Future materials and fire safety

Report by the
Copenhagen Institute for
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Table of contents

PREFACE

The Danish Institute of Fire and Security Technology (DBI) contracted the Copenhagen Institute for Futures Studies (CIFS) to conduct a global analysis on the future of materials and fire safety in the building and construction industry. The analysis has two purposes. First, it is intended to help DBI be on the leading edge of developments within global materials research and developments in the building and construction industries. Second, it is intended to create a platform for dialogue concerning future materials and fire safety with SME's, large organizations and public authorities.

The analysis is a part of the DBI project "Risk Assessment of New materials". The aim of the project is to develop a simple and efficient method for introducing new materials in the building industry and in the maritime sector and to make it easier to apply a performance based approach on projects.

The project "Risk assessment of New Materials" is co-funded by the Danish Agency for Science, Technology and Innovation, and will be running to the end of 2015.

INTRODUCTION: HOW 'NEW' ARE NEW MATERIALS?

Despite growing interest in materials science, engineering, architecture, and building construction, the notion of the new materials is somewhat of a misnomer. In fact, when discussing new materials today, more often than not, we are simply referring to conventional materials that have been reengineered or repurposed in some distinct way.

Materials development for structural and construction environments is not in a radical innovation phase, like it was during the 1950s – 1970s, according to interviewed subject-matter experts. Engineers and materials scientists lack an external driver that would push them in that direction. "In the materials world, they say we need another 'Apollo moment' or 'Sputnik moment' – when the space race drove materials science in many areas towards new development. There needs to be some sort of driver or push that will trickle down throughout the whole value chain. It is rarely one guy in his lab who comes up with a discovery that transitions all the way to global application." [3]

Sustainability and the low-carbon agenda, however, could provide a new impetus for materials development, according to interviewed subject-matter experts. The sustainability agenda is leading to:

- development of materials that are more resource efficient and are more easily up-, down-, or recyclable
- greater understanding of materials, materials systems, and materials performance through life-cycle analyses
- advancement and application of more bio-based, bio-enhanced or bio-inspired materials in buildings to replace less resource efficient or toxic non-renewables

Materials science is to some extent in an optimization phase – there are few truly revolutionary materials that are currently being developed through to commercialization. Rather, the focus today is on enhancing the performance and functionality of conventional materials and the performance and functionality of materials systems. In building and construction industries, engineers, materials scientists and designers continue to research and develop new, scientific processes, materials properties, and applications or design concepts for the following types of materials:

- Concrete
- Glass
- Timber and other bio-materials
- Metals
- Polymers (natural and synthetic)

New, advanced, and sometimes very technical processes are being developed in order to open up otherwise inaccessible properties of conventional materials to engineering[3] in order to bring existing materials together in new ways.[6] These technical processes and the resulting materials can be categorized into the subsequent areas:

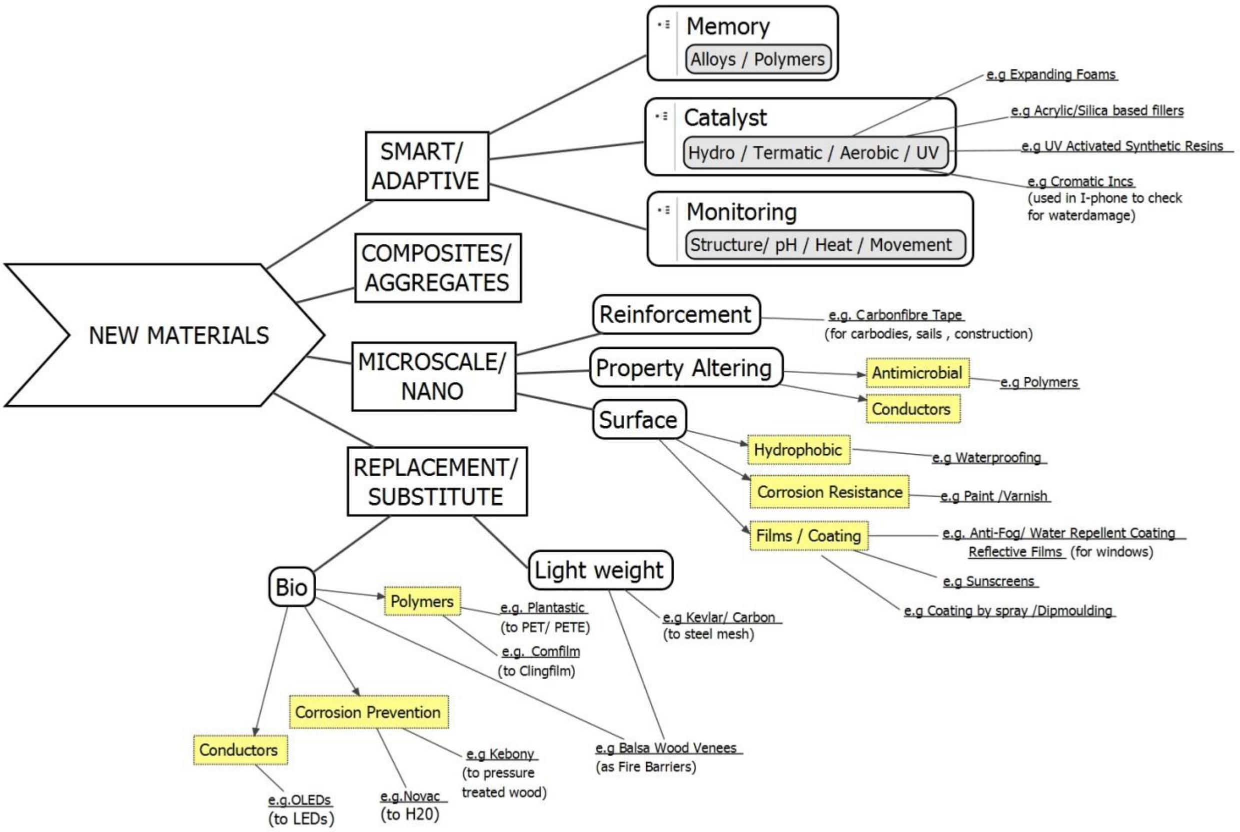
- Smart materials
    - Chemical actuating processes and integrated materials systems
    - Smart tech monitoring, analysis and reporting
    - Property changing materials responsive to stress, temperature, movement, and electricity
    - Shape-memory and self-repair alloys and polymers
- Nanomaterials

    - Nano-processing and reverse materials engineering
    - Reinforcement
    - Property altering
    - Surfaces
- Replacement materials
    - New and efficient down-, up-, and recycling processes
    - Bio-material alternatives
    - Less resource-intensive substitutes
- Composite materials
    - Advanced fabrication processes
    - New, optimized composite materials derived from existing conventional systems

Innovation in materials in the building and construction sectors is looking for procedures to make materials or the design of a materials system as effective or functional as possible. This includes having environmentally, economically, and socially improved life-cycle impacts, and the ability to control cost. To illustrate, concrete buildings are now being optimized using very sophisticated computer analysis: there are a lot of unbounded post-tension slabs, a lot more pre-stressing, a lot more pre-fabrication, and much higher concrete strengths.

For individuals and scientists alike, there is a growing interest in furthering our knowledge and understanding of conventional materials beyond simply the superficial or surface level. One interviewed expert described this period as follows: "We are witnessing a phenomena today where people are starting to 'hack' their devices and are repairing their own things. It is liberating in a way akin to the explosion of hardware stores and do-it-yourself manuals in the 1950's and 1960's."[9]

Figure 1 New materials development (Source: CIFS, 2014)



Materials development is a long and arduous process a slow process that typically takes many decades, yet despite the array of challenges, there is much promise for new materials, properties, and processes in the future. In the early stages of materials research, fire and other testing is rarely done as it is believed to limit the scientific scope or potential of a new material. The closer a material gets to commercialization the more important it becomes to undergo fire safety characterization and performance testing. However, when and to what extent fire safety and performance testing is conducted is application- and context-specific.

In general, the optimization of materials often poses significant challenges for fire safety. For example, reduced concrete covers, the use of high-strength steel (which loses strength very quickly when exposed to extreme heat), and the likelihood of explosive spalling of high-strength concrete in fire are some of the major concerns identified by experts.8 Despite many relevant issues in regards to optimization and fire safety, Luke Bisby, Senior Research Fellow in Structures and Fire at BRE Centre for Fire Safety Engineering, believes that in the future, concrete will be even further optimized in order to have higher concrete strengths, and pushing the limits of design even more.[1]

There is a general understanding among interviewed experts that increased collaboration and a greater use of networks is required. There is, however, little consensus to the role of various stakeholders should play in the development of new materials. There are a variety of interests at play in developing new materials for any application. Be it political, industry-driven or otherwise, they all have an impact on what types of materials get developed when, and how quickly. It is this understanding among stakeholders that recognizes a growing need for knowledge-sharing, resource deployment, market innovation and time-to-market advantage that is driving the development of value networks and business ecosystems.

The regulatory approaches towards construction, buildings, materials, and fire safety vary greatly from country to country and often within countries. Approaches to fire safety regulation and materials used in buildings are historically contingent on the local operating context.

This lack of cohesion among regulatory bodies limits innovation and market penetration for new materials and materials systems. The challenge for regulatory bodies with new materials is to find the right balance between prescriptive and performance-based regulations.[1] Governments need to recognize the critical importance of appropriate regulation in promoting innovation in the building and construction industries – without it, innovation is not likely to occur. [1]

There are a range of obstacles that challenge the successful introduction of new materials at every stage of development in the infrastructure and buildings industries. Experts refer to these obstacles collectively as the 'valley of death'. The valley of death is the gap between science and research, industry and application.[3] Connecting research in materials science to real world applications through commercialization is the most challenging hurdle to overcome. Interviews with experts identified six obstacles that must be overcome before new materials or material processes can make it into the market. These obstacles include risk mitigation, industry conservatism, the limitations posed by pre-existing infrastructure, the lack of communication and education, and difficulty in scaling new materials for mass production.

More often than not, innovative science is discovered and technologies are created that fail to find their way into commercial use. Commercialization of new materials requires finding the right balance between affordability and complexity. Materials scientists and engineers will have to find the "affordable complexity" for a given application. For building and construction applications, new materials or materials systems are used for new structures or for repairing and refurbishing existing structures. In high income countries, for example, most of the building mass already exists, so materials for refurbishment purposes will come to dominate.

SUSTAINABILITY – THE NEW "APOLLO PROGRAM-LIKE" DRIVER?

When discussing new materials for building and construction, sustainability is the most cited development driver for according to subject-matter experts interviewed. Sustainability is an important driver shaping research agendas that will restructure the materials industry and is part of a fundamental paradigm shift at the societal level towards more conscious consumerism by governments, businesses and private consumers.[7] Many regard the issue of sustainability as the logic driving the next phase of radical materials innovation. However, unless the sustainability agenda gets full government support– like the Apollo space missions did in the United States – its immediate impact on the industry will be blunted.

