TRANSFORMATIONAL
FOOD
MANUFACTURING

Transformational Food Manufacturing Workshops

8 – 9 November 2017
National Institute of Standards and Technology
Gaithersburg, MD

18 April 2018
Georgia Tech Research Institute
Atlanta, GA

EXECUTIVE SUMMARY

Vision and Goals

In collaboration with the National Institute of Standards and Technology, a consortium of industry and university partners convened at NIST, 8 - 9 November 2017, and the Georgia Tech Research Institute, 18 April 2018, around the topic of food as an advanced manufacturing industry. This report covers the first in a series of workshops laying the foundation for a national public-private partnership to revolutionize food processing and manufacturing in the US. These workshops are the spearhead of a structured and strategic initiative specifically focused on addressing two grand challenges of national and global importance:

- ensuring a stable and sustainable supply of affordable, safe, nutritious food not only for the US, but for the world, and
- equipping and empowering US food manufacturers and their supporting industries, to establish highly competitive manufacturing plants around the world.

The foundation of these challenges lie in the fact that food manufacturing is a highly competitive, low margin industry that has not fundamentally changed since the early 20th century. At the same time, global access to high quality food is essential for long-term global security and stability. Creating the manufacturing technologies for US companies to compete overseas is essential for economic growth and competitiveness in a core manufacturing industry sector.

The vision therefore is to transform the industry that systemically integrates data-rich, highly efficient processes with a well-paid, highly skilled labor force. The pathway to that transformation, in turn, is to focus on the pre-competitive and unifying technologies related to food safety and security. The goals of the public-private partnership, then, are:

- enhancing food safety, security and nutrition worldwide,
- increasing American manufacturing competitiveness (not just in food, but in the supporting industries comprising the entire supply chain) and in so doing,
- growing the US manufacturing workforce into the 22nd century.

Summary of Discussions

The starting point of the workshops was the general state of the US food industry leading to more specific conversations about critical technology gaps. There was unanimous agreement that food safety and security were appropriate foci as they reflect universal threats and challenges requiring cross-industry collaboration. At the same time, advances in safety and security will also make food production more efficient and more profitable. It was emphasized, however, that improving nutrition must be an essential parallel consideration throughout this initiative.

Though integrally connected, the opening dialogue followed two distinct paths. The first was a systems perspective of the multiple pathways of ingredients from the field to market, *i.e.* from farm-to-fork. This highlighted some of the complexities of the current supply chain, but also identified the need for data availability and integrity along the entire supply chain.

In contrast, the rising threat to the conventional centralized manufacturing model was also emphasized. The alarming increase in food recalls over the past decade, which paradoxically correlates to the rising consumer demand for healthier and safer food, was catalogued. In addition to the need for a transformation in how food is processed and manufactured, the collateral critical issues of consumer education, public policy and improvement of industry codes and standards at the intersection of agriculture and technology were raised.

The more specific problem of traceability along the supply chain was addressed. Imperfect traceability is a primary reason for the breadth of recalls when contaminations occur. This is a consideration in designing for traceability in new food production facilities. While traceability can be lost after mixing ingredients, even when discrete units remain intact, data are not automatically fully transferred along the supply chain. These ultimately raise issues of real-time sensing, smart packaging, big data and analytics. Automated identification and tracking of drugs was cited as an example where transfer from other industry sectors can be effective.

Long and Near-Term Technology Gap Areas

The next level of the discussion involved beginning to identify technology gap areas that are primary barriers to transformation. In the context of building a pre-competitive public-private partnership, it was agreed that technology gaps should be articulated in three broad categories:

- ***supply***: sustainably providing adequate supplies of nutritious food to feed a growing global population of ~10 billion people by 2050,
- ***safety***: ensuring the public safety and trust by preventing illness or injury due to physical, chemical or biological properties of food,
- ***security***: assuring availability of food, integrity of the supply chain and overall viability of the industry.

There is a high degree of overlap and connectivity of the technologies and processes necessary to enable transformations in each area. The underlying cross-cutting technologies include:

- using reconfigurable ***automation/control*** equipment,
- developing ***materials/coatings*** to make food contact surfaces, including ***packaging***, safe while hostile to contaminants,
- deploying ***sensors*** for automation, sanitation, and traceability,
- creating a ***data*** and ***analytics*** ecosystem along the entire food supply chain,
- preparing a ***highly skilled***, technologically literate food manufacturing ***workforce***,
- establishing ***manufacturing and data standards*** integrated with ***safety standards***,
- exploring ***long-range R&D*** opportunities related to new food sources and manufacturing methods, and
- building a focused ***public policy and education*** effort integrating advanced manufacturing with food supply, safety and security as a single recognizable enterprise.

Near Term Opportunities

Initial detailed discussions into projects or areas in which early foundational advances could be made yielded five themes. Detailed listing of ideas and the categorization process are summarized in the full report and in Appendix I. The five themes were:

Advanced process sensor technologies for food safety and security –the need for high resolution, real time sensing, and the associated data and analytics, for food safety and security.

