch-revolutionary-sports-impact-indicator; and *MIT Technology Review*, "EmTech: Reebok and MC10 will Launch an Impact-Sensing Skullcap for Sports," 24 October 2012, www.technologyreview.com/view/429751/emtech-reebok-and-mc10-will-launch-an-impact-sensing-skullcap-for

[53] 480 Biomedical website, "480 Biomedical Announces Initial Observations from OCT Sub-Study of the STANCE Trial Evaluating the First Self-Expanding Bioresorbable Scaffold for Superficial Femoral Artery Disease," accessed on 31 October 2012, www.480biomedical.com/news/news.



Case study — Wearable electronics

Technology start-up MC10 advances new class of high-performance wearable electronics for applications in numerous sectors

Unmet need: Sustainability, cost-efficiency, and demographic shifts are driving needs to better understand the workings of the body, protect from injury, and generate power, which can be addressed through wearable electronics. Conventional electronics systems are inflexible, rigid, and planar, fundamentally precluding their use in soft-form applications on or within the human body.

Material innovation: MC10 is commercializing a stretchable electronics platform of ultrathin, conformal electronics (i.e., that flex, stretch, and bend). Designed to be equivalent to current best-in-class rigid-microelectronic technologies, MC10's platform can be integrated into 3-D applications, dynamic or moving systems (such as the human body), and space-constrained areas. The technology combines conventional electronics and novel mechanics that change the end-user's functional relationship with electronics, beyond the common consumer-electronics goal of simply making traditional electronics smaller. Instead, MC10 is designing wearable systems to be virtually undetectable to the wearer while retaining performance and data quality.

Process technology: Innovative process technologies are applied to create sleek-profile, softer, stretchable versions of existing electronic materials. Solutions are being developed for new product applications and industries that would benefit from devices that diagnose and influence tissue function, and from sensory devices capable of monitoring key systems and functions (such as heart, brain, muscles, body temperature, and hydration levels).

Ecosystem and business model: The company is working with private and government entities to commercialize the technology. The intent is to collaborate with leading stakeholders in end markets served by these products to maximize market access and customer demand.

Path to success: MC10 is seeking to build a diversified platform business to realize the potential of stretchable electronics. The company staked an early claim in an industry-revolutionizing use of electronics for existing and emerging markets, with a focus on novel benefits realized by directly interfacing high-performance electronics with the human body. Initially targeting the sports segment of the consumer products space, the company's pipeline of products will expand to include products in wearable health care, medical devices, manufacturing, and defense.

Source: MC10 website, "Reebok-CCM and MC10 to Launch Revolutionary Sports Impact Indicator," accessed on 29 October 2012, http://mc10inc.com/news/2012/reebok-ccm-and-mc10-to-launch-revolutionary-sports-impact-indicator; and *MIT Technology Review*, "EmTech: Reebok and MC10 will Launch an Impact-Sensing Skullcap for Sports," 24 October 2012, www.technologyreview.com/view/429751/emtech-reebok-and-mc10-will-launch-an-impact-sensing-skullcap-for-sports/.

Case study — Medical device innovation

480 Biomedical's bioresorbable scaffold technology targets and improves on treatment of disease affecting 10 million-plus worldwide

Unmet need: Patients suffering from superficial femoral artery (SFA) occlusive disease that is not well managed by medical therapy alone may require a minimally invasive procedure involving a metal stent to open the artery. The SFA vessel is subject to a high degree of mechanical force and deformation, which can increase the potential for complications with metal stents (e.g., irritation, fracture, and difficulty of retreatment).

Material innovation: 480 Biomedical's Stanza™ scaffold technology combines well-known biocompatible materials with innovative engineering to solve a technically challenging clinical problem. The scaffold is composed of strong polylactic-co-glycolic acid (PLGA) fibers with an elastomer to deliver flexibility, radial strength, and resorbability to optimize the therapeutic impact. The Stanza self-expanding scaffold technology supports the opened vessel during the critical healing period following an intervention and then resorbs, leaving no permanent implant behind.

Process technology: In creating the Stanza scaffold, the company engineered polymer materials into a unique design that enables self-expansion of the scaffold and radial strength sufficient to maintain vessel patency (openness) post-intervention.

Ecosystem and business model: By catering its design plans to the needs of an existing customer base, the company is positioning itself for competitive success. Similar to leading metal stents, the Stanza scaffold is deployed with a conventional retractable-sheath delivery system, while also providing the benefits of resorbability.

Path to success: The company targeted a desirable function (bioresorbability) to treat a specific market need (arterial disease) with innovative solutions using existing materials. 480 Biomedical's proprietary scaffold platform is under investigation in both vascular and nonvascular applications.

Source: 480 Biomedical website, "480 Biomedical Announces Initial Observations from OCT Sub-Study of the STANCE Trial Evaluating the First Self-Expanding Bioresorbable Scaffold for Superficial Femoral Artery Disease," 10 October 2012, www.480biomedical.com/news/news.

recalcitrant to traditional semiconductor approaches such as photolithography.

Biomimetic nanocomposites: Biomimetics copies existing designs or design principles from nature to develop synthetic materials or systems. Current R&D is looking to copy the design of seashells like abalone, one of the strongest and toughest materials known.[54] Its properties stem from a unique combination of nanometer-thick ceramic plates in a matrix of natural polymeric fibers assembled by the organism into a composite structure known as nacre. Industrial harnessing of this design could create armor ten times lighter and ten times more resistant to penetration than existing solutions. Such approaches to composites production are a significant area of emerging materials research for applications across numerous industries; for example, new composites for ultra-lightweight, high-strength construction materials,[55] and options for replacing or regenerating hard tissues in the body, like teeth and bone.[56]

Metal-organic frameworks (MOFs): This class of materials combines metal-oxide "hubs" with organic molecule "spokes" into three-dimensional Tinkertoy-like latticeworks capable of absorbing large amounts of gas, parallel to a sponge's capacity to absorb fluids. Compound-specific absorption can be imposed such that these materials might absorb one particular gas from among a mixture (such as CO_2 from air). MOFs are being developed for applications such as removal of greenhouse gases from the atmosphere, and for safe storage of combustible gases (such as hydrogen and natural gas) in small volumes and at low pressures for alternative or backup vehicular transportation fuels.

Ionic liquids: Ionic liquids are salts that exist in liquid rather than solid state. Although not strictly a new class

[54] Bhushan, Barat, "Biomimetics: lessons from nature–an overview," *Philosophical Transactions of the Royal Society* A, Vol 367 No 1893 pp 1445–1486, 28 April 2009.

[55] See, e.g., Kisailus Biomimetics and Nanostructured Materials Lab, accessed on 31 October 2012, www.engr.ucr.edu/~david/kisailus.php.

[56] For example, see Im, Owen, et al., "Biomimetic three-dimensional nanocrystalline hydroxyapatite and magnetically synthesized single-walled carbon nanotube chitosan nanocomposite for bone regeneration," *International Journal of Nanomedicine*, Vol 7 pp 2087–2099, 24 April 2012.

of materials (in that the first known were discovered over 120 years ago), there has been significant development of new compositions with improved properties. Composed of oppositely charged species (as table salt is made up of positive sodium ions and negative chloride ions), ionic liquids are efficient conductors of electricity, thereby useful in new battery designs. Further, many have unique qualities as solvents, selectively dissolving different components within a mixture at high specificity. This specificity can be designed for extraction applications such as waste recovery and for replacement of more-toxic, volatile solvents used in many industrial chemical reactions, making ionic liquids attractive for green chemistry production platforms.

Hallmarks of the Advanced Materials System approach

Case study — Composite airframes

A leading commercial and military aircraft manufacturer pursues composite airframes to reduce aircraft weight and fuel consumption

Unmet need: Ongoing trends related to sustainability and globalization have created demand for cleaner, lower-cost travel options for an increasingly mobile global population. Fuel accounts for one-third of the total cost per available passenger seat, indicating the additional potential impact of reduced fuel consumption on stakeholder operating costs.

Material innovation: Boeing recognized the impact of reducing aircraft weight on its operating costs and identified existing materials to design planes whose bodies are made up of carbon fiber infused with epoxy resin, enabling up to 20 percent less fuel use than with similarly sized traditional aluminium frames.

Process technology: Process technologies involved in the application of materials to create composite airframes include automated tape-laying to improve quality and reduce cost of frame fuselage and wing structure.

Ecosystem and business model: By spinning off from and collaborating with manufacturing entities involved in the materials and processes required to construct these frames, Boeing was able to control most of the system value.

Path to success: The manufacturer started with an unmet need and identified the materials and process technologies necessary to create a solution. By determining the proper application of these materials and related process technologies to address these needs, the company also created business models and partnerships enabling them to capture much of the ecosystem's value.

Source: Boeing *Aero Magazine*, "Boeing 787 From the Ground Up," accessed on 30 October 2012, www.boeing.com/commercial/aeromagazine/articles/qtr_4_06/AERO_Q406_article4.pdf; Design News, "Boeing 787 Dreamliner Represents Composites Revolution," 4 June 2007, www.designnews.com/document.asp?doc_id=226256&dfpPParams=ind_183,aid_226256&dfpLayout=article.

As suggested throughout this report, opportunities in AMS emerge when unmet needs can be addressed through functional solutions enabled by the combination of innovative materials, process technologies, and business models that can be competitive in a defined end market, as illustrated in the AMS framework (see Figure 3). The potential for AMS to increase both speed to market and the quality of the solutions is optimized when these elements come together in systems-level design, in the context of open innovation, and when system performance and cost are defined by the target market and not the properties of the material.

Open innovation allows differentiated, protected value while optimizing AMS solutions

Open innovation describes companies' use of both external and internal ideas and paths to market in order to advance their technology. The paradigm calls for "the use of purposive inflows and outflows of knowledge to accelerate internal innovation and expand the markets for external use of innovation."[57] The AMS context expands this concept of openness beyond technology development and into aspects of commercialization and partnering; that is, not only to create a solution but to take it to market. Doing so may often involve public-private partnerships. (JONAS, at the forefront of new materials science, mentioned above, is one example).

Historical materials development was typically conducted in a more guarded, closed innovation approach that is proving ineffective in current markets.[58] AMS allows for optimal solutions with maximized value capture for all stakeholders through protective IP strategies, calling for optimal business models and partnerships that preemptively protect IP from the outset. An example from the aerospace and defense industry (see sidebar, **Case study — Composite airframes**) illustrates these points and the extent to which partnerships and business models can capture large shares of value in the AMS space.[59] Another example is solid-state lighting, which was

[57] Chesbrough, Henry, Wim Vanhaverbeke, and Joel West. *Open Innovation: Researching a New Paradigm*. Oxford University Press: New York, 2006.

[58] Observation by the DTTL Global Manufacturing Industry group, October 2012.