The challenge for new materials research is if they can produce new materials that have similar or improved performance compared to existing conventional materials at similar or lower costs: The ultimate goal is to build a building that has no environmental impact, is self-sufficient, and cost-efficient to maintain. [7] According to Christopher White, research chemist for the Materials and Structural Systems division at the National Institute of Standards and Technology (NIST), "the two solutions are to innovate on materials and engineering, and both are occurring right now." [7]

As the issue of sustainability continues to grow in importance, so will the potential for new materials development. The sustainability agenda as it pertains to materials focuses on reducing overall environmental impact of a specific material or on how a material as part of a broader system of materials could help lower the overall environmental impact of a building or complex. Experts spoke of how the increasing prices of raw materials affects the need for down-, up-, and recycling processes and developing less resource-intensive materials; of how the low-carbon agenda influences the way materials are used and buildings are designed; of how predictive life-cycle analyses for buildings are being developed to increase cost-efficiency; or how using new materials as systems could shape the overall energy efficiency of buildings.[1]

In buildings, potential owners, tenants and residents are developing a preference for selecting more sustainable solutions. According to the 2012 *World Green Building Trends* report, the number of "green" or "greener" building projects has grown steadily since the journal's first publication in 2008. Twenty- eight percent of surveyed architects, engineers, contractors, consultants and owners reported that over 60 percent of their work was involved in green projects in 2008. In comparison ninety-two percent of the respondents of surveyed architects, engineers, contractors, consultants and owners were involved in at least one green building project in 2012.

Green voluntary standards are gaining traction. Experts opine that the industry's voluntary standards today are likely to be the regulatory requirements tomorrow.[7] The pursuit of green certification is indicative of the growing commitment to cleaner, lower-carbon development, and the institutional acceptance of energy efficiency, more sustainable living, and responsible waste management for buildings and cities.

There is growing market potential for sustainable materials, sustainable materials systems, and sustainable design concepts, which in turn encourages development in materials processing. Thus, much research in materials today is driven by these demands and centered on sustainable objectives.[7] Many companies now see their sustainable product lines as the fastest growing product lines in their portfolio, as the end-users' demand for it increases.[7]

This demand is pushing research in materials development. The challenge, however, is to make sustainable materials and materials systems cost competitive with existing products on the market. This requires a radical technological breakthrough in how bio-materials or nano-structured materials are developed that makes them as cheap to produce as traditional alternatives. Elsewise, government intervention is required, through subsidies (such as programs for solar panel adoption) or taxation schemes (a carbon tax, for example).

Developing and introducing sustainable solutions to the market is a gradual process. When Laurence Kemball-Cook, CEO and Founder of Pavegen Ltd., describes the development of his company's sustainable flooring product – tiles that convert kinetic energy from pressure (footsteps or carts travelling across the floor) to electricity – as a 'work in progress': "We started with sustainable materials, which are cost efficient. Pavegen tiles are made from recycled truck tires, which are 95 percent recycled material, sourced and transported only within the UK. They have a very low energy cost due to transport. However, we also use steel at the moment, which comes from Italy, is cut in Romania, and shipped to the UK. We know it is not very good and we recycle the steel when we can. But at the moment we need to scale in order to be able to invest in tooling that would allow us to use a recycled polymer as a main material. That is our objective and when it happens, we will have a truly low carbon product made from low carbon materials."[10]

There are a number of funding programs and research initiatives - such as the *Horizon 2020* grant from the EU Commission - that prioritize low-carbon or sustainability-driven projects, and this is likely to increase. There has been a move in many research communities – particularly in the United Kingdom and China – towards developing bio-materials (see bio-materials section) and optimizing conventional building materials – concrete, wood, glass, steel, polymers and plastics.

For example, research is being conducted to optimize the use of concrete materials for infrastructure purposes by using less concrete and recycling old concrete in new building structures.[1] There is an increasing demand to use less concrete in construction processes, which requires that the concrete structure be stronger and thinner. Recycled concrete aggregate is gaining broad usage and is considered a more sustainable way of building large concrete structures. In this regard, the optimization of materials systems is closely linked to the notion of sustainability.

NEW MATERIALS RESEARCH – FOUR CATEGORIES SHAPING THE BUILDING INDUSTRY

In the building and construction industries, engineers, materials scientists and designers continue to research and develop new materials, enhance material properties, and apply new design concepts for concrete, glass, timber and other bio-materials, metals, and polymers (bio and synthetic). The main research and development activities in the materials industry can be divided into four categories: smart materials, nanomaterials, replacement materials, and composite materials.

Smart materials

'Smart' materials are called materials, however, they are not really materials in the traditional sense. Smart materials represent a diverse grouping of materials. Many are more like devices or systems.[9] Smart materials can be divided into two general categories. The first are smart technologies that monitor, analyze and report on changes in a given environment which could be the material or building condition, for example. The second are smart materials that change their properties in response to external stimuli such as stress, temperature, movement, or electricity.

Smart materials typically consist of several different substrates laid or printed on top of one another, and through chemical interaction between and within these layers of materials they react in different ways.[9] They can exhibit properties that most people are generally not familiar with. They can change their state and actively transform themselves when affected by external stimuli. Examples of smart materials include:

- Phase changing materials: Materials that change between solid and liquid form at temperatures. These can be used to regulate the temperature in buildings and store energy.
- Intelligent glass: glass that allows varying amounts of light and heat through, which can control the amount of light and heat that windows let in.
- Shape-memory materials: polymers and alloys that can 'remember' a previous form and return to it under the influence of heat, electricity or other stimuli.
- Self-healing materials: Materials of that can repair themselves when cracked or abraded.
- Color changing materials, including liquid crystal that changes color by variation in temperature, electricity or humidity.
- Thermoelectric materials: Materials that change temperature differences into electricity or vice versa.
- Photoelectric materials: Materials that transform light into electricity or vice versa (mainly used in solar cells).

These materials are very different to what is currently being used in architecture today. For example, there is growing interest in developing granular aerogel, which can be sprayed on to existing buildings in order to improve their insulation value. There are also dye-sensitive solar cells, which are very low-tech, and very easy to manufacture at low costs – albeit less efficient than silicon-based solar cells – and make ubiquitous application and commercial availability of solar cell technology possible. Until recently, when we imagine shape-changing objects, we imagined actuators as mechanical devices. They are quite predictable and require infrastructure that tends to be heavy and strong. The actuators in smart materials however, reside at the chemical level. For example, electro-active polymers, which are simply polymers that can expand when exposed to a strong electrical field, can be used for three-dimensional actuators.[9]

The smart materials category, however, can be misleading and provokes a particular level of conceptual ambiguity. According to Manuel Kretzer, architect and founder of the *Materiability* network, many smart materials are not necessarily 'smart' materials. They are materials that are designed to exploit biological properties like the bio-luminescent properties in algae, for example.[9] Yet, a better way to describe them has yet to emerge.[9]

There is some potential for applying smart materials to the building and construction industries. Many smart materials are already available on the market. One can buy them online as prefabricated products like electro-luminescent displays, which light up in a very homogeneous way, and are flexible and extremely light-weight, or phosphorescent plastics. Companies and individuals can also construct and synthesize them themselves as long as they possess the correct starting ingredients.

However, Manuel Kretzer sees much more promise in surface applications of smart materials than in infrastructure applications: It is much easier to apply a particular product if it does not need to take any force or maintain structural properties.[9] Though, he explains, it is quite dangerous to simply reduce them to their basic visual properties, because a lot of things are happening chemically, which we do not yet comprehend or perceive.

Nanomaterials

One of the most interesting areas in materials science today involves research efforts dedicated to furthering our understanding of conventional materials that can be precisely tailored or controlled at the nano-structure level.[3] Nanomaterials science typically consists of four interconnected dimensions: (1) processing: how the material is made; (2) structure: how the atoms of the material are arranged; (3) properties: how the atoms interact and how the material behaves; and (4) performance: the overall functionality of a material when confronted with external forces. Nano-processing permits enhancement, altering, or addition of properties to materials.

Nano-processing allows materials science to transition from a reactive approach to a proactive one. Traditionally, new materials were first discovered and then studied. Increasingly, however, the performance characteristics of materials are first predefined and then reversed engineered by identifying an atomic structure that would give a material the necessary or desired properties. Lastly the materials are synthesized and applied. Examples of nano-processed materials include:

- Nanoparticles: Microscopic particles of various materials often mixed in liquids or creams. Used among other things, sunscreen and ski wax.
- Nanocoatings: Surface coatings making the surface uneven on the nanometer scale. They are mainly used to make surfaces water repellent or antimicrobial.
- Carbon nanotubes: Tubular molecules of carbon, which are light, strong and good electrical conductors. They are used for reinforcing materials.
- Aerogel: A nanotech porous solid with the world's lowest density. Aerogel is typically produced by drawing water out of the gel and replace it with gas. Aerogel consists of more than 99% air and typically have a density of 3 kg/m3. Aerogel is very strong in relation to its weight and is the best known thermal insulator.

The challenge for the building and construction industries is to build nano-structured materials in bulk quantities. However, according to Suveen Mathaudhu, Program Manager in Synthesis and Processing at the Materials Science Division U.S Army Research Office, “there are newer processes being developed that pass a current through the material as they are processing – and the physics of that are not quite well known yet. But what is known, is that materials can form from nano-structured precursors to bulk much quicker and at lower temperatures, so the nano-structured features are more easily retained.” The benefit that this process offers – spark-plasma sintering, field-assisted sintering, or current-assisted sintering – is that if the grain sizes of materials can be kept below the wavelength of light, then materials that are very strong but typically not transparent, become transparent. The result is transparent construction materials, and the markedly improved performance they enable, that have not been accessible in the past.[3]

There has been a lot of funding towards research that is centered on newer ways of synthesizing transparent materials with much higher strengths than the typical glass type materials. This is research that can develop transparent concrete – though these materials will be much stronger than concrete. This involves processes that allow you to build a ceramic material with transparent properties, or control the properties through doping of the material.[3] The end application for these types of things would typically be ballistic resistant large windows in vehicles or things of that nature. However, these materials or processes could easily be ported to the construction world, and applied to panels or windows that functionally would not break, have high U values, and serve to be load bearing as well.[3]

Replacement materials

Materials science is also developing a category of replacement materials for conventional materials systems in response to sustainability demands and growing concern over cost-efficiency. This includes bio-material alternatives and other less resource-intensive substitutes that are designed to limit dependency on increasingly expensive raw materials.

Bio-material alternatives

As pressure on resources grows and the demand for sustainability rises, much attention is being given to the use of materials from plants and animals as the basis for a wide range of products,[1] and most experts agree bio-based, bio-inspired, or bio-enabled materials will play a greater role in future building and construction industries as alternatives to current materials on the market. Bio-materials are bio-degradable and can be combined with synthetic materials to develop composite materials. Bio-materials' full market potential and consequences related to their development are currently poorly understood.

Biological systems have long been a source of inspiration for materials synthesis. Bio-materials are tremendously resilient, and companies like Dupont, for example, are looking to marry agricultural and biological research with traditional materials.[2] The key question challenging bio-materials development is: "Should we work with a bio-material's inherent properties or should we process it to produce a different structure and achieve a different performance?" [3]

Bio-materials or bio-based materials primarily refer to complex biological systems in which behaviors emerge from interactions among diverse collections of molecules. The field of bio-materials thus envelops the study of materials produced by living organisms.[4] The resulting materials maintain significant potential for a large number of applications given the myriad of properties they possess – from hard materials and composites, to soft materials, to films, interfaces, and surface materials. However, much of the potential for bio-inspired approaches largely remains untapped as there are a number of perpetual uncertainties surrounding their widespread application, especially for infrastructure purposes.

First, bio-materials research demands an interdisciplinary approach in order fully comprehend the complex processes and interactions that occur. In particular, our ability to emulate biology and reprogram biological systems for the purposes of materials synthesis remains limited.[3] To illustrate, wood is a remarkable engineering material that has still not yet been fully explored. Like most all bio-materials, the different species and native regions of wood determine the behaviors and inherent properties they possess. As such, the development of bio-materials occurs in symbiosis with nature and under sometimes particularly extreme climate, or weather, or other conditions.