Advanced packaging and sensors for consumer information and awareness – focus on consumer assurance of the absence of pathogens or allergens, that ingredients can be traced to their sources, and information about the environmental history and quality of the food.

Artificial intelligence and virtual/augmented reality for design and analysis – tapping into technologies employing artificial intelligence, virtual or augmented reality with applications from market analysis to process design and modeling for safety, security and efficiency.

Advancing process technologies for safety and efficiency – addressing i) needs for smaller, local and highly adaptable technologies, and ii) on making current, large-scale batch operations safer, more secure and more agile to meet rapidly changing consumer demands.

Integrating data and communication across the supply chain – establishing robust, accurate and complete data and analytics across the entire supply chain, *i.e.* from farm to fork.

Conclusions and Recommendations

Two seminal workshops on the topic of food as an advanced manufacturing industry were convened in November 2017 and April 2018. The objective of these meetings was to begin building a public-private partnership focused on transforming how food is processed and manufactured into the future. Funding through CESMISS for an initial round of projections is being explored while additional sources including USDA-NIFA and the NSF are also being pursued. Emphasis for the discussions was on capturing the voice of industry leaders in shaping directions and setting priorities. Workshop agendas and participants appear in Appendices I and III, respectively. The key outcomes from these conversations were:

- the initiative must be built around the pre-competitive themes of ***safety***, ***security*** and ***supply*** with recognition that ***nutrition*** is a critical component of the effort,
- technology gaps can be categorized into seven broad areas: ***automation & control***, ***sensors***, ***data & analytics***, ***antimicrobial materials & coatings***, ***codes & standards***, ***workforce***, ***public policy & education***,
- ***traceability*** was identified as a critical cross-cutting data & analytics challenge for the industry,
- five initial areas for early collaborative project development (with significant overlap with CESMII's mission) were identified:
  - ***advanced process sensor technologies*** for food safety and security
  - ***advanced packaging and sensors*** for consumer information and awareness
  - ***artificial intelligence and virtual/augmented reality*** for design and analysis
  - ***advancing process technologies*** for safety and efficiency
  - ***integrating data and communication*** across the supply chain.

The next workshop is scheduled to be held at the General Mills headquarters in Minneapolis, MN on 1 August 2018. This will further explore ideas presented in §5 and lay the groundwork for a project call by CESMII. While collaborative projects develop through 2018 and hopefully start in 2019, additional workshops focused on key technology gap areas articulated in §4 will be planned in the same time period.

Contents

1. Introduction

In collaboration with the National Institute of Standards and Technology, a consortium of industry and university partners has been meeting around the topic of food as an advanced manufacturing industry. This is part a number of workshops laying the foundation for a national public-private partnership that will revolutionize food processing and manufacturing in the US. These workshops are the spearhead of a structured and strategic initiative specifically focused on addressing two grand challenges of national and global importance:

- ensuring a stable and sustainable supply of affordable, safe, nutritious food not only for the US, but for the world, and
- equipping and empowering US food manufacturers and their supporting industries, to establish highly competitive manufacturing plants around the world.

Perhaps the greatest impediments to solving these challenges lie in the fact that food manufacturing is a highly competitive, low margin industry that has not fundamentally changed since the early 20th century. At the same time, global access to high quality food is essential for long-term global security and stability. And creating the manufacturing technologies for US companies to compete overseas is essential for economic growth and technological competitiveness in a core manufacturing industry sector.

The vision therefore is to transform the industry that systemically integrates data-rich, highly efficient processes with a well-paid, highly skilled labor force. The pathway to that transformation, in turn, is to focus on the pre-competitive and unifying technologies related to food safety and security. The goals of the public-private partnership, then, are:

- enhancing food safety, security and nutrition worldwide,
- increasing American manufacturing competitiveness (not just in food, but in the supporting industries comprising the entire supply chain) and in so doing,
- growing the US manufacturing workforce into the 22nd century.

This report provides an overview of results from two workshops, the first held 8 – 9 November 2017 at NIST and the second at the Georgia Tech Research Institute on 18 April 2018. It provides principally industry perspectives on a vision and roadmap for food production in a rapidly changing environment and lays the groundwork for future conversations needed to identify underlying science and technology development necessary to realize that future. It builds on previous workshops and discussions dating back to 2015; a collection of documents including an introductory video produced from the seminal May 2015 workshop may be found at www.transformfoodmfg.com. As discussed in §5, these workshops also serve as a mechanism for developing projects potentially to be funded under the Clean Energy Smart Manufacturing Innovation Institute.

2. The Future of Food Safety and Security

2.1 The Food and Beverage Industry, an American Success Story – The food manufacturing industry worldwide has enjoyed astonishing growth over the last two centuries and is credited with bringing many innovations and technologies to the forefront in the areas of food processing, nutrition, and packaging amongst others. Breakthroughs in manufacturing and technology significantly improved the quality and dietary content of food for the US population, guaranteed a safe and secure supply, enhanced dietary intake of the average person and, together with the great advances in medicine, is responsible for the significant increase of life expectancy over the last century. The quality of life we have come to expect and enjoy in the western world and the prospects of improvement of the developing world is highly dependent on the future success and evolution of the US food and beverage industry.