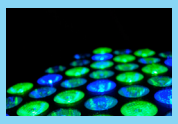
[59] Boeing *Aero Magazine*, "Boeing 787 From the Ground Up," accessed on 30 October 2012, www.boeing.com/commercial/

developed through open innovation yet retained individual IP rights for stakeholders involved (see sidebar, **Case study — Solid-state lighting**[60]), and for substantial value capture. The value of the IP of the start-up company that developed the novel solid-state lighting technology was a primary driver of its eventual acquisition by a large lighting provider, for nearly US$800 million (a 10-times multiple of revenue).[61]

Process innovation expands the functionality of materials for tailored solutions

Numerous possible pathways are available to move from the materials focus of the AMS framework (Figure 3; left-hand side) to processes that design these classes of materials into different systems (Figure 3; right-hand side). This section focuses on three key process technologies expected to be at the frontier of innovation in, and important enablers of, AMS commercialization.

Nanotechnology[62] permits heretofore unavailable levels of structural and functional precision at ultrafine scales, greatly expanding the possibilities for engineering of numerous classes of materials. In one example, nano-imprint lithograpy has allowed the introduction of structural design at much smaller scales than achievable



Case study — Solid-state lighting

Solid-state lighting innovation addresses unmet need for more-efficient artificial lighting and increased energy-efficiency

Unmet need: Lighting accounts for between 13 and 18 percent of total electricity generated in the United States. Increased market penetration of light-emitting diode (LED) light sources (one mode of solid-state lighting) could result in energy savings of up to US$30 billion in 2030, reduce greenhouse gas emissions by up to 210 million metric tons of carbon, and decrease electricity consumption for lighting by roughly 46 percent (against a scenario with no LED market penetration).

Material innovation: Color Kinetics created an Advanced Material System around solid-state lighting using LEDs composed of existing compound semiconductors such as gallium nitride.

Process technology: High-volume, high-yield production used scalable approaches to manufacture LEDs for drop-in substitution of incandescent bulbs as well as custom lighting solutions.

Ecosystem and business model: Color Kinetics employed process innovations and systems-level innovation to assemble complete fixtures comprising individual LEDs, electronics, optics, and mechanical designs for thermal dissipation. Financial support from the U.S. Department of Energy (DOE) and open innovation collaborations and partnerships with LED suppliers enabled competitively priced lighting solutions using patent-protected systems and designs.

Path to success: Color Kinetics increased its revenue from approximately US$15 million to US$80 million between 2000 and 2008.

Source: U.S. Department of Energy (DOE) Energy Efficiency and Renewable Energy (EERE), 2011 Building Energy Data Book, March 2012, http://buildingsdatabook.eren.doe.gov/docs/DataBooks/2011_BEDB.pdf; U.S. Energy Information Administration website, FAQ, accessed on 24 October 2012, www.eia.gov/tools/faqs/faq.cfm?id=99&t=3; U.S. DOE EERE, Energy Savings Potential of Solid-State Lighting in General Illumination Applications, January 2012, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_energy-savings-report_jan-2012.pdf; U.S. DOE EERE, Solid State Light Research and Development, Multiyear Program Plan, April 2012, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2012_web.pdf; U.S. DOE Color Kinetics, SEC Form S-1 filed on 9 April 2004, www.sec.gov/Archives/edgar/data/1048611/000095013504001808/b48986cksv1.htm; Philips, "Color Kinetics to release fourth quarter and full year 2004 earnings on February 3," 26 January 2005, www.colorkinetics.com/corp/news/pr/archive/2005-01-26-earningsdate.htm; Philips, "Color Kinetics reports record revenues and earnings for fourth quarter and full year 2005," 9 February 2006, www.colorkinetics.com/corp/news/pr/releases/2006-02-09_q4earnings.html; Philips, "Color Kinetics reports financial results for fourth quarter and full year 2006," 8 February 2007, www.colorkinetics.com/corp/news/pr/releases/2007-02-08_earnings.html.

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aeromagazine/articles/qtr_4_06/AERO_Q406_article4.pdf; Design News, "Boeing 787 Dreamliner Represents Composites Revolution," 4 June 2007, www.designnews.com/document.asp?doc_id=226256&dfpPParams=ind_183,aid_226256&dfpLayout=article.

[60] Source: U.S. Department of Energy (DOE) Office of Planning, Budget and Analysis, Energy Efficiency and Renewable Energy (EERE), *2011 Building Energy Data Book*, March 2012, http://buildingsdatabook.eren.doe.gov/docs/DataBooks/2011_BEDB.pdf; U.S. Energy Information Administration website, FAQ, www.eia.gov/tools/faqs/faq.cfm?id=99&t=3 (accessed on 24 October 2012); U.S. DOE EERE, *Energy Savings Potential of Solid-State Lighting in General Illumination Applications*, January 2012, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_energy-savings-report_jan-2012.pdf; U.S. DOE EERE, *Solid State Light Research and Development, Multiyear Program Plan*, April 2012, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2012_web.pdf; U.S. DOE Color Kinetics, SEC Form S-1 filed on 9 April 2004, www.sec.gov/Archives/edgar/data/1048611/000095013504001808/b48986cksv1.htm; Philips, "Color Kinetics to release fourth quarter and full year 2004 earnings on February 3," 26 January 2005, www.colorkinetics.com/corp/news/pr/archive/2005-01-26-earningsdate.htm; Philips, "Color Kinetics reports record revenues and earnings for fourth quarter and full year 2005," 9 February 2006, www.colorkinetics.com/corp/news/pr/releases/2006-02-09_q4earnings.html; Philips, "Color Kinetics reports financial results for fourth quarter and full year 2006," 8 February 2007, www.colorkinetics.com/corp/news/pr/releases/2007-02-08_earnings.html.

[61] Ibid.

[62] See also section on "Biomimetic nanocomposites," above.

with optical lithography (the latter largely a tool of 20th century microelectronics). Likely even more disruptive than ultrastructural capacities is the entire horizon of truly novel functionalities (e.g., self-healing fabrics, digestible packaging, nanoscale sensors) afforded by nanotechnology that have yet to be brought to proof-of-concept at commercial scale. Entirely new sets of unique mechanical, optical, and electronic properties that emerge at the nanoscale will eventually be enabled from existing materials, with potential game-changing applications in every industry.

Government commitment of research dollars can be a strong indicator of potential short- and medium-term market trends. In the U.S., the 2003 signing of the 21st Century Nanotechnology Research and Development Act was a significant milestone, creating a framework for coordinating research spending among 26 different federal government departments and agencies, from the Department of Energy (DOE) to the Department of Homeland Security.[63] Total U.S. government spending on nanotechnology initiatives increased to roughly US$1.5 billion per year in FY2011 (with US$1.8 billion requested for FY2013); US$18 billion has been spent since the inception of the program.[64] Funds are dispersed across basic research, development, and commercial-manufacturing process development. Funding recipients have included major multinational companies, university research labs, start-ups, and government-operated labs and research centers. Internationally, the Nanowerk nanotechnology online database counts 520 nanotechnology research initiatives, networks, and associations worldwide.[65] The global nanotechnology market, valued at nearly US$20.1 billion in 2011, could generate total sales of as much as US$48.9 billion in 2017; nanomaterials, specifically, will account for an estimated US$15.9 billion in sales in 2012, and up to US$37.3 billion in 2017.[66]

Industrial biotechnology stands to be a major contributor of highly disruptive platforms in numerous industries, particularly in the energy and chemicals sectors[67] with potential revenues as much as US$165 billion by 2020 (in biorefining outputs of biofuels, biobased bulk chemicals and bioplastics, power and heat, and downstream chemistry).[68] While research efforts are looking at creation of new "materials" (e.g., completely novel bacteria created through synthetic biology/genetic engineering), industrial biotechnology's main contribution may largely stem from novel methods of producing existing materials (with drop-in substitution of processes and products, like drop-in alternative fuels or biobased-chemical intermediates). While cost-parity of biobased chemicals with petroleum-based counterparts has yet to be achieved, concerns over energy security, feedstock availability, and carbon-emission limits should keep industrial biotechnology as a main enabler of materials innovation in the coming decades.

Additive manufacturing is an advanced manufacturing process that fabricates solid three-dimensional objects composed of polymers, ceramics, or metals directly from a digital "model" (an electronic file containing the compositions and dimensions of the object to be created). The process of depositing and "curing in place" successive layers of material creates structures. This approach is distinct from traditional subtractive machining techniques, which again typically remove material by methods like drilling and cutting to render a final shape.

There are several reasons why additive manufacturing is an important emerging process technology. First, it is a distributed means of manufacturing that affords scalable customization; that is, production at different orders

[63] U.S. Federal Government, 21st Century Nanotechnology Research and Development Act, accessed on 24 October 2012, www.gpo.gov/fdsys/pkg/PLAW-108publ153/html/PLAW-108publ153.htm.

[64] National Science and Technology Council and Office of Science and Technology Policy, *The National Nantotech Initiative: Supplement to the President's 2013 Budget*, 13 February 2012, http://nano.gov/sites/default/files/pub_resource/nni_2013_budget_supplement.pdf.

[65] Nanowerk website, accessed on 24 October 2012, www.nanowerk.com.

[66] BCC Research, *Nanotechnology: A Realistic Market Assessment*, September 2012, www.bccresearch.com/report/nanotechnology-market-applications-products-nan031e.html.

[67] European Commission High Level Expert Group (HLG) on Key Enabling Technologies (KET), *KET — Industrial Biotechnology Working Group Report*, June 2011, http://ec.europa.eu/enterprise/sectors/ict/files/kets/4_industrial_biotechnology-final_report_en.pdf; Erickson, Brent, Janet E. Nelson, and Paul Winters, "Perspectives on opportunities in industrial biotechnology in renewable chemicals," *Biotechnology Journal* Vol 7 No 2 pp 176–185, February 2012, http://onlinelibrary.wiley.com/doi/10.1002/biot.201100069/abstract; Biotechnology Industry Organization (BIO) website, "The Third Wave in Biotechnology: A Primer on Industrial Biotechnology," accessed on 29 October 2012, www.bio.org/articles/third-wave-biotechnology.

[68] World Economic Forum, *The Future of Industrial Biorefineries*, pp 18–20, 2010, www3.weforum.org/docs/WEF_FutureIndustrialBiorefineries_Report_2010.pdf.

of magnitude (be it 10 parts per unit, 1,000 parts, or 100,000) differs only in the instructions specified by the computer file that drives the machines that make the product. Each part, regardless of scale, may be unique and customized without cost-variance, allowing for tremendous customization. This type of manufacturing also scales out rather than up: as users wish to double, triple, or quadruple production, they can simply increase their inventory of production tools, instead of making any particular equipment bigger. Finally, this approach allows decentralized customization and production of objects that cannot be made in any other way. This sort of customized distribution of manufacturing favors smaller-scale localized facilities versus large centralized capital-intensive production sites.

Additive manufacturing will potentially disrupt a breadth of manufacturing sectors, with an estimated global market of approximately US$1.8 billion in 2012, reaching as much as US$3.5 billion by 2017.[69]

Systems-level thinking and innovation in AMS are ushering in a new era of engineering

The shift in focus from discovery and development of new compositions of matter, to innovation in the design of systems and process technologies using existing materials, represents a new era of "integration engineering." The shift is analogous to what is happening in the life sciences. Twentieth-century advances in biosciences occurred mainly in the realm of molecular biology, as constituent components were identified and functional pathways determined. Molecular biology was, and continues to be, fundamentally about cataloguing the basic molecular building blocks of life — specific genes and nucleotide sequences that constitute the genomes of living organisms and the proteins they encode to effect the molecular mechanics of life.