Second, Jeff Martin, CEO of the US natural rubber company Yulex, argues that integrating plant-based sciences with materials-focused sciences is difficult, as funding for agricultural research to support the research into bio-materials and advanced bio-fuels from renewable resources is lacking. In addition, many bio-materials are not yet as cost competitive as other alternatives.[5]

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[1] Mundy, Jo. "Sustainability of Biomaterials in Construction". http://bit.ly/1faMmhM
[2] Silverman, Lee. "The Future of Materials Sciences and Engineering: An Industry Perspective Symposium," *Georgia Tech School of Materials Science and Engineering,* 2013. http://b.gatech.edu/1jV4jGd
[3] Mundy, Jo. "Sustainability of Biomaterials in Construction". http://bit.ly/1faMmhM
[4] National Science Foundation. "Biomaterials - Important Areas for Future Investment", *Workshop*, 2012. http://bit.ly/1jV4BNl
[5] Martin, Jeff. "The Future of Materials Sciences and Engineering: An Industry Perspective Symposium," *Georgia Tech School of Materials Science and Engineering,* 2013. http://b.gatech.edu/1jV4jG

Third, the mechanical, structural, or end-use benefits of bio-materials are poorly understood, and scientists and engineers have not been able to develop models that can predict or model their behaviors well. Bio-based materials tend to have problems in regards to environmental durability, when it comes to things such as humidity and moisture.[1] For architects, one of the general guiding principles is to avoid decay – surfaces are expected to retain the same look and properties as long as the building exists. Yet, longevity and other durability factors are new dimensions to consider when using bio-materials, especially since they are much more dynamic than conventional materials such as steel.[9] The long-term performance of such systems is largely unknown, but the mechanical properties as they are understood today tend to be inferior to synthetic systems.[1] However, these behaviors should not be avoided – instead, they should be better understood and leveraged as a design value.[9]

Fourth, bio-materials pose fire risks that need to be mitigated. For example, bio-materials tend to lose half of their structural integrity when they ignite.[5] In addition, bio-materials are currently combined with various fire retardants, which is controversial due to concerns over toxicity (see fire retardant section), though research is ongoing to explore natural alternatives to these man-made chemicals.

Despite the challenges, many experts agree the benefits far outweigh the disadvantages.[2] According to a British study on the use of bio-materials in buildings and construction industries. Bio-materials have the potential to provide construction materials with the following benefits:

- Capture and storage of carbon, extracted from atmospheric CO2 by recent photosynthesis
- Sustainable production as crops grown annually or as longer harvest-cycle forest
- Bio-degradability at end of life (controlled decay inside an anaerobic digester would produce both organic fertilizer and bio-methane to supply energy)
- Low or almost zero linear coefficients of thermal expansion
- The property of controlling temperature and humidity in enclosed spaces by phase changes of water in cells
- High vapor diffusivity and 'Fickian' vapor dispersal
- Usually high heat capacity
- Low thermal diffusivity
- Often good performance-to-weight ratios
- Lower embodied energy. [6]

For example, one of the benefits of wood is its high weight-to-strength ratio. It is a material that is easy to triangle and transport, and also easy to change – not only before you build, but also on a building site and once it is installed. Indeed, it remains flexible material throughout its entire lifespan.[2]

Experts expect to see more development of bio-polymers, and bio-synthetic composites like fiber-reinforced plastics (FRPs) that are derived from things like corn oil.[1] Currently, scientists are working to develop FRP repair systems with bio-polymers as the adhesives as opposed to more traditional epoxies, and many are experimenting with bio-composites – specifically, plant fibers inside of a bio-based polymer matrix.[1]

The promotion of bio-materials permits the recycling and potentially upcycling of materials to a greater extent. New technologies have allowed for the use of cellulose byproducts from wood processing to make interesting structural and construction materials. The US Department of Forestry has funded efforts on the recovery of cellulose – typically a waste material in wood processing – for developing new materials.[3]

When combined with nano-processing, such as in the case of nanocrystalline cellulose (NCC), new attributes can be applied to wood. For example, NCC is made from wood pulp and is therefore very cheap. NCC is also eight times stronger than steel in strength-to-weight ratio, is transparent and can be used as a substitute for plastic, glass or in computer displays in buildings.

Bio-material systems have potential, because of their inherent properties. Nothing else is required other than the

[6] Mundy, Jo. “Sustainability of Biomaterials in Construction”. http://bit.ly/1faMmhM

material itself, which is able to change, transform, light up or create energy for example.[9] Bio-materials are known for their ability to adapt and capacity to evolve over time. The idea of having a building that is able to adapt is particularly intriguing for many. Learning the fundamentals of biological adaptation will provide a basis for the design of new materials that autonomously optimize their performance in changing environments, sense and signal damage, and self-repair.

For example, bio-materials are also being developed to mimic the capacity of cells and organisms to sense their surroundings to protect our homes, communities, and workplaces from chemical and biological threats to human health at a manageable cost.[7] Already, microbial systems are widely used for environmental protection in many areas, most importantly in a water or wastewater treatment capacity.[6]

Greenovate – Europe's ECO-SEE project – aims to develop new bio-materials and components for the purpose of creating more efficient and healthier buildings. The central focus is to create natural bio-materials for healthier indoor environments through hygrothermal (heat and moisture) adjustments and removal of airborne contaminants through chemical capture and photocatalysis.[8]

Less resource-intensive substitutes

There is a growing demand for less resource-intensive substitute materials, which are perceived to be more cost-efficient. The focus is to decrease reliance on increasingly expensive raw materials through optimization, upcycling, and recycling. According to Anne-Mette Manelius, Material Ambassador and Senior Consultant at the Danish Technological Institute, "in the long term, there is no doubt that we will have to deal with our resource issues and think smarter."8 As such, there is a change in mindset that is required, that forces us to rethink the way we approach materials and the processes we use to develop them. For example, "in masonry, there are some bricks that have to be fired at 1000°C – it requires a great deal of energy. So sustainability here can focus on how to cure the bricks differently, replacing the fossil fuels required for the firing process, or replacing energy-intensive materials with other, less resource-consuming materials."[8]

Further, industry is seeking to develop light-weight materials, such as carbon fiber, ceramics, NCCs, and alternative metal alloys for structural purposes. Ceramics, for example, are good thermal and electrical insulators, and some also possess piezoelectric or semiconductor properties, which can be used in buildings to replace wiring for lighting and displays. Further, 3M's Novec products are synthetic, engineered fluids that act as a substitute for water. These products are less-resource intensive as they decrease water consumption, but also offer greater, more robust fire protection when used in active systems. Lastly, synthetic fibers with a high tensile strength-to-weight ratio, such as Kevlar, can in many cases replace steel mesh.

Research is also directed towards finding new applications for aluminum, titanium, magnesium, and to a very limited extent beryllium. However, much of the research in this area resides in the transportation, medical, and sports industries, where production volumes are small and margins are high.[9] The application of light-weight metal alloys in the building and construction industry poses challenges, however. They are expensive compared to traditional alternatives, and there are fire issues – such as flammability when submerged in water. And, as Suveen Mathaudhu explains: "For building and construction applications of light-weight metals, I think there is some potential, but in the long term – it will be very difficult to compete with conventional cheaper materials. However, the primary driver for the use of light-weight materials in structural and framing applications right now is the transportation industry, because of fuel constraints. The auto industry and the aircraft industry are interested in using more aluminum and

[7] National Science Foundation. "Biomaterials - Important Areas for Future Investment," *Workshop,* 2012. http://bit.ly/1jV4BNl
[8] Read more about Greenovate Europe's 'ECO-SEE' project here: http://bit.ly/1jYSbnE
[9] Damadei. "Design and advanced materials as a driver of European innovation," 2013. http://bit.ly/19V3xSO

magnesium alloys. So the study of flammability for these materials is less on static building or construction applications, but more in the transportation realm.[3]

Composite materials

Composite materials have been defined differently by research organizations. They are aggregate materials made up of two or more components in order to attain a new set of properties. Usually a composite material is constructed by fabricating two or more non inter-soluble physical or chemical components. Desired properties could be fibers or structural components from one constituent, appropriately arranged, and then attached to another.[10] Composite materials are often engineered to solve problems for extreme applications, such as race car bodies, dental restorative materials, swimming pool panels, storage tanks, boat hulls, underwater setting cements, and as structure and support for bridges and buildings.

An example of a new composite material is the EQ-Grid, which represents brickwork reinforcement for earthquake safety, which consists of alkali-resistant glass fibers combined with highly elastic synthetic fibers. The system uses a specially tempered plaster, adjusted for hard or soft brickwork. The material is breathable and durable, and claims to increase the bearing capacity of the entire building by approximately 50 percent, without adding substantial mass. [11]

Other composite materials being developed and commercialized are (1) underwater setting cements for submerged structures, (2) the commercialized 'LitraCon' or translucent concrete that is a concrete aggregate with glass fibers, or (3) Balsa Wood Veneers, which can be used as 'natural' light-weight fire barriers; as they have non-flammable properties.

Despite their benefits, many challenges have to be overcome when introducing composite materials to the market. The first challenge is the cost of manufacture, as many composite materials – particularly those using carbon fibers – are expensive. Automation of production, however, could help solve this challenge. The second challenge is that testing procedures are still lacking for many of these materials, and third, products or structures that contain composites are difficult to reuse, repurpose or recycle.[12]

[10] http://bit.ly/1jV1Jjn
[11] Ibid.
[12] Damadei. "Design and advanced materials as a driver of European innovation," 2013. http://bit.ly/19V3xSO

Materials development for refurbishment – a critical focus

Most of the building stock in high-income countries has already been built. The focus in these markets is on maintaining and refurbishing existing building infrastructure at reduced cost. On the one hand, a branch of materials research focuses on developing materials for rehabilitation and refurbishment purposes. On the other hand, there is a growing body of research that focuses on reducing maintenance costs by designing materials for retrofitting and optimizing buildings. Research in these fields is concerned with developing predictive life-cycle analysis to better understand the long-term performance of materials. This includes developing standards predicting the longevity of materials, managing their life-cycles, and planning retrofits and replacement of worn materials. Research also focuses on developing materials that can improve the energy efficiency, and safety of existing buildings. Interviewed experts identified the development of man-made materials, specifically plastics and FRPs, for structural repair and modification of existing buildings, as particularly interesting areas for future development.[5]

Polymeric-based building materials offer a number of benefits as they have adhesion and elasticity properties, which make them popular in building and construction industries. However, the functionality and durability of these materials is affected by weathering – they become brittle, fracture, and fail. Reinstalling adhesive or panels to glass insulated buildings when they fail, is exceedingly expensive. Thus, finding the right adhesive that could extend the time before which replacement adhesive is needed will save money.[7] There is a push for innovation on the materials side, in the form of high performance, structurally durable refurbishment materials.