Harnessing this genetic information in systems-level approaches is now the focus of the systems biology and bioengineering being employed for industrial applications today. Systems biology (the study of systems of biological components, be they molecules, cells, organisms, or entire species) and biological/genetic engineering (including synthetic biology) seek to elucidate and combine biological building blocks into complex networks of the hundreds of thousands of intermolecular interactions that occur in each cell of a living organism. Systems biology requires interdisciplinary collaboration among biologists, chemists, physicists, electrical and chemical engineers, and computer scientists, similar to the open innovation nature of the partnerships that will capture value in the AMS framework.

The AMS landscape, too, advocates an increasingly systems-level approach. The present collection of available materials comprises the building blocks, with well-understood physical and chemical properties that, together with innovations in process technologies and systems-level design, are enabling new functional solutions. There are now several materials databases that document available industrial materials,[70] and some even claim a "genome" approach, akin to genetic databases cataloguing the elements of the human genome.

As in systems biology, the challenge and opportunity in AMS is to leverage existing building blocks within systems-level design, toward functional solutions. To do so requires a breadth of expertise that, given both scale and technological knowledge needed, may be possible only through novel collaborative innovations among materials suppliers, industrial designers and engineers, and process engineers and systems integrators. As is also the case in industrial bioscience, a key accelerator for AMS innovation is high-performance computing and predictive modeling at multiple length-scales, including at the material and system level.

Applying systems-level thinking to target a whitespace need can have game-changing effects on markets and stakeholders both. Consider the e-book reader, which was enabled by electronic ink technology (see sidebar,

[69] Markets and Markets, *Global Additive Manufacturing Market (2012–2017), By Application (Medical Devices, Automotives, & Aerospace) and Technology (3D Printing, Laser Sintering, Stereolithography, Fused Deposition Modeling, Electron Beam Melting, & Tissue Engineering)*, October 2012, www.marketsandmarkets.com/Market-Reports/additive-manufacturing-medical-devices-market-843.html.

[70] Examples include the Materials Genome Initiative (http://materialsinnovation.tms.org/genome.aspx), the Material ConneXion online database (www.materialconnexion.com/Home/Services/MaterialsLibrary/MaterialsDatabase/tabid/735/Default.aspx), and the Materials Project (www.materialsproject.org).

Case study — e-Book reader

Taking advantage of a material innovation for low-power electronic ink, Amazon created a market for e-readers and captured significant value in that space

Unmet need: In response to a market demand for mobile access to a range of print and media publications and entertainment, Amazon, in collaboration with E Ink Corporation, shaped a market for e-readers.

Material innovation: E Ink, a start-up, developed new materials that enabled electronic ink with low power consumption in thin, light devices.

Process technology: After seeing several smaller consumer applications, E Ink ultimately became the base display technology of Amazon's Kindle™, the premiere example of an early, successful e-reader.

Ecosystem and business model: By partnering to leverage E Ink's technology and the customer base and Kindle ecosystem that Amazon was looking to build, these two companies created a new ecosystem for not only e-readers but a variety of other types of consumer products that constitute the present e-tablet industry.

Path to success: Using an innovative new-material technology, Amazon created a new market for sales not only of the Kindle but also e-books, MP3 products, streaming video, applications, advertisements, and data, each with opportunities for tremendous value capture, which Amazon has capitalized on.

Source: Business Insider, "How Amazon Makes Money From The Kindle," 18 October 2011, http://articles.businessinsider.com/2011-10-18/research/30292632_1_amazon-s-kindle-kindle-hardware-digital-books; Mashable Business, "Ebook Sales Surpass Hardcover for First Time in U.S.," 17 June 2012, http://mashable.com/2012/06/17/ebook-hardcover-sales/; Bloomberg, "Barnes & Noble Sinks Most Since June After Halting Dividend," 22 February 2011, www.bloomberg.com/news/2011-02-22/barnes-noble-falls-after-dividend-halt-same-store-sales-rise.html; Brookings Institute, "Amazon's Kindle: Symbol of American Decline?" 25 February 2010, www.brookings.edu/blogs/up-front/posts/2010/02/25-tech-muro.

Case study — e-Book reader). This technology opened an entirely new market for e-reader devices, by permitting production of low-power reflective displays that can be produced in high volume at viable cost. By integrating technology developed by another company into a device to appeal to a new market of e-reader users, the system provider captured a significant portion of the market's value. The company achieved new revenues not only with the e-readers and e-books themselves but, eventually, through expanded sales of MP3 products, streaming video, applications, and advertisements, as well as data and network streaming for major carriers.[71]

Success requires that the target market — not the material — define system performance and cost

In traditional commercial development of new-materials-enabled systems, the first step is the invention of a new material. Specific systems made possible by that material are then envisioned, before any stakeholder goes to market. This has been the development path typified in innovation from universities to start-ups. AMS turns the standard process on its head and starts instead with the market. That is, players should look to understand what the market opportunity is, as a function of end-user-defined performance criteria, and focus on both performance and cost. Accordingly, players must first understand the markets and performance requirements to form solutions that adequately address specific unmet needs.

The development of new photovoltaic (PV) materials for converting solar energy to electricity illustrates how this can be done effectively. A large library of PV materials that were developed over time had been catalogued by the National Center for Photovoltaics within the U.S. DOE's National Renewable Energy Laboratory (NREL).[72] A recent

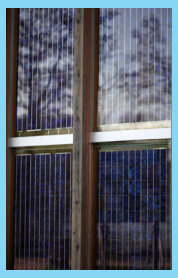
[71] Business Insider, "How Amazon Makes Money From The Kindle," 18 October 2011, http://articles.businessinsider.com/2011-10-18/research/30292632_1_amazon-s-kindle-kindle-hardware-digital-books; Mashable Business, "Ebook Sales Surpass Hardcover for First Time in U.S.," 17 June 2012, http://mashable.com/2012/06/17/ebook-hardcover-sales/; Bloomberg, "Barnes & Noble Sinks Most Since June After Halting Dividend," 22 February 2011, www.bloomberg.com/news/2011-02-22/barnes-noble-falls-after-dividend-halt-same-store-sales-rise.html; Brookings Institute, "Amazon's Kindle: Symbol of American Decline?" 25 February 2010, www.brookings.edu/blogs/up-front/posts/2010/02/25-tech-muro.

[72] U.S. DOE NREL website accessed on 24 October 2012, www.nrel.gov/ncpv/ and U.S. DOE SunShot Initiative, "Photovoltaics Research and

NREL report estimates that the technical potential of PV cells and concentrated solar power in the U.S. is as much as 200,000 gigawatts, or enough to generate about 400,000 terawatts of energy annually.[73] To achieve market penetration, however, PV materials must ultimately be attractive, in terms of performance and cost, to specific target markets. This has posed a major challenge for the PV industry, likely attributable to the "materials first" thinking of the past, rather than the "market first" thinking of AMS; but companies that surpass convention are taking advantage of newly created opportunities (see sidebar, Case study — Solar window technology).[74]

In the AMS framework, then, the market is considered first, before the assessments of performance and cost trade-offs possible that will ultimately define the market opportunity in more granularity; it is the market, not the material, that defines the systems-level performance criteria. Different materials have characteristic cost structures and performance that can be plotted. (In the case of PV materials, performance would be measured as efficiency.) One way to visualize the performance-cost relationship is through what are called frontier curves that plot performance as a function of cost, to define a "frontier" identifying the trade-off between performance and cost that consumers would be willing to accept.[75] Companies that fall behind the delineation will likely not see market success; those "ahead of the curve" will actually be creating a new frontier and disrupt the market.

Once a performance frontier benchmark has been decided, the materials that might best provide a solution, and how



Case study — Solar window technology
Pythagoras Solar's photovoltaic glass technology enables efficient windows that also generate energy

Unmet need: Ongoing trends related to sustainability and resource scarcity have created a demand for more-energy-efficient buildings that more effectively maintain, and generate energy by taking advantage of available resources.

Material innovation: Start-up company Pythagoras Solar determined that technology using existing photovoltaic solar cells and prisms, embedded in windows to capture solar energy, allows buildings to take advantage of natural sunlight to be used as a power source.

Process technology: By using innovative process technologies to apply existing solar-capture and insulation materials into their windows, the company developed a product capable of generating similar amounts of energy as solar panels that could yet be effectively used in existing window glass systems.

Ecosystem and business model: By establishing an innovation that fits within an existing system and promises to pay for itself within three to five years, the company was able to capture investments by larger companies, for more effective product commercialization.

Path to success: By identifying an unmet need and applying existing materials using innovative process technologies and business models, this company created a new product with an existing end market and captured value in this space.

Source: Pythagoras Solar website, "Pythagoras Solar Announces Photovoltaic Glass Unit (PVGU), First Green Building Material to Combine Energy Efficiency, High Density Solar Power Generation and Transparency," 18 May 2010, www.pythagoras-solar.com/news/pythagoras-solar-announces-photovoltaic-glass-unit-pvgu-first-green-building-material-to-combine-energy-efficiency-high-density-solar-power-generation-and-transparency/; Gigaom, "The vision for solar windows," 24 June 2011, http://gigaom.com/cleantech/the-vision-for-solar-windows.

Development," accessed on 29 October 2012, www1.eere.energy.gov/solar/sunshot/pv_research.html.

[73] U.S. DOE NREL, *U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis,* July 2012, www.nrel.gov/docs/fy12osti/51946.pdf.

[74] Pythagoras Solar website, "Pythagoras Solar Announces Photovoltaic Glass Unit (PVGU), First Green Building Material to Combine Energy Efficiency, High Density Solar Power Generation and Transparency," 18 May 2010, www.pythagoras-solar.com/news/pythagoras-solar-announces-photovoltaic-glass-unit-pvgu-first-green-building-material-to-combine-energy-efficiency-high-density-solar-power-generation-and-transparency/; Gigaom, "The vision for solar windows," 24 June 2011, http://gigaom.com/cleantech/the-vision-for-solar-windows.

[75] As described in Michael E. Raynor's *The Innovator's Manifesto: Deliberate Disruption for Transformational Growth*, Crown Publishing Group: New York, 2011, which focuses on Clayton Christensen's landmark disruption theory.

might they be accessed and integrated into a system through strategically chosen partnerships, can be decided upon. The best options may involve licensing the material from a university, for example, or partnering with a materials company that boasts the technology in its IP portfolio.

Players must finally determine how to put together the overall open innovation framework to bring that material to market in a business model that specifies how the created value can be ideally shared across the participants in the ecosystem. All the while, AMS opportunities are considered from a systems-level standpoint, such as the PV materials designed into solar-energy-generating windows. Rather than just comprising PV modules that bolt onto a roof or get deployed in a field, many PV systems that will ultimately have a unique advantage in the marketplace will come from integrating PV functionality into other existing structures such as windows or shingles (as described in sidebar, **Case study — Solar window technology**). This approach to building integrated PV is growing rapidly,[76] to demonstrated success: in the case of solar windows converting sunlight to electricity while permitting the passing of light, one company identified innovative whole-technology solutions that fit within existing use- and demand-patterns for efficient window glass. The result was a window system both more efficient in retaining energy within buildings (current use) and capable of generating electricity from approximately 14 percent of traversing sunlight (functional innovation).[77] The takeaway is that the technology solution was designed to meet end-user defined performance and cost criteria.

[76] Pike Research, press release, "Building Integrated Photovoltaics Market Revenue to Quadruple to $2.4 Billion by 2017," 21 August 2012, www.pikeresearch.com/newsroom/building-integrated-photovoltaics-market-revenue-to-quadruple-to-2-4-billion-by-2017.
[77] SF Gate, "Pythagoras Solar windows and energy breakthrough," 25 June 2011, www.sfgate.com/business/article/Pythagoras-Solar-windows-and-energy-breakthrough-2366579.php; Daily Finance, "Glass Ceiling: Solar Startup Wants to Electrify Your Skylights and Windows," 19 May 2010, www.dailyfinance.com/2010/05/19/glass-ceiling-solar-startup-wants-to-electrify-your-skylights-a.

Who will see the greatest opportunities in Advanced Materials Systems?

Value capture in the AMS landscape encompasses more than ownership and control of a particular material or platform, irrespective of industry or size of company. Awareness of market needs and of emerging markets and agility in corporate culture are somewhat intangible but nonetheless important drivers of value capture and creativity — yet are often overlooked by traditional approaches in the chemical and materials space.

Based on analysis of several relevant cases, the unique combination of attributes highlighted in the DTTL AMS framework offers companies in the AMS ecosystem a means to *create* and maximize value in the marketplace. Depending on the particular relationships that players develop across the ecosystem (e.g., business models and IP rights), the *capture* of this value can be isolated or shared more broadly.

The companies that stand to potentially benefit from AMS solutions span value chains across several diverse industries

Again, DTTL's analysis has identified over 6,000 publicly traded companies, each with annual revenues greater than US$100 million, that have the potential to be involved with functional solutions enabled by the AMS framework. These companies span a breadth of industries and end markets, from manufacturing (sized at US$8 trillion globally[78]), transportation (US$77 billion[79]), construction materials and equipment (US$656 billion[80]), construction services (US$2 trillion[81]), machinery (US$230.7 billion[82]), electronics (US$2.5 trillion[83]), chemicals (US$3.4 trillion[84]), pharmaceuticals (US$1.1 trillion[85]), and textiles and apparel (US$3 trillion[86]).

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[78] The Manufacturing Institute, *Facts about Modern Manufacturing*, 8th ed, 2009, accessed on 25 October 2012, www.nist.gov/mep/upload/FINAL_NAM_REPORT_PAGES.pdf.

[79] Dow Jones Industries Snapshot, "Air transportation, industrial transportation, airlines, pipeline transportation, marine transportation, energy, port and harbor operations, crude/natural gas transport, airports, and railroads," accessed on 21 August 2011.

[80] Datamonitor, *Global Construction Materials Industry Report*, June 2011.

[81] Datamonitor, *Global Construction and Engineering Services Report*, July 2011.

[82] MarketLine, *Global Machinery Report*, June 2012.

[83] Datamonitor, *Global Technology Hardware and Equipment Report*, June 2011.

[84] MarketLine, *Global Chemicals Report*, July 2011.

[85] Datamonitor, *Global Pharmaceuticals, Biotechnology, and Life Sciences Report*, May 2012.

[86] MarketLine, *2012 Global Textile, Apparel, and Luxury Goods Report*, May 2012.

Shared value typifies Advanced Materials Systems development

Companies that have leveraged new and unique approaches, partnerships, and business models (see **Decommoditizing the business model: Unleashing the value of Advanced Materials Systems**) to create and capture value using the AMS framework demonstrate the possibilities open to stakeholders across the value chain. Smartphones are an iconic example of systems-level value creation that distributes value across stakeholder networks. The core functionality of smartphones is enabled by basic advances in materials and process technologies in several components (camera, touch screen, advanced memory, etc.). Each individual advance effectively creates value only insofar as it integrated into the functional solution of the resulting "whole-solution technology" (the smartphone); that is, through systems-level integration, each component captures value from specific customer and end market needs. Such systems-level integration affords opportunities for shared value. In the case of smartphones, one leading manufacturer captures approximately 40 percent of the value of its market share as the system designer and enabler; the remaining 60 percent of that value is distributed across the multinational suppliers of the component parts.[87] Interestingly, this approach captured substantial value in nontraditional markets for the company[88] by combining an attractive functional solution made with advanced materials in a system that includes a retail network, online content shopping, and a plethora of applications.

The performance of industrial-products companies that have started to evolve in similar directions indicates value potential is high (see sidebar, **Case study — Composite airframes**).[89] In the case of airlines, commercial fleets in the U.S. alone spend US$4 billion per month on jet fuel;[90] merely a 20 percent improvement in fuel-efficiency across the country's fleet represents a potential US$10 billion per year in cost savings.[91]

Market leaders are turning to AMS partnerships to open new value chains

An agreeability to value sharing among large-market-cap companies is seeing certain manufacturing industry leaders look beyond conventional options for product development. These companies are seeking to reinvigorate growth and innovation through partnerships and collaborations according to the AMS-approach, examples of which are given below:

Cost-competitive production processes through strategic positioning: With funding from the U.S. DOE, Ford Motor Company is developing composite automobile body panels for lighter-weight vehicles,[92] affording greater fuel-efficiency and manufacturable with less energy. Vehicles with composite frames weighing 225 pounds (25 percent less than conventional 300-pound steel frames) would consume 1.6 percent less fuel than standard vehicles, greatly reducing overall fuel usage over the life of the automobile.[93] The automaker has partnered with a large chemical company (The Dow Chemical Company), which is providing the core materials technology, and with U.S. DOE's Oak Ridge National Laboratory (ORNL), providing cost effective process technology for making fibers for the composites. Ultimately the aim is to render composite panels that are cost-competitive with metal

[87] Kraemer, Kenneth, Greg Linden, and Jason Dedrick. "Capturing Value in Global Networks: Apple's iPad and iPhone." July 2011, http://pcic.merage.uci.edu/papers/2011/Value_iPad_iPhone.pdf.

[88] Data from comScore MobiLens shows that iPhone users now account for one-third of the 114 million U.S. smartphone users, www.comscore.com/Insights/Blog/What_is_Next_for_the_iPhone.

[89] Design News, "Boeing 787 Dreamliner Represents Composites Revolution," 4 June 2007, http://www.designnews.com/document.asp?doc_id=226256&dfpPParams=ind_183,aid_226256&dfpLayout=article.

[90] U.S. Energy Information Administration, "High airline jet fuel costs prompt cost-saving measures," 13 June 2012, www.eia.gov/todayinenergy/detail.cfm?id=6670#.

[91] Advanced Materials and Chemicals, *Composite Materials Promise Increased Fuel Efficiency*, Research and data for Status Report 94-02-0040 were collected during October–December 2001, www.atp.nist.gov/eao/sp950-3/budd_co.pdf; ICRA, *Auto & Auto Components Industry: Relevance of frugal engineering to increase in the backdrop of rising commodity and fuel prices*, 2010 to 2011, www.icra.in/Files/ticker/Auto&Auto-Note-June-2011.pdf; U.S. Energy Information Administration, T*ransportation Energy Consumption Surveys energy used by vehicles*, accessed on 25 October 2012, www.eia.gov/emeu/rtecs/contents.html.

[92] Oak Ridge National Lab (ORNL), *Innovations in Manufacturing: Ford–Dow Partnership Linked to Carbon Fiber Research at ORNL*, accessed on 25 October 2012, www.ornl.gov/sci/manufacturing/success_stories/CF_Ford-Dow.pdf.

[93] Advanced Materials and Chemicals, *Composite Materials Promise Increased Fuel Efficiency* (Research and data for Status Report 94-02-0040 were collected during October to December 2001), www.atp.nist.gov/eao/sp950-3/budd_co.pdf.

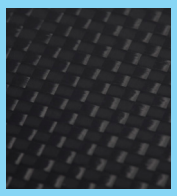
body panels (see sidebar, Case study — Public-private partnership: Carbon-fiber composites).[94]

Strategic partnerships to extend core capabilities and define new markets: A large digital wireless telecommunications company (market cap of US$100 billion) is pursuing wearable health-monitoring technology to permit cost-effective diagnostics and patient monitoring outside of hospital settings. The company is accessing core materials and process technologies through partnerships with an array of smaller companies and start-ups. The intention is to produce high-performance electronics for wear on the body such that they are invisible to the wearer and cost-effective for the health care system (see sidebar, Case study — Wearable electronics). Many of the solutions being developed will also be appropriate for medical diagnostics and health monitoring in emerging markets that currently have little to no access to centralized health care.

Highly differentiated, IP-protected solutions for high-value market: A large international integrated medical device company (market cap of US$40 billion) is developing minimally invasive, implanted medical devices for treating cardiovascular diseases, a rapidly growing market that should evolve to reach over US$97 billion by 2015, up from nearly US$85 billion in 2010.[95] The company is leveraging innovations in materials and in strategic partnerships to target whitespace opportunities. In one case, the company partnered with a start-up to bring bioabsorbable implantable devices to market that treat diseases and then dissolve into the body. Separately,

[94] U.S. DOE, Press Release, "Energy Department Announces New Investments in Innovative Manufacturing Technologies," 12 June 2012, http://energy.gov/articles/energy-department-announces-new-investments-innovative-manufacturing-technologies-0 and www.eere.energy.gov/pdfs/imi_project_descriptions.pdf; U.S. DOE ORNL, *Innovations in Manufacturing: Ford–Dow Partnership Linked to Carbon Fiber Research at ORNL*, accessed on 25 October 2012, www.ornl.gov/sci/manufacturing/success_stories/CF_Ford-Dow.pdf; U.S. DOE ORNL, "Dow team including ORNL receives $9 million for carbon fiber R&D," *Energy & Environmental Sciences Quarterly* No 6 p 1, 2012, www.ornl.gov/sci/ees/newsletters/EESNo62012.pdf; Budd Company Design Center, *Advanced Materials and Chemicals*, *Composite Materials Promise Increased Fuel Efficiency*, Research and data for Status Report 94-02-0040 collected October–December 2001, www.atp.nist.gov/eao/sp950-3/budd_co.pdf.

[95] BCC Research, press release, "Global Market For Cardiovascular Devices To Be Worth $97.4 Billion In 2015," 15 December 2009, www.bccresearch.com/pressroom/report/code/HLC065A.