However, knowing the upfront price is not enough to determine the economical choice between two similar products. Materials cost is often a small fraction of the net present value of a material. In fact, 90 percent of the cost is in the labor involved in installing and servicing the material.[7] The challenge however, is that there are no effective methods for determining how long materials will last a priori. Though currently there is work being done to develop predictive models that will effectively provide less than real-time estimates for how long polymeric-based materials will last, so that is something that can be expected in the future. The challenge is that we do not know and cannot predict is when building materials will fail. In this regard, one central area of focus at the U.S National Institute for Standards and Technology is on developing models for predicting the lifespan and cycles of polymeric materials, called 'service life prediction'.[7] The focus is inclusive of the chemical properties of the materials themselves, as well as their exposure to regular wear-and-tear (weathering) and extreme events (fire or explosions). In life-cycle analysis and greening projects for example, people want to know, not only the first installation price but also the long-term service costs of the material because this will come to dominate.[7]

There is a clear demand and apparent need for predictive models for many materials used in building and construction industries, yet there is a systemic challenge for why research has been lacking in this arena. Individual companies do not research this mainly because it offers them no competitive advantage. It takes a long time and is really expensive. Industry-based solutions run into competition laws concerning anti-collusion or trust. Standards organizations do not have the money to support research, and universities do not engage with this because standards development takes too long.[7] This is an instance where government-backed research organizations can play a role, yet there needs to be guidance in order to do this in the right way. According to Christopher White, this can best be achieved through Public-Private Partnerships (PPP), but PPPs in the materials world have not happened until recently, at least in the United States.[7]

In the early 1990's, the Bureau of Standards changed its name to NIST along with a change of mandate that established a legal framework to work with industry. In general, there has not been much linkage between laboratory testing and outdoor exposure, so the warranty information that is typical for many materials are primarily based on the company-based history of performance. As a result, there are few industry-wide standards, but a growing interest in developing predictive lifespan and lifecycle models and processes for building materials in the construction industry.

The development of more adept, comprehensive life-cycle assessment standards and processes is becoming increasingly important.[6] There are countless measurement systems, but none of them address life-cycle assessment specifically. Although some life-cycle assessment standards for materials can already be seen in the auto and transport industry, such as cradle-to-cradle practices, they are not as widespread in the construction industry.

FIRE RETARDANT CONTROVERSY

The two central methods for addressing fire performance in materials have remained relatively persistent – adding chemicals to the materials, or using materials with larger volume.[2] However, there is a growing concern over the safety of chemical additives designed to reduce flammability of materials that are used in buildings and construction.[1] The chemical fire retardant issue has seen vigorous debate, primarily between scientists in human and environmental toxicology, and chemical industry representatives and scientists.[13] The fire retardant controversy stems from the challenges in balancing concerns with the chemical toxicity of flame retardants and fire life-safety considerations. The controversy has sparked a shift in US regulations on fire retardants and fire safety in 2013. This shift potentially has a global impact and is an ongoing driver of fire safety research.

The use of fire retardants have been subject to a large exposé in the United States by the Chicago Tribune. This exposé is called *Playing with Fire* and levels several pointed charges at the chemicals industry – which produces fire retardants. The Chicago Tribune accuses the chemical fire retardant industry of:

- using phony consumer watchdogs to mislead law makers and the public
- allying themselves with the tobacco industry and fire officials to play up the risks of fire
- distorting science to show that their products are safe when they are not
- distorting science to show that their products work when they do not

The Chicago Tribune also accuses regulators of passively accepting generations of flame retardants without assessing the risks. According to the Chicago Tribune,

> *The average American baby is born with 10 fingers, 10 toes and the highest recorded levels of flame retardants among infants in the world. The toxic chemicals are present in nearly every home, packed into couches, chairs and many other products. Two powerful industries — Big Tobacco and chemical manufacturers — waged deceptive campaigns that led to the proliferation of these chemicals, which don't even work as promised.*[14]

As a result, California's furniture flammability requirements have been updated in Technical Bulletin 117 (TB117) that is designed to eliminate the use of dangerous flame retardant chemicals. However, in comparing the effectiveness and toxicity of flame retardants in furniture specifically, there are no definitive, fully-supported causal links or conclusions that can be drawn. Flame retardant producers often state that there is no evidence that their chemicals are harmful. This argument is also made by some fire scientists who may acknowledge the limited benefit of fire retardants but who also see no evidence of harmful side effects or do not see the environmental side of the issue as relevant to fire safety decisions.[15]

One interviewed subject-matter expert explains: "As academics we work with all types of flame retardants. We strongly disagree with the general perception taken by some lobby groups that all flame retardants and halogenated flame retardants in particular, are toxic. Yes, some of them produce toxic smoke, have health hazards, and have been banned. However, a blanket banning of all flame retardants without underpinning hazard and risk assessment evidence cannot be justified scientifically. People are so paranoid about using flame retardants. This is an emotionally-based response. It is an issue with chemicals in general, but the flame retardants seem to be most attacked. We must

[13] Rich, David. "Effectiveness vs. Toxicity of Flame Retardants," *Fire Safety Science News,* 2014: Issue 36. http://bit.ly/1dvkTef
[14] Chicago Tribune. "Playing with Fire". http://bit.ly/1idaBz8
[15] Rich, David. "Effectiveness vs. Toxicity of Flame Retardants," *Fire Safety Science News,* 2014: Issue 36. http://bit.ly/1dvkTef

not forget that many chemicals are used in other household products, which serve their function safely and are desired by consumers."[5] As such, fire scientists are hesitant to engage on this issue due to a lack of proper quantification of fire safety benefits, a lack of demonstrated adverse health effects, and the muddying of the issue with involvement of special interests.[16]

Further, the review of studies by Fire Safety Science News indicates that the TB117 regulation does not decrease fire hazard, and performs no different than untreated materials.[17] This is problematic as nearly all furniture in the United States is manufactured to meet TB117, the updated requirements are effectively a change at the National level, which has implications for global markets.

However, the fire retardant debate is not over. Flame retardants will continue to garner attention, and an increasing amount of research funding is being directed towards understanding the flammability of materials, and the effectiveness or role of flame retardants in improving fire safety (see figure 2). That is, how do you prevent materials from burning and what are the processes and techniques to do that without involving chemicals that are potential halogens and carcinogens? In response to the new California standard, the National Fire Protection Association's Standards Council has indicated the need to establish a new test method to evaluate the fire performance of particular materials.

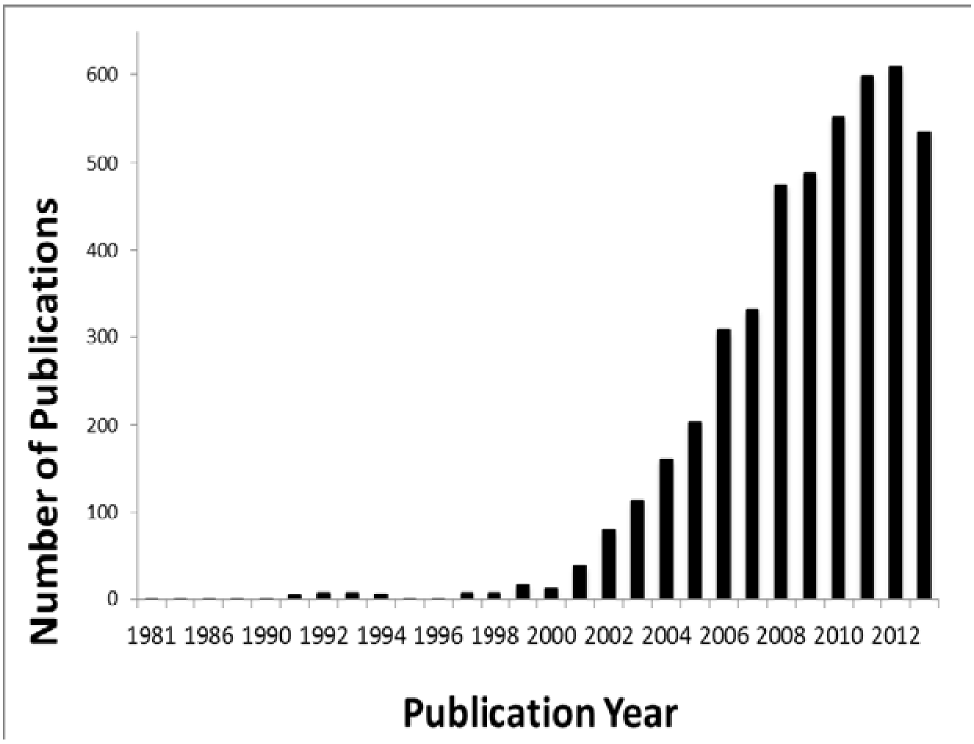

Figure 2: Total number of publications on one flame retardant family called polybrominated diphenyl ethers (PBDEs)[18]

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[16] Ibid.
[17] Ibid.
[18] Ibid.

TESTING, PERFORMANCE, AND APPLICATION

Materials development is a long and slow process that consists of a number of stages. However, these stages and the testing of materials throughout the development processes are both application-specific and context-specific. The importance of different performance and fire safety objectives is relative to the application of a new material, but also the context in which that material is situated. For example, an aluminum bike rack in a city might require less rigorous testing and characterization than surface or infrastructure applications of aluminum in a building or house. In the early stages of research, fire and performance testing is rarely done as it limits basic exploration of materials properties. As materials research approaches commercialization or end-use applications, fire testing and other performance objectives become more clearly defined.

Process of development – it's long and slow

It takes anywhere up to 20 years or more for materials to make it from the laboratory to commercial applications, and become accessible for larger or more ubiquitous applications, such as construction.[3] In some cases longer, such as the development of commercially viable aerogels, the process has taken more than 80 years from discovery for it to reach the market. There are two paths of materials development. The first is research that begins through scientific exploration, and the second is designed to match consumer demands with a material or materials system.

Richard Harris, Professor at BRE Centre for Innovative Construction Materials, Department of Architecture and Civil Engineering, University of Bath, describes the first path as the curiosity driven scientific research process, consisting of three phases. Phase one starts by problematizing and experimenting with solutions, and 'real-world' applications are not immediately defined.

During the second phase, engineers explore solutions or products within a context, such as a need to reduce embodied carbon, to improve insulation properties, or better attune the response of the fabric to their internal and external environment, for example.

The final phase of research is usually conducted in conjunction with industry. The aim of this phase is to develop a product and commercialize the research. Even when the research comes out of a university lab, it needs to be adopted by an industrial collaborator, and then proceed through to implementation that involves marketing, manufacturing, and skills development.[6]

This process is time consuming and oftentimes does not result in any commercial viable materials. For instance, the Department of Architecture and Civil Engineering is developing a new form of connection using non-metallic connectors for timber construction. The first phase of research was completed four years ago, and the second phase of research, which was designed to better understand the behavior of this new materials system in fire, began two years ago. At the moment, researchers are interested in determining the temperature in the middle of the connector through analytical modeling. This research is being conducted in the early stages of development, where much of the onus remains with the academics or researchers to prove the merits of the technology at the most basic level. If industrial collaborators adopt the research outcomes, they will then become responsible for turning basic research and technologies into a commercially viable product, and perform the required tests and obtain the required certification. This case has yet to reach industry and illustrates the long-term thinking required for materials development.[6]

The other manner in which materials research is conducted is to develop solutions for customer-specified applications. Researchers screen these materials through ad hoc testing, where the customer provides a sample of a new material and their concerns as to what they are trying to demonstrate. Based on these requirements, researchers determine the most rational or credible way of asking the question experimentally and develop a test method to understand the material better.[1] However, it is not possible while developing a new material to do all accredited tests to meet the standards. The primary focus for researchers is to make sure the materials fulfill the needs of the specific application, verify the performance of the materials and how it can be used for a specific purpose.[2]

Fire performance

Challenges brought by optimization and the development of sustainable options will increase the importance of fire testing in new materials development for the building and construction industries. For example, as FRPs become significant in the refurbishment of older buildings, and wood or other bio-materials become more commonly used as structural materials, fire safety is a greater concern. Despite maintaining a general understanding how materials respond to fire, the need of fire testing for application-based materials development in academic and industry research projects will grow in demand.