Case study — Public-private partnership: Carbon-fiber composites

Stakeholders Ford Motor Company, The Dow Chemical Company, and Oak Ridge National Laboratory partner to explore carbon-fiber composites for low-cost, energy-efficient transportation

Unmet need: Ongoing trends related to sustainability and energy-efficiency have resulted in a need to decrease high-volume-vehicle weight and reduce energy consumption.

Material innovation: The manufacture of lighter-weight vehicles calls for carbon fiber to be developed at lower cost and high volume. The Dow Chemical Company (Dow) has partnered with U.S. Department of Energy's (DOE) Oak Ridge National Laboratory (ORNL) toward the expansion of sources of precursors for the carbon fibers (beyond the traditional use of polyacrylonitrile) needed to make composites affordable for the automotive industry.

Process technology: Process and design technologies that enable these materials to be applied to composite automobile frames, as well as manufacturing methods for high-volume applications, will be key for success. Frames made with these innovative designs and manufacturing processes could potentially reduce vehicle weight by up to 750 pounds.

Ecosystem and business model: To best leverage their combined expertise in materials, process technologies, and federal research grants, Ford Motor Company (Ford), Dow, and ORNL established a partnership in April 2012 to develop these lower-cost energy-efficient vehicles, to which the U.S. DOE committed US$9 million in June 2012.

Path to success: This example of an Advanced Materials System was jump-started by an unmet need for more-energy-efficient automobiles. Ford, Dow, and ORNL are merging their abilities to devise a cost-effective solution to this unmet need, ultimately to create shared value.

Source: U.S. Department of Energy (DOE), Press Release, "Energy Department Announces New Investments in Innovative Manufacturing Technologies," 12 June 2012, http://energy.gov/articles/energy-department-announces-new-investments-innovative-manufacturing-technologies-0 and www.eere.energy.gov/pdfs/imi_project_descriptions.pdf; U.S. DOE ORNL, *Innovations in Manufacturing: Ford–Dow Partnership Linked to Carbon Fiber Research at ORNL*, accessed on 25 October 2012, www.ornl.gov/sci/manufacturing/success_stories/CF_Ford-Dow.pdf; U.S. DOE ORNL, "Dow team including ORNL receives $9 million for carbon fiber R&D," *Energy & Environmental Sciences Quarterly* No 6 p 1, 2012, www.ornl.gov/sci/ees/newsletters/EESNo62012.pdf; Budd Company Design Center, *Advanced Materials and Chemicals*, *Composite Materials Promise Increased Fuel Efficiency*, Research and data for Status Report 94-02-0040 collected October–December 2001, www.atp.nist.gov/eao/sp950-3/budd_co.pdf.

the large integrated medical device company partnered with another start-up to integrate electronics onto small catheter devices for minimally invasive detection of sources of disease inside the body. In both cases the new medical devices are enabled by a novel combination of materials and process technologies for a functional solution directly targeting an existing market and unmet need. In each, a highly differentiated solution was protected by an extensive array of patents. Importantly, much of the innovation was done outside of the "four walls" of the large medical device company via strategic partnerships.

Start-ups play a vanguard role in the AMS ecosystem

In addition to large publicly traded companies in the AMS ecosystem, DTTL assessed emerging start-ups, reviewing the portfolios of 18 top venture capital firms known to invest in materials-related technologies (see sidebar, **Venture capital investments in Advanced Materials Systems start-ups**).[96] The venture capital firms were invested in a total of 268 different AMS-related companies; the top 10 areas of focus of these companies, in turn, were: microelectronics and semiconductors, biorefining and industrial biotechnology, solar, batteries, solid-state lighting, medical devices, nanostructured materials, water treatment, displays, and wind energy.

Direct interviews of lead partners at many of these firms about their standards for investment in materials-technology start-ups identified three consistent themes.[97] First, the start-up ideally has a solution that addresses an unmet need in a large, existing market. Second, the start-up's technology solution should be at least "two generations" better in performance than existing solutions (non-price value) and not cost more than existing solutions (price value). Third, the solution should be capable of moving from concept to market in less than eight years and ideally less than five years. These criteria are in addition to the baseline standards of strong IP protection and a capable team. More often the start-up should also already have in place a strategic relationship with a large partner that can help to bring the solution to market and help fund development through equity and other types of investments. This report suggests that start-ups may represent the forefront of the AMS framework. (Consider again the case of the company that captured sufficient value with its solid-state lighting innovation to be acquired by a major materials company; see sidebar, **Case study — Solid-state lighting**).

Regardless of market capitalization or revenue, particular industry, or where a player sits along the value chain, companies seeking to master the AMS approach have a learning curve ahead of them. They will come to understand how to creatively design — and redesign — production processes and business partnerships with integrative solutions that address specific needs. They may well find themselves bolder and more agile in positioning themselves for leadership success in newly emerging economies, particularly through early responsiveness to emerging market trends.

[96] DTTL Global Manufacturing Industry group, February 2012 to October 2012.

[97] Observation by the DTTL Global Manufacturing Industry group through the various research on chemicals and material manufacturers, February 2012 to October 2012.

Venture capital investments in Advanced Materials Systems start-ups

The DTTL Global Manufacturing Industry group examined 18 top U.S. venture capital firms (as at 31 July 2012) that collectively invested in a total of 268 different Advanced Materials Systems-related start-ups (first investment made between 2010 and 2012). Although venture capital is a global industry, the top U.S. firms (in terms of total dollars under management, total dollars invested in AMS-related companies, and top return on investment) do reflect the leading trends in early-stage investments in AMS-enabled start-ups. The top 10 areas of focus for the start-ups point to the attractiveness of Advanced Materials Systems opportunities in the following areas:

- Microelectronics and semiconductors (40)*
- Biorefining and industrial biotechnology (38)
- Solar (26)
- Batteries (25)
- Solid-state lighting (18)
- Medical devices (15)
- Nanostructured materials (13)
- Water treatment (9)
- Displays (9)
- Wind energy (8)

* Number in parentheses is number of start-up companies engaged in each focus area.

Source: DTTL Global Manufacturing Industry group, October 2012.

Decommoditizing the business model: Unleashing the value of Advanced Materials Systems

In hindsight, it seems as though advances in materials technology might be inevitable. In actuality, the business of advancing materials in markets is difficult and risky. To position even the most promising new Advanced Materials System in an emerging or existing industry requires a leadership team to consider additional variables to those of more conventional business strategies and business models. This report has presented new perspectives on open innovation, changing the time scale of idea to solution, systems-level engineering as the primary driver (versus inventions of new compositions of matter), and new opportunities created by tectonic shifts in societies worldwide.

As IP pioneer Hiroyuki Itami argues, "Until technology has been put to use, three types of uncertainty are important to the strategist: discovery does not always result from technology development efforts; markets do not always result from technology development efforts; and newly developed technology can become obsoleted."[98] While these observations are still valid, an addition to this is that the likely success of a promising technology can be made or broken depending on how it is positioned in the value chain, the way it is brought to the market and to emerging industries, and how key success factors and control variables are measured. Said differently, if a business model is meant to describe the rationale and measurement of how an organization creates, delivers, and captures value, and if the scope of value is determined not only economically but socially, culturally, and in other ways (e.g., in terms of sustainability), then an Advanced Material System is as dependent on its business model and the team that delivers it, as on its technology.

Numerous successful materials technologies have been developed and scaled as broad end-market and customer-product plays, especially during the industry-expansion phase of the mid-20th century.[99] The core of "product-by-volume"-based strategies and business models was as much about capital-efficiency as about growth. As a result, business models were not so much a point of differentiation as they were a discipline. While a tremendous amount of commerce in materials should continue to be through product-by-volume business models (commoditized products will yet have their place), the AMS framework argues in favor of innovative approaches to selecting business models and even new business models themselves that preemptively allow for dynamic adjustments once in play.

Surpassing convention: A role for new business models in the AMS approach

Business models are about how a business adds value and makes money. Business model definitions are diverse and many. It is beyond the scope of this report to impose any overriding consensus. The Advanced Materials Systems approach to business models calls for a reevaluation of the role of business models themselves (see Figure 6). Selecting business models within this framework acknowledges that there are important ecosystem components and variables to be considered in commercializing new functional solutions, such as markets, customer behaviors, and environmental forces such as economy, ecology, culture, and IP landscape (see Figure 6).

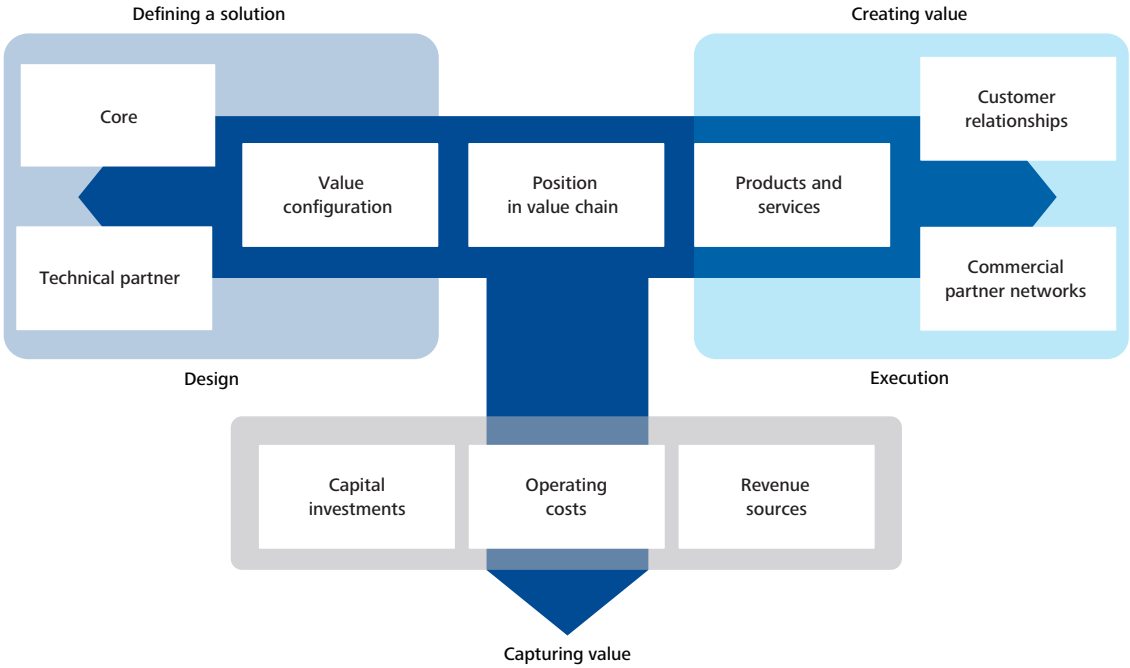
There are critical elements to hold in view while selecting business models to target — ranging from understanding core capabilities within the four walls of a business, to the nature of a company's IP and how that IP would factor into the overall ecosystem, to engagement with technical and commercial development partners and customers. In the AMS framework, a business would define its partner network, if and as required, to better develop and deliver solutions to market, recognizing that both internal and external partner capabilities are anchors to configuring value creation and capture within the ecosystem.

Situating the business in the value chain and against competition brings focus to the design and implementation of conventional business strategy and operating elements

[98] Itami, Hiroyuki and Thomas W. Roehl, *Mobilizing Invisible Assets*. Harvard University Press: Cambridge, Massachusetts, 1991, http://books.google.com/books?id=wEQ2QOaD0twC&pg=PA188&lpg=PA188&dq=Itami,+Hiroyuki+and+Thomas+W.+Roehl,+Mobilizing+Invisible+Assets.+Harvard+University+Press:+Cambridge,+Massachusetts,+1991&source=bl&ots=CFI3SOlgx2&sig=DTUDq6lMzH9GNswuatBBR-BtOKE&hl=en&sa=X&ei=vtaTUMLoPIuP0QGC5oCIDw&ved=0CCEQ6AEwAQ#v=onepage&q=Itami%2C%20Hiroyuki%20and%20Thomas%20W.%20Roehl%2C%20Mobilizing%20Invisible%20Assets.%20Harvard%20University%20Press%3A%20Cambridge%2C%20Massachusetts%2C%201991&f=false.

[99] Observation by the DTTL Global Manufacturing Industry group through the various discussions with chemicals and material manufacturers, February 2012 to October 2012.

Figure 6: Definition of what a business model does



Source: DTTL Global Manufacturing Industry group, October 2012.

(see Figure 6): product and market focus, competitive positioning, positioning influences, location and scale of production, operations to execute on a target market opportunity, identifying and building customers, and developing distribution networks. Meanwhile, allocation of capital and measurement of returns encourage capital to be used efficiently and operating costs to be competitive. If the entire business model framework is optimized, revenues will likely grow.

This walk through business models will be a very familiar story for manufacturing companies — and reinforces the notion that commoditization has spread from product lines to business models themselves. Hence, opportunities arising from the more novel concepts of systems-level design as a starting point, development of functional solutions using extant materials, and delivery of solutions that address a real and urgent market need, call for a rethinking of business models and design.

AMS business models weight the ecosystem perspective heavily

No matter the technology solution, systems-level design is an underpinning, early step toward meeting market-performance requirements to capture market share. As noted, it was most common in the past for companies to first conceive an innovative material or process technology before considering where to market that material. Decisions to proceed and scale up were often based on potential share and cost of products and homologues. As stressed herein, this strategy no longer appears to be sufficient to identify and capture new market opportunities, and AMS players in the current landscape can likely no longer rely on such traditional approaches to maintain or grow market share.

Conventional wisdom, for instance, suggests that a differentiated system based on any given material should likely aim to capture only a circumscribed percentage of the target market, simply because the material might have performance limitations as compared to the requirements of the more demanding segments in the larger market.

The AMS framework proposes a different line of thinking, encouraging companies to continue iterating solutions—without being restricted to only a single, or starting material being used — in order to gain a more ideal initial foothold. That is, AMS principles urge companies to continuously identify how to maximize value and address the largest market need.

In prioritizing smart, systems-level design, the ultimate AMS solution brought to market may or may not be a material that the company itself has invented or previously acquired. A company remaining true to an iterative process of honing material and process technology to optimize an end solution will encounter both different challenges and broader opportunities along the way. Also, because factors like open innovation (in practical terms, here referring to scientific and value chain partnerships) and speed to market are such decisive variables in the success of AMS, individual business models in this space may look very different, even with the common elements described herein.

Flexibility: AMS business models are preemptively responsive to "triggers"

When changes arise during the development process, an effective response requires flexibility and agility — especially for key market deviations and critical decision points (i.e., occurrences, milestones, technical hurdles, market changes, etc., herein referred to as "triggers").

Triggers tend to have both a technical and commercial dimension. Emergence of a new market or the discovery of a technological element may point to a change in focus due to a new, better fit elsewhere, or the market may suddenly be subject to fundamental change, such as through introduction of a government subsidy.[100]

Internal and external triggers are likely to be encountered in AMS-solutions development. Preemptive anticipation of, and agile response to triggers may enable certain strategies, require strategies to be altered, sway decision pathways, or strike other opportunities or options from consideration altogether. Internal triggers, particularly, may become milestones that guide, gauge viability, or set the progress of commercialization efforts. All triggers can have a fundamental and creativity-inducing impact on how companies focus on the market and innovate systems to address new market needs. The AMS framework stipulates a means of addressing these even while AMS solutions are in development.

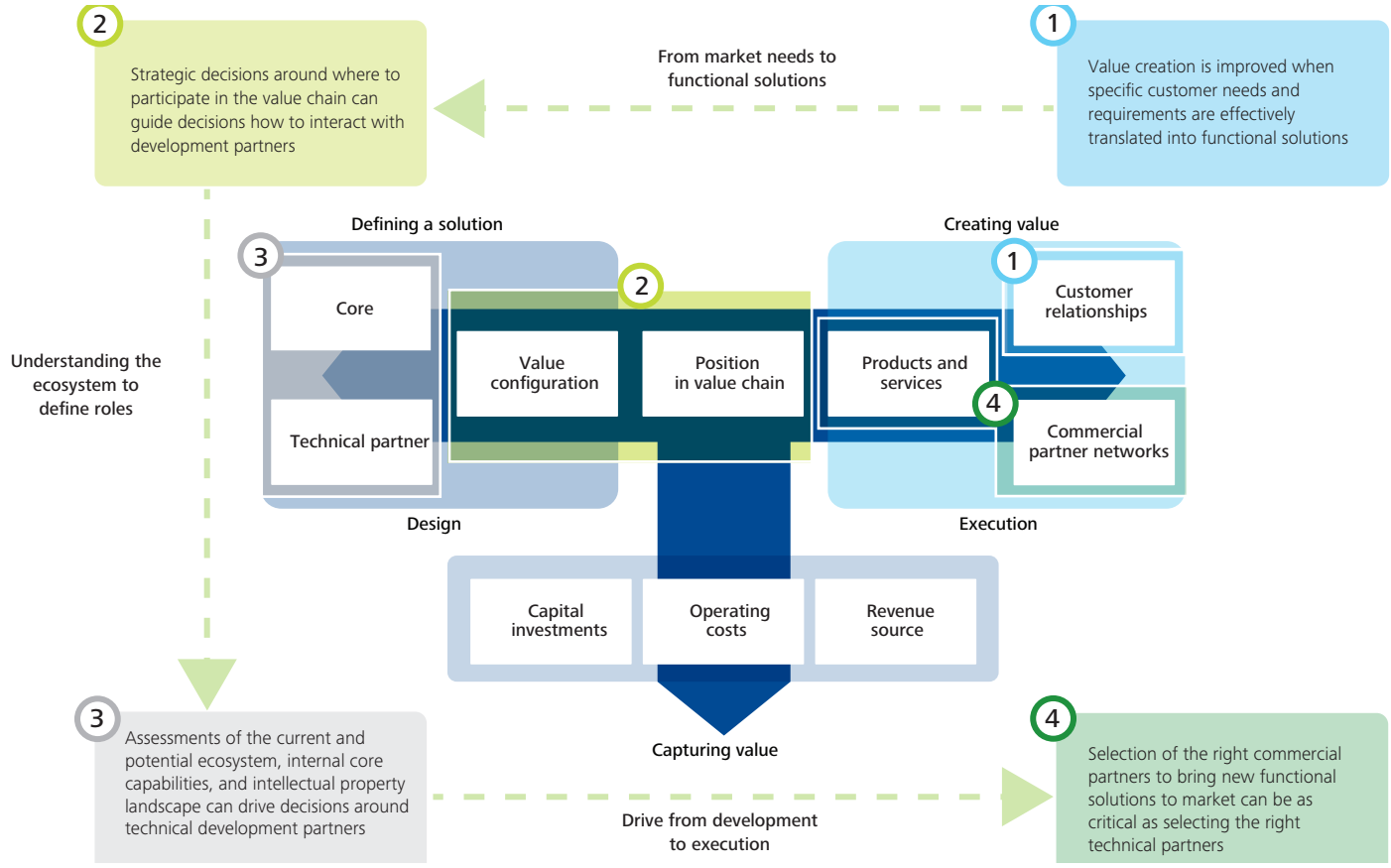
AMS business models as dynamic systems for value creation

An AMS approach to business models (see Figure 7) overlays several key concepts onto conventional approaches (see Figure 6), by considering standard variables in light of specific aims, outlined below.

- To understand and translate market requirements into a viable functional solution designed for delivery within a system; that is, to design a system for the material solution and a system for delivery of the solution.
- To establish a concrete understanding of the customer base and clear definition of potential performance requirements such as cost and functionality. Once these parameters become clear, companies evaluate and exploit their core internal capabilities, as well as those available in the broader ecosystem.
- To establish a differentiated network of capabilities that, along with IP, creates competitive barriers. In many cases, given the magnitude of the "problems" (market needs) that AMS solutions are positioned to address, it may be necessary to consider viable, and potentially complex, collaborative networks as a business-model fundamental, given the risks of going it alone. In some cases formal acquisitions and ventures may be better alternatives than less formal measures (i.e., partnerships) as a means of market and technology access. Of course, these decisions are heavily influenced by the IP position of various players in the ecosystem, and mapping this

[100] In alternative energy solutions, for instance, infrastructure has not kept up to speed with technical innovation, i.e., the technical capabilities have often been shown in proof-of-concept and demonstration-scale production, but cost-parity through volume production and market demand have not yet been realized (see, e.g., Bracmort, Kelsi, *Congressional Research Service Report for Congress, Meeting the Renewable Fuel Standard [RFS] Mandate for Cellulosic Biofuels: Questions and Answers*, 11 January 2012, www.fas.org/sgp/crs/misc/R41106.pdf). Given energy-security concerns, governments have been proactive in introducing subsidies and funding for alternative transportation fuels (see, e.g., www1.eere.energy.gov/biomass/financial_opportunities.html). The intent has been to bridge existing economic gaps at the critical large-capital-investment stage, in which alternative-energy markets yet find themselves before they can bring mass-scale refineries online.

Figure 7: The Advanced Materials Systems approach to business models expands on conventional approaches with a focus on bringing functional solutions to market and iteratively assessing performance along the way



Source: DTTL Global Manufacturing Industry group, October 2012.

early on to create clarity of how the market works and where constraints exist is critical.

- Once the above parameters are understood, build out a value chain position and value network that can be configured for flawless and consistent execution in the market and as a foundation for further development.

The AMS perspective on business models also reflects the collective decisions about the "who, what, and how" in going from targeted needs to commercializing a functional solution. Therefore, business models in this view are neither, strictly, templates nor frameworks but rather a dynamic collection of tactics along the development cycle. The process starts with definition of a guiding strategic philosophy (see Figure 8) that could be as broad as "revenue before cost" or "better before cheaper." With priorities established for making strategic choices, one moves into the process of functional solution and system design. This involves asking a series of questions about who does what (e.g., "Who designs? Whose materials? Who manufactures?"), each decision steered by strategic objectives.