There are two stages in the fire testing of a material. The first stage involves developing an understanding of the behavior of a material under fire exposure, and the second stage is conducting repetitive tests against standards to provide ratings for a material.[6]

There are a range of standardized tests, which are used to certify and characterize materials in regards to fire safety, but there are also ad hoc tests that researchers develop to study concerns that are of interest. They test many properties that are related to both to the reaction of a material to heating, and to the consequences of that in terms of further heating, flame spread, toxicity, and smoke density.[1]

Fire testing, however, is not common in the first stages of pure research. As Manuel Kretzer emphasized, at the initial stages of the development fire testing is typically not done, as researchers try not to be influenced or limited by practical issues or constraints: “there are so many things that one can criticize about new materials at the early stages, but if one starts with all of these things in the back of the mind, one will not get very far.”[9]

Anne-Mette Manelius supports this notion: “Our customers do not place great emphasis on fire safety. Of course, it is an issue when they are part of a building, and there are various legal requirements, but it's not the starting point. We have a much greater focus on the material's durability and how to break it down and produce it.”8

In the United States, there are very few materials scientists who test for flammability. According to Suveen Mathaudhu, these tests tend to be very rudimentary and non-scientific in nature. This mindset is expected to continue, but there is growing interest in studying flammability of materials from an academic perspective as the rigorous characterization and testing of factors that control flammability in materials today are still somewhat unknown. A key example, which is controversial, emerged following the 11 September 2001 attacks on the World Trade Center. There has been lots of discussion and contentious debate amongst materials scientists and engineers as to whether the temperatures and the conditions would have been enough to actually melt the materials, and cause the flames.[3]

Moreover, fire testing depends also on whether the application of new materials has a specified context, such as a public place. As Laurence Kemball-Cook explains, “Pavegen tiles were tested and received fire safety certification. However, when we sought to install them in subway stations, fire safety standards were much stricter. It is very difficult to put new technologies in subways, unless they are completely fire retardant.”

There are significant concerns with materials flammability, which prevent the application of many materials in buildings. A typical example would be, if you have an existing concrete building, and that building is structurally deficient in some way – insufficient internal steel reinforcement or internal reinforcement has corroded, for example– and you need to take some remedial action in order to increase the strength of your structure, a very popular and easy technique is to bond FRP to the exterior or the concrete. There is vast research, going back 15-20 years that looks at the performance of these FRP repair and strengthening systems at ambient temperatures. However, the major concern, and the reason why they have not implemented as widely as they could be, is that these systems are combustible and flammable.

The growing trend to use bio-based materials also has a number of significant implications for fire performance.

Companies are increasingly looking to use wood – they use big panels of prefabricated timber for framing, and a number of wood applications in building's interior. The challenge is that wood and bio-based materials are known for their flammability, and loss of structural integrity once ignited.[5] Yet, despite concerns of flammability, wood generally behaves well in fire and is remarkably predictable.

There has been extensive experience with timber structures and a substantial body of knowledge regarding the performance of timber structures in fire. New active and passive systems have been developed in order to compliment the deficiencies inherent in wood.

There are situations when an active system such as a sprinkler system is a viable solution for fire control for example. However, Richard Harris strongly argued for eliminating the problem before it occurs, rather than having a responsive active system: "If you can fire engineer your design away from sprinklers that is what you do. We are trained to design safety hazards out of our project rather than protect against them. My instinct is to avoid active systems, by having a safe design that works passively."[6]

This means that a passive system of fire control is the preferred choice. For example, ceramic, and other surface applications with fire retardant properties are gaining increased attention. However, these systems have traditionally increased the structural weight of buildings. Thus, it is important to strike the right balance between the optimization and fire performance of materials, economic and otherwise.[5]

NETWORKS, COLLABORATION, AND STAKEHOLDERS

There is a general understanding among stakeholders that increased collaboration and a greater use of networks is required.[12689] There is, however, little consensus as to the role various stakeholders should play in the development of new materials. There are a variety of interests at play in developing new materials for any application. Be it political, industry-driven or otherwise, they all have an impact on what types of materials get developed when, and how quickly. Interviewed stakeholders recognize a growing need for knowledge-sharing, resource deployment, market innovation and time-to-market advantage that is driving the development of value networks and business ecosystems. In order for all stakeholders to gain value, it is important to understand who the different stakeholders are, the expectations they hold, and the role they play in new materials development.

Stakeholders include scientists, engineers, manufacturers, general contractors, designers, and end-users. It also includes local city councils, which provide building permits; insurance companies, which assume risk if things go wrong; and the banks which provide financing. The introduction of new materials introduces uncertainty and this uncertainty must be rewarded with a great potential upside, before stakeholders are willing to take the risk.

The introduction of new materials takes time, as value chains are long and complex. Because the building and the construction industries are low-margin and, as a result, conservative industries, many stakeholders' concerns must be allayed and satisfied in order for a new material to breakthrough and become widely accepted on the marketplace. Due the complexity and length of the value chain, researchers are weakly linked to end-users. Companies tend to drive this development, which occurs in more-or-less a linear process. However, the conventional value chain has been disrupted.

Financing of new materials research and development has been decreasing due to the economic downturn that has occurred since 2008. Given the economic circumstances, more integrated solutions are being sought after. For example, many companies such as Kodak, have ceased the operation of their own research laboratories, and began collaborating with universities and academia to solve some of their basic materials problems.[3]

Thus, as value chains transform into value networks, all stakeholders have equally valid concerns that should be taken into account. One particular material may offer benefits to the end-user from a contractor's point of view, while a different material may have other advantages only apparent from a design perspective. In fact, when looking at the key stakeholders involved in the development of new materials, it is difficult to define and depends on the industry.[13]

Both Richard Harris and Peder Fynholm, team leader of the Building and Construction, Wood Technology division at Danish Technological Institute, identify the primary stakeholders as the designers, manufacturers, and contractors, who maintain a significant influence on what is happening in the industry. It is important to understand that contractors cannot use new material unless the designer specifies it. So the first challenge in implementing new materials comes from designers. However, in practice, Richard Harris contends, "it is contractors who pull the designers, rather than designers who push the contractor. Often a constructor sees an opportunity through the new material."[6] For instance, a self-compacting concrete offered huge advantages to contractors in quality and time, so they approached designers asking them to specify this concrete. This material offered an advantage and they wanted a designer to approve the use of it.

Central actors:

Academics, researchers, and scientists

Academics, researchers, and scientists have a central and growing role in exploring the opportunities in the development of new materials. They are pioneering the scientific research in new materials and provide the industry with innovative solutions. In many cases, academics are not limited by real world considerations during the early research stages, and are free to explore and experiment. However, this also means that academics are often working in isolation from commercial or user requirements.

Suveen Mathaudhu explains, "in my position I am funding science that could become useful to civilians and defense in the long term, so I try to steer the people that submit proposals to my program away from the idea of making a product, but more to the idea of what kind of revolutionary science can you develop. If you let the academics try to propose on their own what the end application for a material will be, they often do not have a good enough understanding of things like scalability or the end-use environment. As an example, in the defense world, I get so many proposals for armor applications, but all real armor is classified, so there is no way they can accurately design for an environment like that."[3] As a result, there are lots of materials, which have gone through the basic research stage, but never entered the industry and manufacturing stage, because the research community is often times disconnected from real world considerations.

Academia's role is growing as many industries cease to own or use their private laboratories: They now outsource fundamental materials research and testing to various research institutions and university labs. As such, a greater number of scientists and academics are gaining increased exposure to the commercial and practical dimensions influencing materials development. This trend, which inherently drives towards collaboration, creates challenges over authorship and ownership in new materials developments.[9]

The issue of patent "trolls" is a growing challenge as non-practicing entities (NPEs) make or acquire patentable discoveries in materials sciences with the objective of either enforcing potential infringements or licensing rights to companies to develop them. Some of these organizations file lawsuits to force settlements for sometimes dubious infringements on their intellectual property rights.[19] While not remedying the patent troll problem, open-source platforms were cited as examples that could overcome the current fragmentation of knowledge generation.

Suppliers, manufacturers, and contractors

Suppliers, manufacturers and contractors are the key stakeholders introducing new materials to the market and driving a change in the building and construction industries. The ability of academics to engage with these stakeholders is dependent on their degree of consolidation in a given material's industry. Their role is to create value by investing in the creative use of materials and applications as various solutions. As important a role academics and researchers play in laying the foundation for future innovation through research, there has to be a pull by industry that will create opportunities and funding for research.

It is manufacturers who invest the most when pushing materials into the application and commercialization stages. They "are at the helm of the innovation bridge between materials and designers. But they are also probably facing the innovation challenge the most."[20] Meaning, in order to sell their manufactured material to the contractors and designers, they have to be able to demonstrate the advantages of a new material over a conventional system.[6]

According to Laurence Kemball-Cook, the manufacturers' role in new materials commercialization is crucial. In order for materials to be usable, there has to be a manufacturing process that provides an economy of scale. "When materials are new, it is very hard to manufacture them at a cost effective price. We have experimented with a number of different new materials from polymers to different kinds of foams, but the problem is that they are not industrialized. It is one thing to see a viable material, but I also have to see it manufactured at a cost-effective price before I am willing to invest in it."[10]

Suppliers, for example, play an important role in materials development and maintain a central position along the value chain. They look for new applications, and often also act as manufacturers, as a degree of manufacturing is involved while synthesizing raw materials into usable forms, or into various composites. However, "material suppliers often fail to explain the potential of application."[21]

[19] Ashby, Jones. "The Patent 'Troll' Tactic Spreads," *Wall Street Journal*, 8 July 2012. http://on.wsj.com/O19uce
[20] Damadei. "Design and advanced materials as a river of European innovation," 2013. p.39. http://bit.ly/19V3xSO
[21] Ibid, p.39.

It is often very challenging for academics to engage with industry. The degree of difficult, however, is very country- or region-specific. Looking at concrete specifically, the industry in the United Kingdom is a disconnected group of small companies. It is very difficult to get them to agree to anything and to fund research and development work. Luke Bisby explains that small or medium sized companies are currently difficult to engage with.[1]

According to interviewed subject-matter experts, the groups that most academics can easily engage are large consortium groups. In the United Kingdom, there is no such credible organization. In France for example, because of the system of taxation and government research labs, there is an industry-based, tax-funded concrete testing lab called Cerib. Cerib represents the whole of the French concrete industry, and is easy to work with.

Further, the timber or cross-laminated timber (CLT) industry in the United Kingdom is really nascent, and has not fully come into existence yet. There are only a limited amount of small suppliers with little money to fund research. These suppliers are still learning to navigate the industry. Yet, in Germany and Austria for instance, the CLT industry is already much more developed, and off-site, prefabricated construction is much more commonplace. They are quite well organized with greater access to funding.

The degree to which industries are consolidated is strongly indicative of their capacity to engage and collaborate with academia and other stakeholders. Suppliers, for example, have a crucial role as being at the source of the traditional materials value chain. They look for new applications, and often also play a dual role as manufacturers, in that a degree of manufacturing is involved while synthesizing raw materials to usable forms, or into various composites. However, "material suppliers often fail to explain the potential of application." In all, industries must build more coherent networks within themselves and between a greater number of industry partners, in order for value to be created and progress to be achieved.

Designers and architects

Architects and designers are often believed to lack significant influence in the process of new materials development and commercialization. Architecture is not really an industry that drives materials innovation. Concrete, steel, glass, plastic, and wood have really reached their architectural limits. Other materials are not really applied to an extent that becomes relevant architecturally. Meaning, if new materials become commercially available, they are typically designed for a specific purpose, or specific function, which is usually not architectural. As such, Manuel Kretzer explains, "you end up with a product which is not exactly what you need or what you want, and you are forced to work with this end product." Their influence in materials development has grown over the last few years.

However, during the last few years architects and designers have experienced a growing involvement in materials development. The awareness among these stakeholders about existing and potential materials is crucial, as they are the ones specifying and approving materials in the project proposals. Designers bring in the required "perspectives to human needs, sustainable material and manufacturing choices."[22] Ultimately, designers are the ones who make the decisions on what materials are used for in a given project.

Given the relative importance of designers as the ones who bring everything together, there is a need for them to cooperate with other stakeholders – especially researchers, scientist and academics – who are working with the materials at the very initial stages of the development. "The biggest challenge for the designers and architects is the optimization and selection of materials, especially when there is no such a thing as the perfect material for any particular application."[23] Indeed, greater channels of communication between scientists and designers are needed in order to get a more comprehensive knowledge of how the particular materials work, where they come from, what they are developed for, and how they are fabricated. "Then," Manuel Kretzer explains, "we can develop a language or an understanding that allows us to communicate with the people who developed them."[9]

In order to make greater use of the materials available, designers and architects should be encouraged to approach

[22] Ibid, p.67.
[23] Ibid, p.66.

material scientists, especially as many of new materials are still very far away from being commercially available. Most of them are still at the research state and somehow scientifically mystified. It is therefore very difficult for a designer or architect to access them currently.[9]

Being more explicit about their needs could help for designers and architects find out about the new applications for many materials, which have already been developed by scientists and researchers. There are a number of materials that have a value and might be used in the future, or are already used today to some extent. However, the biggest problem is the lack of knowledge that impedes their ability to fully apply them.[9] According to Baljinder Kandola, Professor at the Institute for Materials Research and Innovation at University of Bolton, multi-disciplinary networks or cooperative platforms that link designers with other stakeholders are the most beneficial ways to drive new materials development forward.[5]

End-users

The strongest driver in the development of new materials is the consumer – the owner of the building or the person who lives or works in a building, because they ultimately dictate the market. However, it largely depends on who the user is and what the end-use application is.

In some cases, the concerns of the end-user are absolutely central, and in other cases, the end-user really does not have a preference. For example, "in my own view, when discussing housing, I do not think that someone who buys a house really cares what it's built from – if the wall is light-frame timber or solid concrete, it looks like a wall. Some developers and some homeowners might care to know that their building is put together in a more environmentally friendly way, but I think that interest comes at the level of the developer and not the individual home-buyer,"[1] explains Luke Bisby.

The direct involvement of the end-user in new materials development however, is rare. Generally, the end-user has specific requirements, but lacks a technical understanding of the materials and building processes that limits their involvement. Individuals require or expect buildings to be structurally and dynamically safe and affordable in terms of upfront costs and energy efficiency: "When it comes to infrastructure – buildings and houses – I think the end user cares less and less. I think it's more about cost savings, low carbon, increased sustainability, and that the interests are predominantly at the contractor-developer level because they're the ones who can skim money off the top and put it in their pocket."[1]

Integrated cooperative platforms

Bridging the gap between fundamental research and industry is a huge challenge when introducing new materials. With an increasingly fragmented value chain and specializing stakeholders, the need for cooperation is growing. Integrative collaborative platforms are emerging to improve the transition from research to product, though typically on a regional level. In many countries, collaborative relationships among the aforementioned stakeholders emerge on application-specific bases. Some networks are established and funded by governments, while others are industry-led.

Creating networks that involve researchers, manufacturers, designers, contractors, and end-users are difficult due to their competing motivations and differing measures of success.[7] Researchers develop knowledge for knowledge's sake, while the companies' focus on commercially viable products and profit driven ventures. Students are not necessarily required to pursue a project that solves industrial problems to complete their education, or to get an advanced education, for example.[3]

Focusing on the long-term is perhaps the biggest obstacle in creating integrated cooperative platforms. The challenge is to get end-users in industry interested in something that has a potential 10 years from now, while they are typically interested in things at most, six months ahead. There is a lot of difficulty in involving people interested in research with a potential over many years.[6]

Interviewed experts typically participate in region-based networks, which have their own engagement models. Many European countries, like the Fraunhofer Institute – Europe's largest application-oriented research organization – have mechanisms in place where academia is paired with industry, where funding is sustained, and the research findings transition all the way through to quicker applications.[3] Germans are particularly praised as being much more successful at making the transition from research than in the United States, where a critical infrastructure between National Science Foundation funded research projects and industry is still lacking.[7]

In Denmark, there is a new approach in industry that links stakeholders together: The Materials Ambassador. At the Danish Technological Institute, Anne-Mette Manelius acts as the Materials Ambassador, and is responsible for providing more knowledge about materials to designers, architects, and other industry professionals. She explains, "we see it as a problem when they do not know which way to go, and they need some guidance. I play a bridging function."[8]

Due to targeted funding and scientific interest, academic institutions have become more open to cooperation depending on the materials properties they are interested in exploring. Luke Bisby explains that collaboration with other institutes during materials testing is usually based on the properties they are interested in investigating. This center works with other universities under collaborative research agreements within the UK and elsewhere, as well as industry labs, suppliers, external test houses and companies who have their own facilities.[1]

For example, funding from the BRE created a relationship between the Centre for Fire Safety Engineering at Edinburgh University and BRE Centre for Innovative Construction Materials at University of Bath. BRE has been a privatized, not-for-profit industrial organization for more than 20 years that sponsors various research centers via government funding, in this way encourages them to collaborate with one another.[6]

An interesting global network, based in Stockholm, consists of researchers in timber and fire safety, with a specific focus on wooden buildings. The researchers in this network work together, because of the challenges they face due to the flammability of timber.[4] One of the outcomes of this network was a document "Fire Safety in Timber Buildings: Technical guideline for Europe", which is used in countries like England, Sweden, Germany and Italy. Thus there is a large educational or knowledge-sharing aspect of these cooperative networks as well.

Cooperative initiatives are also coming from the industry. Due to the decline of company-run labs, there is a growing need for collaborative frameworks from an industry perspective. Industry collaboration arises at conferences and meetings, where participants get the latest discoveries in science.[3] Examples of industry-led networking include the Danish InnoBYG and the Australian-New Zealand "Structural Timber Innovation Company".

The InnoBYG is an innovation network for energy efficient and sustainable construction industries in Denmark. The network focuses on knowledge sharing, networking and industry development among its domestic and international members. One of the crucial functions this network supports is the maintenance of a database of contacts. Being a part of the construction industry means that stakeholders earn money by working together, under a network that is based largely on customer relationships. Some of the commercial projects are funded directly by customers, while others are funded through government programs or other governmental institutions.[2]

The other example of industrial cluster is the "Structural Timber Innovation Company", which established a research consortium in the wood industry in New Zealand and Australia. This network promotes wood's use as a structural material in multi-story office building, challenging steel and concrete's long standing role. This cluster is partly funded by industry and matching funding from government.

REGULATIONS, STANDARDS, AND CERTIFICATION

The regulatory approaches towards construction, buildings, materials and fire safety vary greatly from country to country, and oftentimes within countries. Approaches to fire safety regulation and materials used in buildings are historically contingent on the local operating context. This lack of cohesion among regulatory bodies limits the innovation and the market penetration of new materials and materials systems. The challenge for regulatory bodies with new materials is to find the right balance between prescriptive and performance-based regulations.[1] Governments need to recognize the critical importance of appropriate regulation in promoting innovation in the building and construction industries – without it, innovation is not likely to occur.[1]

In Germany, for example, the "safe way" to innovate is expensive and conservative – a material cannot be used without being certified through the technical approval process.[6] Certification regulations are strong, slow, secure, and predictable. However, this approach does not lend itself towards realizing the concerns of all local markets in one comprehensive set of standards and certifications nor does it facilitate the introduction of new materials.

Another casualty of austerity? The transition from prescriptive to performance-based regulatory models

All regulation falls somewhere along a spectrum between prescriptive and performance-based approaches in terms of how much detail is specified and what is left to interpretation or dependent upon external factors. Prescriptive regulations, in principle, define how activities are to be undertaken and constitute a set of rules that must be followed.[24] This approach emphasizes a known degree of risk mitigation over innovation or cost management. Performance-based models place greater emphasis on specifying a performance standard for the desired outcome while not deliberately constraining how compliance is to be achieved.[25] Most interviewed experts spoke in favor of applying performance-based regulations. However, they noted that government austerity is cutting the funding needed to successfully make the transition to performance-based models, making it a casualty of austerity.

In both cases there is a fundamental dependence on external factors – standards, code systems, and strong regulatory authorities in order to make the regulation effective. Both approaches also require that quality assurance processes are upheld through effective monitoring and enforcement.[26] Prescriptive models are generally viewed as the safe, 'tried-and-true' approach that draws on experience and known processes. This approach is, however, more costly and requires greater resources to ensure standards are met.

Most experts tend to favor conditions under a performance-based model: "I would like to see governments put more funding into supporting the ongoing development of more advanced building codes and the regulatory process that is required in order to encourage a move towards performance-based design or engineering environment – where competent engineers are able to do whatever they want that meets the performance objectives for a piece of infrastructure using any materials they want."[1]

However, regulatory authorities in the United States, the United Kingdom, and elsewhere are currently looking into the transition from prescriptive to performance-based regulations.[7] In the United States, this transition is further advanced in fire safety regulations than in other areas of building regulations.

In these markets, the shift towards performance-based regulations is being driven to counteract unnecessary implementation of ineffective countermeasures. For example, "companies are using performance-based fire engineering to produce designs with the same estimated or calculated level of safety, but at much lower costs. Some firms are claiming millions of dollars of savings with this performance-based approach."7 In this case, the shift

[24] New Zealand Treasury. http://bit.ly/1f19wvo
[25] Ibid.
[26] Ibid.

towards performance-based regulations would eliminate the unnecessary cost of installation and maintenance of an ineffectual fire prevention system, lowering costs for the construction firm and the end-user.[7]

The challenge is that the regulatory infrastructure, process and skilled personnel to execute performance-based regulation effectively do not yet exist. New Zealand, the one market that attempted performance-based regulation, failed to make the transition.[7]

Fifteen years ago, New Zealand applied a performance-based regulatory model for fire and structural design, but did not put in place an appropriate regulatory framework for third party review of such designs. There were a number of significant failures of buildings, as a result. Now, however, the government in New Zealand is stepping back and shifting towards a prescriptive-based model. Subject-matter experts believe that that there needs to be strict regulation in regards to testing, and once those test results are obtained, there needs to be an understanding of what that means for long-term performance.[2]7

If governments attempt to transition to a performance-based approach without the proper support, the likely outcome will be poorer regulation of designs that should have been checked much more carefully. As a result, there is an increased potential for structural failure or poor fire performance of buildings. Yet "the only way that a [performance-based] regulatory process will come into existence is if government decides to put money, people, and education into the regulatory process, which in the UK for example, is the exact reverse of what is happening."[1] There is downsizing of government occurring in many European countries, which entails a move towards less funding for regulation and a move back towards prescriptive rules – simply because there is nobody to check, and if there is nobody to check, engineers are unable to do what they want because they will start to do things they should not.

Despite this, there are a number of changes in regulation that need to occur, such as the more rapid testing and qualification of materials or more rapid determination of the required specifications to get a material into a product.[3] In the United States, there is often an economic burden on the developer of the company that is trying to introduce a new product or material, because there typically limited funding for third-party testing and qualification.[3] Specifications need to be developed in such a way that they can utilize streamlined contesting and qualification procedures to make the testing phase more cost efficient. This requires a learning process to identify the correct balance between costs, performance, and regulations.