In the AMS framework, successful businesses cannot hold onto rigid approaches and methodologies for system development and commercialization, even if it means going so far as to change, mid-development, a specific material one has started with. Companies may need to evolve a solution and their perspectives on business models they are targeting to a second, third, or *n*th

iteration before actually taking it to the market. Even in absence of triggers (unanticipated variables arising once development has started), the flexibility called upon by the AMS approach should be evident from the outset: having identified an ideal business model or role in the ecosystem to maximize value capture will not likely override a lack of core capabilities that would argue against commencing development or business model execution at all. Further, an anticipated partner — one that may not be open to partnering or acquisition — may yet fill that market spot. To the best degree possible, AMS thinking preemptively accommodates for all contingencies.

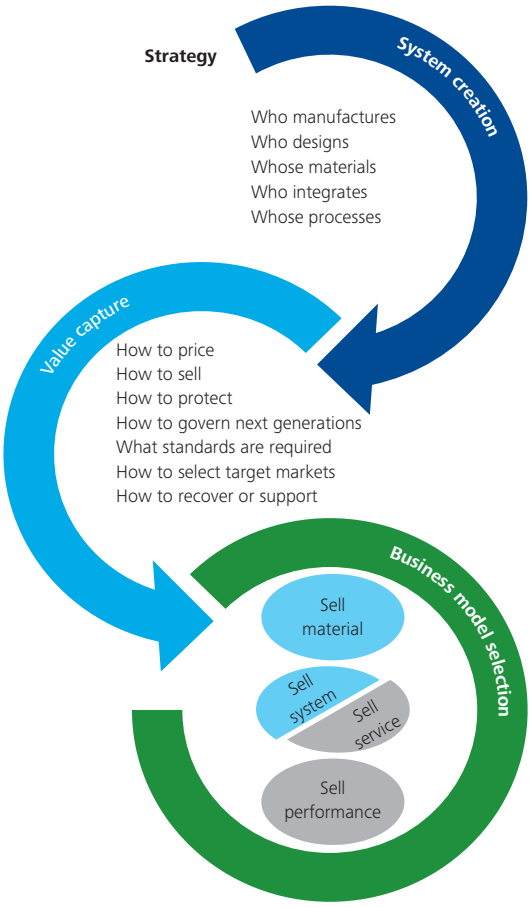
Open innovation: Partnering to impel technical and commercial development

In the past, materials companies seemed to focus mainly on what was achievable in-house. When a desired innovation could not be realized internally, some might choose to find contract developers or development partners, in order to share the risks and rewards of product/process development; but a large majority of companies might abandon an idea altogether if they could not be in dominant control of the main aspects of any venture.

Information flows, analytics, and exposure to open architectures have evolved to allow Advanced Materials Systems players to more comfortably and proactively build partnerships in an ecosystem or to build out an ecosystem itself. Such alliances and the business models behind them are increasingly common. Partnerships between mobile phone makers and network service providers, between satellite radio networks and automakers, and between aircraft manufacturers and carbon-fiber composite fabricators (see sidebar, **Case study — Public-private partnership: Carbon-fiber composites**) exemplify this option.

Ultimately, in selecting partners, the best possible capabilities across technical and commercial development should be sought, whether in-house or externally. Still, 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 at stake. Nonetheless, external experience and resources are often available to access strategic technical know-how and new technological capabilities, including through engagement

Figure 8: Business model selection strategy



Source: DTTL Global Manufacturing Industry group, October 2012.

with government entities and universities. As such, AMS partnering networks are not only worthy of consideration but often the source themselves of differentiated and protectable new platforms.

Ultimately the AMS approach summons companies to think very differently about risk and exposure, both in terms of cash and invested capital. A large chemicals company, for instance, may come to market with a new solution but may not, in the end, be the principle manufacturer of the initial-stage materials, if another party can be identified that has a more cost-effective production platform. This point may be of particular relevance to big process industry companies. A healthy humility and goal-focused intelligence will best inform partnership strategies to potentially create new and immense value streams that could dissipate struggles with massive capital invested in infrastructure and generate continued returns year over year.

AMS opens options for IP protection and differentiation

Choosing to partner within an AMS open innovation framework begs the consideration of value protection within the partnership. While challenging, IP should be a core component of a company's strategy (see sidebar, **Case study — Solar window technology**).

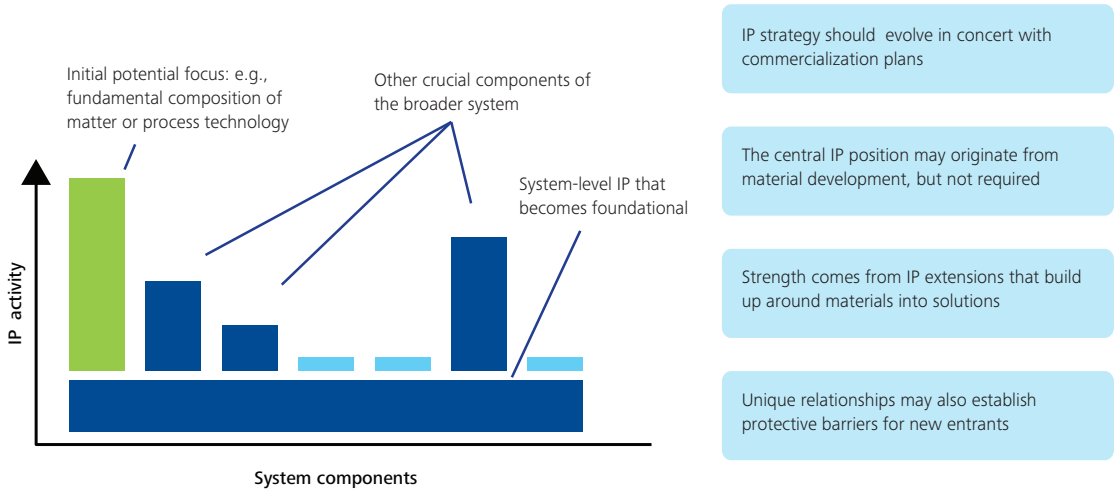
Clearly, as a company moves down different paths into developing new systems and pursuing different business models to capture value beyond "merely" a material itself, strong IP will help to protect against loss of value to other players in the space. Ideally, players will protect their positions from the start (early development), not just the point of market entry. If one has devised a new molecule, AMS component, or whole solution, it would be wise to patent not just the specific development proper but, preemptively, the fullest extent of applications that development might see; that is, to protect both materials and applications (see Figure 9). An effective IP strategy not only provides a good defense to value, but could also become a key component of an offensive market strategy. Business models within an AMS framework incorporate shared value and, therefore, call players to effectively maneuver IP concerns with collaborative stakeholders. While posing challenges, there are strategic benefits to be gained through targeted partnering activity.

The differentiation afforded by strategic partnerships and relationships that are difficult to replicate can be an important adjunct to IP infrastructure, setting a company's AMS apart from other potential competitive solutions. This type of strategic positioning through partnerships may prove even more protective than IP: it is usually incredibly difficult to replicate the leverage gained through collaborations strategically entered for the specific, unique contribution of given companies or organizations (for instance, a start-up's IP-protected microorganism production platform integrated with a leading chemical company's market and distribution channels and end-product design, integrated with a major national lab's biocatalytic enzyme).

In cases like the aforementioned partnership between Ford Motor Company, The Dow Chemical Company, and U.S. DOE's ORNL, the unique combination of specific players largely defines this system, one whose capabilities any potential competitor would be hard-pressed to duplicate as they would not have access to the same platform resources.[101] Intelligent, preemptive selection of partners and collaborators can enable a certain "x factor" inaccessible to would-be competitors. Among the national labs and big original equipment manufacturers (OEMs), for instance, there may only be a few possible partners that offer a particular competence. By combining platforms,

[101] Strategic partnerships can erect substantial technical and commercial barriers against would-be competitors but the businesses models describing such partnerships must be well thought-out to optimize agreeable value capture across the partnership. The aim of the unique partnership between Ford Motor Company, The Dow Chemical Company, and U.S. DOE's ORNL is to drive low-cost production of materials for vehicle manufacture. Technical development is being supported by a US$9 million U.S. DOE grant, as part of a U.S. government program to improve energy-efficiency through advanced manufacturing; that program focused on unmet needs and supported unique ecosystems and business models very much aligned with the AMS framework. The ultimate path to success in that partnership may lie in how the three organizations work together to bring the solution to market. Within an AMS approach, the business model must define who will specifically develop the experience in engineering the carbon-fiber composites, both from a manufacturing and design perspective. Other successful players who have attained value in the market for aircraft-frame composites had to develop their own tools for modeling large composite structures, as well as process technologies for laying those composite materials over very large areas, which they largely outsourced into their supply chain. The takeaway is that such partnerships identify how constituents will work together to produce that supply chain and who will earn which parts of the value created in the new AMS ecosystem.

Figure 9: Protected, differentiated solutions within an Advanced Materials Systems framework consider intellectual property (IP) activity and strategic partnerships



Source: DTTL Global Manufacturing Industry group, October 2012 and data from Capital IQ accessed on 29 September 2012.

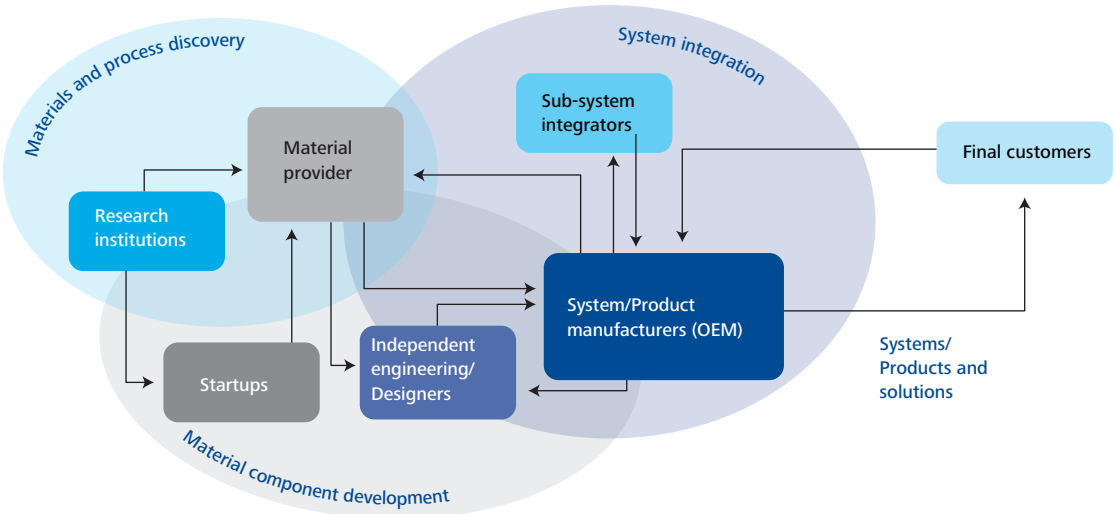
through partnerships with players who are clear leaders in a particular space and whose success in a market or type of innovation would be challenging to emulate, strategic partnerships afford preemptively protective access to skills, capabilities, resources, and, potentially, markets themselves (e.g., if one partner is a state-owned entity).