Industry dynamics and the emergence of quasi-regulators

Quasi-regulators play a significant role in the development of new materials, and this is not easy to change given the influence they maintain. Further the lack of harmonized standards and regulatory frameworks gives a distinct advantage to larger organizations, in that many have in-house testing facilities and are not reliant upon third-party testing institutes in order to get products certified for plenty of attributes. Due to the power they possess, regulations are created to satisfy the needs of quasi-regulators. This makes it difficult small and medium-sized enterprises (SMEs) to enter the market and compete.[5]

Well-organized actors on the market can and do influence developments in their direction especially when up against less well-organized competitors. For example, well organized actors in the steel industry have been able to sway the market in their favor and away from concrete structures: "If you look at what has happened to the construction industry in the UK over the last 20 years it is reasonably obvious that one reason the market share between concrete buildings and steel buildings has swayed so much towards steel-framed buildings is specifically because the concrete industry is less well coordinated and they do not have a powerful lobby presence. Whereas the steel industry through a small number of very large companies that are extremely coordinated, have much deeper pockets, and have successfully influenced changes in regulation that favor steel buildings."[1]

Companies exist to make money, and as such, anytime something new emerges, which disrupts the manufacturing or the value chain, companies have an interest in blocking its development unless it provides a huge economic benefit for them. For something as broad and ubiquitous as construction materials, the profit margins are so low that innovation can be regarded as very disruptive to the established actors in the market.[3]

Any change to current regulatory processes takes time, and regulations are very much a political issue. Academics agree that they have little to no influence in that process.[5] It is well known that industry has a great deal of influence on the regulatory process through lobbying efforts.[4] Larger companies, specifically manufacturers due to their size, massive lobbying efforts, and large market share maintain an extraordinary influence on the construction industry. Due to their purchasing behavior, some can exist as quasi-regulators, determining which sorts of products and product attributes make it to the market.[3]

Standardization

There has been a continual effort in many regions of the world to adopt a standardized regulatory framework designed to promote progress and innovation in building construction. The standardization of regulatory systems is necessary, as it allows for greater economies of scale and removes uncertainty. The challenge is to develop a framework that also balances regional variation in order to account for local specifications and other contextual details. The process is long and time consuming. Some products such as laminated timber have taken more than 15 years to make into the regulatory system. During this time, the product has become highly successful on the marketplace. If products show great benefits, they will be used even if regulations and standards have not yet come to a final adjudication.

Traditionally, when you talk about building materials, much of it is based on government regulation. In the EU system this emanates from the Conformité Européenne (CE) system known under its marking. Applying the rules of this system is the primary focus in Denmark, for example. In other EU countries, they are regulated under the same EU rules but there are usually some national approval standards that are also needed for some product types. Though experts in Denmark affirm there is a greater need for standardization and transparency in the regulation of products and materials,[1] especially when discussing fire regulations and bio-materials such as wood.[2]

Despite the national variation from EU standards, Europe is widely considered the leader in developing unified regulations through the Eurocodes – regarded as the most advanced consolidated regulations system. They are a set of standards meant to govern in a harmonized way throughout the European community. The Eurocodes have experienced much development over the last 20 years and as a result, many regions outside Europe are following in an effort to catch up. Further, many experts hold up the Eurocodes as a prime example of standards development: "Eurocodes have been an incredible achievement – absolutely extraordinary. It provides those in the community a whole suite of standards that are coordinated between materials and other areas of the building. Other countries have not got anywhere near to this that is why they see Eurocodes as a leading set of standards."[6]

One of the problems seen with the Eurocodes however, lies in the variation of historical techniques, requirements, tools, and materials of construction among countries. There is a base Eurocode and then every country has its own national annex, which provides very specific rules. Geography and design requirements represent an additional concern. In Sweden for instance, the requirements for energy efficiency would be massively different to those in Portugal.[1]

Getting materials into the Eurocode is challenging. There are two processes to go through: first, the committee develops the normative reference, and, second, that committee has to seek the reference to coordinate the design code, which has proven to be a difficult process.[6]

The standardization challenge is profound for radical innovations. For example, while developing Pavegen tiles, the company complied with existing US and British fire, health and safety regulations. Since the flooring was piezoelectric and had never been commercialized before, Pavegen had to development CE and EMC (electro magnetic charge) standards for their materials themselves. This challenge is particularly daunting for SMEs, which lack technical and legal departments that are experienced in dealing with such challenges.

In terms of timber, the big new development in recent years, as discussed earlier, has been cross-laminated timber. In making a European standard for a product as such, there has to be normative references which detail the manufacturing of the material, what the components are, performance specifications, and lastly, links to the design code.

The cross-laminated timber standards have been in development for at least ten years and the intention is to get them properly coordinated into the Eurocode system by 2018.[6] As such, it is going to be around 15 years to get a relatively simple product into the European standardization system. Meanwhile cross-laminated timber has developed into an important, widely used material all over Europe that is manufactured in huge quantities. Eurocodes are a great achievement, but it is not necessarily a fast or simple process to register new materials certified or registered.

Because cross-laminated timber offers such great construction advantages, it continues to be widely used despite not being a registered in the regulatory framework.[6] If a material has profound advantages and is cost effective, it will be used, regardless of being fully coordinated in a regulatory system. If one cannot find a way to use the material effectively, it is not because of regulatory obstacles, but rather, inherent deficiencies or limitations to the material or materials system.

COMMERCIALIZATION OF NEW MATERIALS REQUIRES CROSSING THE VALLEY OF DEATH

There are a range of obstacles that challenge the successful introduction of new materials at every stage of development in the infrastructure and building industries. Experts refer to these obstacles collectively as the 'valley of death'. The valley of death is the gap between science, and research, and industry and application.[3] Connecting research in materials science to real world applications through commercialization is the most challenging hurdle to overcome. Interviews with experts identified six obstacles that must be overcome before new materials or materials systems can make it onto the market. These obstacles include risk mitigation, industry conservatism, the limitations posed by pre-existing infrastructure, the lack of communication and education, and difficulty in scaling new materials for mass production. More often than not, innovative science is discovered and technologies are created that fail to find their way into commercial use.

Risk

There are many dimensions of risk associated with the introduction of new materials in the building and construction industries. The types of risk include financial risks associated with materials development and potential liability. As such, risk is often very difficult to overcome and viewed as a primary constraint to the development, and further, the commercial availability of many new materials. First, materials research is costly and time consuming, and competition for funding is strong. Second, the cost associated with the lifespan of materials is growing more important.

Funding research in the development of new materials or processes requires substantial, prolonged investment. In the United States, funding for research comes in two or three year chunks, with some funding periods lasting six months with deliverable requirements at the end. To make the kind of discoveries, and do the kind of research in order to qualify, and properly inspect materials along the way, there has to be some sort of sustained funding with periodic checks on whether the technology is actually being developed or not.[3] The market for materials in the construction industry is dominated by a few major players, who control the conventional materials systems regarded as the status quo for multi-story buildings.

Obtaining funding for research in materials is competitive. Unless a particular new material or technology is proven to be of significant economic value when compared to conventional materials, it is unlikely to receive funding for continued research.

Buildings already have a tremendous amount of risk associated with them throughout the construction process from development and associated timescales, which are combined with financial risks.[7] There is only a certain amount of risk tolerance available for testing either new approaches or materials. Much of this tolerance is absorbed elsewhere, leading towards selecting existing technologies and procedures that are less risky. Exposing oneself to unproven technologies is perceived as taking a huge risk.[7] Thus, functional errors in the materials' properties or seemingly variable miscalculations or oversights in engineering when materials are used in contextual environments are often extremely costly.

The failed launch of PEX tubing, despite being well-functioning technology today, is an example of a new material system that experienced many expensive oversights. While the product sees some use today, the history of problems with the fittings, and the materials' poor performance under exposure to different conditions, have largely dismissed it as an alternative material people are willing to commercially invest in.[7] As such, there needs to be ways to remove risk before technologies will be adopted in the building industry. One way PPPs are used is to remove risk barriers through demonstration projects to show that the new technologies are feasible and could save them money. The aforementioned Fraunhofer model in Germany – is an oft-cited example.[3]

Materials development in infrastructure and buildings is fraught with liability risk. As Luke Bisby explains, "when you want to do something new and innovative, the building codes that exist probably do not cover what you are attempting to do, which leaves you legally open to criticism should something go wrong. Whereas if you stay within conventional design and conventional materials and you meet the requirements of the building code and something goes wrong, it is very difficult for someone to hold you liable for that."[1] There is a tremendous comfort among civil structural engineers that comes from operating within the confines of the building code, which inherently prevents innovation.[1] There are very few actors involved in the building and construction industry that are willing to take such a risk.

Conservatism and industry inertia

Much of the risk involved in materials development for building and construction applications has resulted in widespread conservatism in the industry. The industry is relatively risk averse, which naturally restricts innovation. This is the dominant explanation as to why the building and construction industry rely on conventional materials systems. There is an inherent inertia, in that people generally do not like change, and there is an industry inertia that is fed by lobbying power and the desire for different industries to retain or increase their market share.[1]

The pervasiveness of conservative attitudes in many industries involved in building construction inspires a strong propensity towards what is comfortable, safe, predictable, and expected. This is, in part, explained by a profound adversity to change – rooted in political and economic dynamics – and the rejection of anticipatory models that encourage change without any external catalyst or stimulant. In many ways, the industry is very reactive - only when problems or constraints exist or are perceived to exist, does change occurs. For example, in the 1960's there were lots of new materials and new systems used, which proved to create many problems in regards to water, fire and the durability of concrete.[6]

Further, Manuel Kretzer explains that architecture is likewise developing slowly. It is a very conservative industry and that is why there is not so much new material development.[9] In architecture, there is heritage and other cultural factors that must be taken into consideration. Users are conditioned to expect particular designs or structures upon entering a building.

Pre-existing infrastructure

One central challenge to the introduction of new materials is that there is a limited need to use them independently of other materials or systems. In high income countries, most of the building infrastructure has already been built. So more often than not you are forced to work with something that is already there, which by its very nature limits the application of new materials, especially for infrastructure use.

Very often new materials are applied in order to replace existing components. The light bulb is a good example – they used to be incandescent and now they are LEDs. However, LED lights can be something completely different as they have very different properties than incandescent light. The shape of the light bulb does not necessarily need to persist, yet it remains the same due to the electrical infrastructure that is already in place in most buildings.[9] The design of light bulbs does not need to be this way, and this is viewed as backwards and restricting in terms of new material application and development.

There is slightly more potential for new materials to gain traction in emerging markets not limited by existing infrastructure, given the progress of development. However, there are not many examples anywhere in the world where new materials are applied in a really innovative or novel way. Even in the Middle East, for example, where massive development is happening, and giant towers are being built, construction is based on existing technologies that have been around for 150 years.[9] There are a number prototypical projects or artistic experiments, where they are trying to introduce and experiment with new materials, but they are not really seen in architecture yet. The International Building Exhibition in Hamburg had a number of smart material houses for example. They were implementing a number of materials in a new way, albeit on a small scale, but the architecture was more or less the same – it was still shoebox-style architecture.[9]

Complex regulatory processes

Asking the industry what the primary obstacles are in the introduction of new materials for structural use in buildings they will say that there are many tests they must fulfill and certifications they need to obtain prior to entering the market.[2] In the European and US contexts, regulation is a huge challenge. With new materials in buildings, the end-users need assurance that the material is useful, safe, reliable and that all the risks and liabilities have been mitigated to a degree comparable to existing materials.[7] This is precisely why standards are used, but standards have to first be developed. Standards development however, can be a long and cumbersome process. With a novel material based on a new technology or chemistry, the standards community has to work 8 to 9 years to develop new standards.[7]

More specifically, fire is more controlled than any other regulatory part of the system, but the primary issue in the UK design system for instance, is the question of who is responsible, and who is going to guarantee the product or the system? Thus, the key to commercialization surrounds insurance.[6] As such, the stages in fire regulation are in many cases, quite complex, in order to ensure the building meets the standards expected by the end-users. For example, there is a first stage of gaining building regulation approval, which is very light touch and is mostly concerned with design aspects such as fire escape plans. Second, there is a fire certificate of public buildings, where a building certificate is required, and fire authorities are involved. It is quite a difficult process that involves everything from the properties and safety of the materials themselves, to the structural design elements of the building.[6] In this regard, it may be unclear or particularly expensive for designers and others attempting to enter the market, to fully understand or fund the required certification.