In sum, according to an AMS framework, value creation and distribution for players seeking the highest-value opportunities can be achieved organically, i.e., by developing in-house IP with a company's own materials as part of the Advanced Materials System, or through partnerships, licenses, or acquisitions (if the highest-value markets are not otherwise naturally accessible), all the while intelligently garnering patent protection, whenever possible and, as relevant and to the extent available, establishing unique relationships to create competitive barriers.

Power networks: Exploiting points of value across the ecosystem

Figure 10 illustrates the simplified view of a potential AMS ecosystem, showing inherent complexities and possible value-creation opportunities. "Materials and process discovery" (Figure 10, upper left) outlines several avenues by which new matter or molecules are developed. Certain entities may demonstrate excellence in formulating new compositions of matter and processes, such as universities like MIT and Stanford, and national labs worldwide — such as the U.S. DOE's ORNL, Idaho National Laboratory, and Lawrence Berkeley National Laboratory; Australia's Cooperative Research Centres; National Research Council of Canada's National Institutes for Nanotechnology and for Biological Sciences; the French National Center for Scientific Research (CNRS); and numerous others.

Figure 10: Overview of the Advanced Materials Systems ecosystem



Source: DTTL Global Manufacturing Industry group, October 2012.

From a corporate perspective, leading material providers, product makers, and system integrators devote a small but important fraction of total resources to "pure innovation." Figure 10 describes "Material component development" (see Figure 10, bottom center), which has seen a new set of players focus on commercial development of novel materials. Such stakeholders include start-ups and smaller companies that develop system components or even complete systems, incorporating new materials and technologies into broader solutions. This space also includes independent engineering and design firms that contract or engage with system integrators to bridge gaps in incorporating a solution in the market. "Systems/ Products and solutions" (see Figure 10, lower right) subsumes system-integration activities (which often involve large OEMs for industrial products), transportation, and any other players that help transition materials from business to consumer.

What Figure 10 and this section highlight is that, in this ecosystem, not only the entities themselves but their interactions determine value creation and capture. Historically, system integration in materials and component development took a more myopic view (for example, players collaborated only directly upstream or downstream of their position along the value chain). With the AMS approach, companies instead establish networks that integrate different avenues and optimize all components in the value system. This sort of evolution calls for players not only to maneuver the existing value chain and the Tier One (direct supply to OEMs), Tier Two (supply to suppliers to OEMs), and Tier Three-plus relationships fostered in the past, but to boldly create a unique ecosystem, with new kinds of partnerships and strategies, catered to market need.

Value-capturing innovators in AMS apply creativity to attracting talent and measuring and incentivizing performance

In maximizing resources across the AMS framework, from materials to partnerships to business strategy, the importance of an adaptive, forward-thinking approach to human resources cannot be sufficiently stressed. Fresh-mindedness breeds innovation, and the AMS framework specifies strategies to develop the right talent to enable success. Looking to best practices among creative start-ups, certain strategies stand out that, adapted and implemented, will allow AMS players to emulate the creative cultures that see start-ups taking their concepts to market with such rapid, effective agility. These best practices include:

- Selective recruitment
- Flat-lattice hierarchy
- Contribution-based development
- Creative development

In *selective recruitment*, players look for candidates with a mix of business skills, personality traits, and the ability to tolerate ambiguity. Efficacious AMS approaches identify, motivate, and incentivize self-starters who can work without a lot of direction and structure and independently identify business needs. Companies should hold out for the right fits for these positions. This is a very different approach to that taken by companies with legacy hiring cultures that focus more often on well-defined job specifications than the unique beneficial qualities of potential hires.

The *flat-lattice hierarchy* is a concept drawn from the successes of certain smaller companies and start-ups that operate largely without assigned job titles among staff. These organizations instead adopt flexible teaming structures that encourage peer accountability and allow staff members to take on a variety of leadership roles. Any individual with a development concept is given freedom to explore the idea or initiate product development within a healthily, intraorganizational competitive environment; the best ideas and concepts rise to the top. The concept-initiators are then given responsibility to recruit the development team. This encourages staff not only to come up with good ideas but also to assume the leadership of building and leading the best in-house teams capable of bringing those concepts to fruition.

Contribution-based evaluations focus on employees' capacity to make meaningful contributions rather than solely on bottom-line impact. Employees receive credit on their evaluations for completing trainings that enhance their ability to contribute to their teams. Further, ratings are not only tied to positive contributions but to the ability of players to extract lessons from both successes and failures, which encourages risk taking and entrepreneurial mind-sets to innovative ideas.

Creative development encourages employees to focus on their interests and passions through side projects, thereby keeping them engaged in their work and fostering an optimal environment for spurring innovation. With this approach, "sponsorship" of "pet projects" provides internal funding, other resources, and allowed time to pursue early-stage development initiatives typically associated with significant early-stage risk and not ready for full investment. The expectation is that such projects have the potential to create value.

This strategy broadens leadership-development tracks; e.g., allowing technical persons to develop some marketing skills or even to evolve a hybrid role combining technical and business development responsibilities. This approach may expand the capacity for demonstrating value and realizing innovation, as it encourages creativity and innovation in support of direct bottom line impact.

Conclusion: Reigniting growth

This report calls on manufacturers and integrators of materials to boldly rethink value creation and the means of achieving it, to revisit innovation, and forge new frontiers of opportunity. It proposes building upon and expanding beyond traditional mind-sets of product development, partnering, and business models. Opportunities exist to successfully approach and fulfill global unmet market needs that require new functional solutions — especially functional solutions that incorporate existing materials, through inventive processes, into differentiated offerings. Substantial market share stands to be captured across numerous segments by companies willing to transcend and venture beyond conventional paradigms.

The Advanced Materials Systems approach is not a new industry pursuit but a distinct roadmap to guide future innovation. *Reigniting growth* has aimed to delineate the major anchors through the Advanced Materials Systems framework and endeavored to synthesize observable data and trends in a developing area. This report has explored discernible prevalent aspects of the Advanced Materials Systems framework as it is being adopted by companies to date:

- Open innovation encourages differentiated AMS solutions but makes IP and value-sharing arrangements more complex.
- Worldwide, end user needs, increasingly defined by global, shifting megatrends, are defining new markets while demanding deft balancing of performance and cost.
- Systems-level design and process innovations like nanotechnology, industrial biotechnology, and additive manufacturing could provide an abundance of new capabilities, but their adoption can be thwarted by company cultures hesitant to assume the associated risks.
- Collaborative partnership networks may expand as players increasingly see the value of combining capabilities and assets to shorten development times for whole solutions. This may stretch some boundaries between large-market-cap companies, start-ups, universities, and government research labs.

For those willing to leap forward with the new growth possibilities the Advanced Materials Systems approach offers, adaptive business models will be needed that build on the strength of successful strategies to date while heavily weighting the new complexities and breadth of possibilities.

The foundations for the future of Advanced Materials Systems appear to be building in an increasing number of companies, large and small. Tenets of the Advanced Materials Systems approach are being developed in labs and funded by governments. Worldwide, university scientists and investors, as well as corporations and entrepreneurs, are looking deeply at the potential of systems-level thinking and multidisciplinarity as catalysts for technology breakthroughs. New open innovation partnerships are announced with increasing frequency.

Still, it remains to be seen whether the Advanced Materials Systems approach will reach critical mass sufficient to become mainstream. Certainly the global economy can use a growth engine; certainly, society will continue to demand solutions and products that solve problems and elevate standards of living. In fact, end markets requiring Advanced Materials Systems are projected to reach over US$7 trillion in revenues by 2030, from under US$3 trillion today, and the materials provider contribution alone is expected to grow from less than US$100 billion currently to US$400 billion in the same time period (by 2030).[102]

The *Reigniting growth* report begins to decode Advanced Materials Systems, to examine the role Advanced Materials Systems play in meeting the needs of a growing world and to elucidate the composition and dynamics of present and future ecosystems. While this report has documented an encouraging set of examples of Advanced Materials Systems and approaches, it has also presented the complexity, degree of difficulty, and scarcity of certain capabilities. *Reigniting growth* further discussed a new managerial framework in which cycle times for new innovation will compress and in which solution development could depend both on effective partnerships and the need to coexist with potentially powerful systems integrators (or become one). The report has also questioned whether companies might find success best

[102] World Economic Forum in collaboration with the DTTL Global Manufacturing Industry group, *Future of Manufacturing: Opportunities to drive economic growth*, 24 April 2012, www.deloitte.com/futureofmanufacturing.

attained by venturing further into the global value chain and occupying unfamiliar positions in the ecosystem.

These and other issues explored herein create a tension and uncertainty about whether Advanced Materials Systems will be adopted either universally, pervasively, or minimally among a small few leading companies — the latter, as has been the case until now. The future view will be the subject of the next phase of the DTTL Global Manufacturing Industry group's Advanced Materials System research. The forthcoming study will highlight progress, analyze future potential and trends, discuss possible scenarios for Advanced Materials Systems evolution, and explore enabling questions such as:

- *How will companies decide whether an Advanced Materials Systems approach makes sense? What are the prerequisites? How would a company best get started? How will value be ascribed and measured?*
- *Will the dominant nature of IP in the materials industry shift from claiming compositions of matter instead to functional solutions, business methods, and go-to market approaches? How might a shift in IP focus and open innovation partnerships change the basis of competition?*
- *Might the scope of current materials and process technologies support a viable open-source infrastructure, as in the software industry? Would such an infrastructure be accessible by players across enough industries and segments to allow assembly of Advanced Material Systems solutions?*
- *Will norms or standards emerge to reflect the impact of compressed cycle times from idea to market? From where would such standards arise? How will companies adapt to faster cycles and a shift to a solutions-focus, as developers and as a competitive threat?*
- *As partnerships evolve and collaborative networks become more common and more broadly accepted, will coalitions become important? How will current public-private partnership models evolve?*
- *What changes will be necessary in companies' methods of managing market and technical risks in the development of system-level solutions? How can ecosystem risk be better understood? How will competitive response be determined?*
- *How can the markets of the future be explained, and how will they be defined? Will emerging industries be analyzed through the same methods as today? Will the solutions focus of Advanced Materials Systems alter the way markets are understood and managed?*
- *What will be the impact of successive waves of innovation and solutions-focus? Where will the technology breakthroughs of the future develop, and how will those breakthroughs influence the Advanced Materials Systems approach?*

Inasmuch as commoditization of most, if not all, 20th century materials is probable, developers and assemblers of materials have powerful motivation to find new ways to reignite innovation and growth. While it is tempting to consider Advanced Materials Systems solutions as a potential approach to this end, it is important also to weigh the profound change and disruption the framework would usher in. Few companies, having invested significant efforts to capture as much value as possible from current platforms, will likely be able to fully change course without massive changes in their portfolios. But whether or not an Advanced Material System or other approach is adopted, it is clear that scores of companies across numerous manufacturing industries are at a crossroad between honoring the core business and growing (or growing enough). The opportunity is to reignite growth and the innovation of materials to meet emerging and future needs of markets and customers.

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