This may come easier to larger companies already established in the market with conventional materials, which know more about what is actually needed in relation to tests and standards.[2] In this case, they are better prepared to bring new products into the market. On that account, the innate complexities in developing standards and regulations that offer safety through insurance mechanisms is a long-standing barrier to commercialization for many new materials and their application in buildings.

Lack of communication, the education "gap", and new skills development

The pervasive lack of dialogue between key stakeholders throughout the process of new materials development is a central challenge in realizing the commercial potential of many products. There also exists a discrepancy in the level of education and understanding between the stakeholders involved that ultimately limits communication. As Manuel Kretzer notices, "it is almost impossible to communicate with some scientists or academics if you do not have a basic knowledge – they either do not take you seriously, or they want to know what the problem is, so they can picture an application and develop for it. But if you have a basic understanding of what they are doing, you can communicate in a very different way. You can also come up with new ideas, rather than telling them what you want, and they deliver a product."[9] It is this two-way communication that feeds innovation, but this takes a certain degree of 'scientific literacy'.

There needs to be better education on the usage and the property space available to the new material, such that designers know what is out there, and they know that they just do not have to go with whatever conventional systems currently exist.[3] In addition, there needs to be education on the pros and cons of the use of a new material. Lastly, from a training perspective, there needs to be some sort of continuous education of the stakeholders as to what new opportunities are there and what kind of benefits the new materials can enable.[3]

With new materials, there is a lack of empirical knowledge.[9] Providing architects with these materials as finished products without this understanding makes it very restrictive to work with. In some ways it is a vicious circle – architects and designers cannot come up with new ideas because the materials and space they have access to do not necessarily fit with new concepts."[9]

Manuel Kretzer contends architects often only have a notional understanding of new materials. This shallow understanding of materials limits the development of new design concepts and the better use of materials and space. “Materials are usually presented in a superficial way in a material lab or catalogue, where you only see the surface and maybe you are able to touch it, but still you really do not get to know the material, and the material properties.”[9] This is typically not a problem if it is a static, conventional material such as wood or concrete. There exists a certain, historical, empirical understanding of them. One can easily anticipate what these materials do and how they can be applied.[9]

The challenge is to expose architects and specifiers to new ways and methods. “Materials libraries and conferences help, but do they attract the people who need to know about new materials?” asks Christopher White. As well, how do you get people in this situation exposed to the opportunities offered by new materials or processes?[7]

There is a gap in the transfer of knowledge, and it takes enormous effort and investment to bridge this gap. Materials are rejected at every stage. Not all new materials will find industrial developers, and not all industrial development will succeed, so at every stage materials will drop out, but the lack of the right skills is one of the biggest challenges.[6] Richard Harris provides an example: “Weather conditions recently damaged many roofs in UK, which were built 40 years ago. When asking insurance companies to change the roofing, most of them would suggest rebuilding them in the same way, which is actually completely out of date. The problem is that none of them have the skills to install a roof in a different way. Therefore, for the new materials to be properly adopted, the right skills are needed.”[6]

If materials are truly innovative, this requires using it in a different way and in a different context than conventional materials. Getting to the person with the tools at the end of the line, who is actually applying and installing these materials and making them understand it, is a huge challenge. To illustrate, there are cases of companies like Hilti, which have been famous for innovations in fixings. Yet, they have gone through the process of having fixings fail, because they were poorly installed. Looking at Hilti now, they have much more emphasis placed on developing the tools necessary for installation, training the installers, and providing support for designers. Even for a very simple product, there has to be a support structure.[6]

The legal and financial consequences of using materials incorrectly are huge. Indeed, the process of developing new skills for the use of new materials is the biggest challenge – much bigger than regulatory constraints. We typically think about big multinational contractors, employing subcontractors, who know exactly what they are doing. But in fact, that is not a nature of construction. Construction is done by low-skilled, poorly trained individuals, and is poorly regulated. The people who are responsible for reassuring that materials are used correctly are the manufacturers or the promoters of the materials.[6] They should be selling the materials with training packages and with full data on how they should be used.

There is a need for networks that open new channels for communication, education, and innovation across all stakeholders involved. Greater involvement throughout the entire process will not only be good for industry because the feedback loop is increased, but also for academia, testing institutes, and regulatory bodies since there will be an increased awareness in regards to the demands and the challenges in the market.

Difficulty in scalability, bulk production, and longevity

Scalability is a huge challenge in the introduction of new materials. As a result, there are probably hundreds of thousands of transformative or revolutionary materials that are reported by academia sitting in cardboard boxes on the shelves of offices and labs that will never be applied in the construction industry. While many can be made to small and moderate production, the ability to take that material and those properties to mass manufacture is a huge challenge.[3] Academics are often not connected with commercial challenges and manufacturing, so when they determine some properties, such as strength or durability on a tiny little piece, there is no guarantee that that will transition all the way through to commercial application. There are a lot of interesting ideas, but the problem of being able to economically scale them, keeps many of them from getting there.[3]

New materials are usually not developed for architectural purposes. Rather, they are mostly being developed by the entertainment, medical, defense, transportation, and sports industries. Thus, architects cannot apply them in buildings due to cost and lack of architectural scale.[9]

Manuel Kretzer hypothesizes “maybe it is not the materials that have to change in the future – it could be that architecture has to change in the future.”[9] Perhaps materials do not need to last for twenty years, and maybe it is enough that they last for 2 or 3 years if economics allow them to be mass produced so that they can effectively compete with conventional materials. This gives a different dimension to architecture – when there are materials in which time becomes an issue, and which will ultimately be reflected in the types of buildings and spaces that are designed.

REEVALUATING OWNERSHIP AND BUILDING VALUE NETWORKS

Identifying ways around obstacles to the development and commercialization of new materials is a critical challenge, and trends towards open-source and decentralized processes that make new materials and technologies more accessible might be a solution.

For example, Marblar is a crowdsourcing platforms exclusively dedicated to science and technology. It is a platform that focuses on product development by connecting patented science from world-leading research institutes such as the National Aeronautics and Space Agency (NASA) and Electronics and Telecommunications Research Institute (ETRI) with students, academics, investors, and other industry professionals. In particular, Marblar hosts a category for materials and chemistry that showcases some of the leading developments in materials science today that have yet to be turned into a product and commercialized.

By contributing to the concept, market research, technical feasibility, or development, individuals earn 'marbles' which translate into ownership. Making science more accessible relies on the creative commons to spur innovation – it creates large value networks. Models of crowdsourcing differ from value chains and existing value networks because the process is more decentralized. Value networks are more effective the larger they are, and much more conducive to open-innovation.[27] Taking steps towards accessibility by sharing ideas, communicating knowledge, and thus disseminating ownership, opens entirely new realms of possibility. According to Anne-Mette Manelius, in the future, "there will be different ownership structures that will require users and manufacturers to think in completely different ways about building materials."8

Harnessing the collective intelligence through open-source science with individual incentive mechanisms offers a new platform to connect – it eliminates the need for major external drivers for materials development, limits the influence of quasi-regulators, and streamlines innovation.

Most innovation, no matter how significant is premised upon a solution to a problem – natural or constructed. Currently, materials development is very context-specific, in which the end-use application is a major determinant. Thus, there exists a perpetual tension between practicality and creativity. The challenge lies in finding the 'innovation sweet spot'. Crowdsourced innovation indicates a change from a reactive or problem-solving approach to a proactive approach with increasing degrees of freedom that allow the potential of materials and technologies to be explored to a greater extent.

[27] Chesborough, Henry. "Open Innovation: The new imperative for creating and profiting from technology," 2005.

INTERVIEWED SUBJECT-MATTER EXPERTS

1. **Luke Bisby**, Senior Research Fellow in Structures and Fire, BRE Centre for Fire Safety Engineering, United Kingdom
2. **Peder Fynholm**, Team Leader, Building and Construction – Wood Technology, Danish Technological Institute, Denmark
3. **Suveen Mathaudhu**, Program Manager: Synthesis and Processing; Materials Science Division; U.S Army Research Office, USA; and Adjunct Assistant Professor Department of Materials Science and Engineering Institution: North Carolina State University, United States
4. **Andy Buchanan**, Professor, Department of Civil and Natural Resources Engineering, University of Canterbury, New Zealand
5. **Baljinder Kandola**, Professor, Institute for Materials Research and Innovation, University of Bolton, United Kingdom
6. **Richard Harris**, Professor, BRE Centre for Innovative Construction Materials, Department of Architecture and Civil Engineering, University of Bath, United Kingdom
7. **Christopher White**, Research Chemist, Materials and Structural Systems Division, U.S. National Institute of Standards and Technology, United States
8. **Anne-Mette Manelius**, Material Ambassador/Senior Consultant, Danish Technological Institute, Denmark
9. **Manuel Kretzer**, Researcher and Tutor, Chair for Computer Aided Architectural Design, E.T.H Zurich, Switzerland, Founder and Administrator, Materiability Research Network, Founding Partner, Responsive Design Studio, Switzerland
10. **Laurence Kemball-Cook**, CEO and Founder, Pavegen Systems Ltd., United Kingdom

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APPENDIX: INTERVIEW QUESTIONNAIRE

1. Which new materials or processes will have the biggest impact on the construction and design industry in the future? (Use the following list to begin discussion)

    a. Fiber-reinforced plastics (FRP)
    b. Phase-change materials
    c. Nanomaterials
    d. Flame retardants
    e. Structures
    f. "Cradle to cradle" / LEED
    g. Organic materials

2. What areas of research in new materials is your institution developing at the moment?

3. When do you expect these materials will be introduced to the market? Within the next:

    a. 2 years;
    b. 5 years;
    c. 10 years?

4. What kinds of tests are you conducting with new materials in your organization?

5. Are you testing the new materials for fire safety? If yes, at which phase of the development process are you doing it?

6. In your opinion, who are the key stakeholders in the development of new materials in your field of research?

    a. Do you have an interesting user engagement model? If so, what are some of the key learnings that you have developed that would be of benefit to others working in the area of new materials?

    b. What networks are you a part of?

7. What do you think are the biggest obstacles to be overcome as it concerns the introduction of new materials in buildings?

8. Holistic design approaches are becoming popular research and discussion topics when discussing new materials.

    a. How is a designer, SME general contractor, etc. to keep abreast the latest developments in material science and develop a working familiarity to a whole generation of unfamiliar inventions?
    b. What recommendations could you provide to improve the collaboration among researchers, designers, building contractors, etc.?
    c. What are you plans for participating in multi-stakeholder collaborative networks?
    d. Do you use active systems to compensate for deficiencies in passive building designs and if so how?

9. What sort of challenges do new materials pose for our current regulatory frameworks? What – if anything – should be changed about our regulatory approach?

10. What sort of challenges does new materials development require of various stakeholders?

    i. Local governments
    ii. Fire research & Testing
    iii. Inspection process

11. Do you feel there are challenges/tensions emerging in regulating the current market of new materials?

12. Where do you think are the most interesting clusters in materials science and fire safety?

    a. Are you aware of any that could be fast movers?

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