Much of the thrust of this innovation activity coincided with the industrial revolution. It first took place in Western Europe, and later in North America. Entering the 20^{th} century, a number of driving forces created conditions for the formation of food & beverage manufacturing and R&D hubs in the US and Canada. Key accomplishments of the industry over the last hundred years include: *safety*, *affordability* – macro nutrition, *availability* – micro nutrition, *quality* and *convenience*.

2.2 The Rising National and Global Food Crisis – In the last fifty years, however, the industry has not continued on a consistent and broad transformative path. In that same time period, the global population has continued to grow at an exponential rate. As a result, poverty, which manifests as hunger of epidemic proportions, is a major destabilizing force in the world. In developing nations, up to 40% of the food supply is lost to spoilage, contamination and mishandling before it gets to market. In the developed world, an equivalent amount is lost through waste, after the food is processed. It should be noted that preventing food waste could feed an additional 2 billion people. This situation demands more creative processes and components in food design, development and manufacturing. It is at the heart of the Food Safety Modernization Act recently signed into law.

In the U.S., poverty presents less as a problem of hunger than one of quality of life. Americans living in poverty lack the financial resources to acquire healthy, nutritious foods. The obesity crisis is inversely correlated to income. The food processing technology and supply chain also lacks the flexibility to serve lower sales volume urban neighborhoods resulting in large “food deserts” across economically depressed areas. Market factors such as manufacturing costs, numerous competitors, manufacturing overcapacity and limited use of advanced manufacturing technologies throughout the production pipeline create a highly competitive, extremely low margin industry facing significant challenges to make investments required to produce improved, more abundant food products to meet growing national and global demand. As a result, food manufacturing in the 21st century is largely done using the same 20th century processes.

The causal relation between food and water availability with rising global instability and the rising tide of terrorism is becoming increasingly obvious. This, in turn, threatens the safety and security of the nation’s food supply chain. Additionally, despite the fact food sanitization is one of the biggest production expenses it still remains one of the greatest threats to our food safety and security due to lack of modern technology and consistent application of sanitation policies. Approximately four hours of each day in a food manufacturing plant are spent cleaning and disinfecting equipment and surfaces; the nation’s food manufacturers annually expend ~$10B, or 2-3% of sales, on sanitation. This cost reflects how energy and water intensive sanitation (and indeed food production in general) is. The food and beverage industry accounts for nearly 7% (>1,200 trillion BTU) of the U.S. industrial energy consumption. These costs must be borne while margins are minimal, forcing major corporate restructuring to maintain profitability. A major source and vector of food contamination is the high number of people who physically handle manually food during production. This also highlights vulnerabilities of our food production system to possible intentional biological or chemical attack that can be easily mitigated through processes and new technology installed in the food factories of the future.

2.3 American Food and Beverage Manufacturing, an Industry Under Stress – Currently the food and beverage industry employs 1.46 million individuals and it represents one of the nation’s largest, most valuable industries. This sector is responsible for more than 10 percent of all manufacturing shipments, and annual U.S. food manufacturing receipts climbed from $459 to $748 billion from 2002 to 2012.

Though there is, in fact, quite a bit of automation and advanced manufacturing integrated in some sections of the industry, the actual processing of food (*i.e.* development, processing, packaging and transport) has largely remained a highly labor intensive, 'low-tech' enterprise. This is exacerbated by the fact that the manufacturing processes and plants employed by the US food industry currently are at least thirty to forty years old or are modifications and evolutions of technologies that were invented in the early 20th century. No critical and transformative technology has been brought forward in food manufacturing in the last fifty years (except in beverage manufacturing and certain high volume commodity processing) that would propel the industry towards meeting contemporary consumer demands for more fresh, less processed and more natural products.

In spite of changing consumer trends, the industry currently is immersed in an exhaustive exercise of cost cutting which prohibits the focus of capital and resources on the emergence of a new demand for CPG products that are classified as Ready-to-Eat (RTE) as opposed to traditional Ready-to-Cook (RTC) products. Consolidation and infusion of private equity management has further severely reduced innovation and investment in new technologies or products. Capital investments principally are now only to repair and support current factories and infrastructure. Simultaneously, massive reduction in trained management and technical personnel is depleting the industry of the innovative driving force needed to produce next generation technological breakthroughs.

This critical gap in US food manufacturing capability, *i.e.* to produce and distribute ***safe*** RTE products, led to the recent increase of foodborne illnesses outbreaks that precipitated several major recalls. According to a survey by Grocery Manufacturers of America, 77% of the food executives surveyed considered a possible food recall as "a catastrophic event" in their company. With the average cost of a Class I recall around $30 million, this is the single biggest threat to the profitability of the US food industry; this does not even account for the damage to national brand equity.

At the same time, foreign competition, especially from Asia with lower cost structures, are forcing US food companies to further retract and compete on cost, and not on protectable IP-based sustainable competitive advantages. If the technology gap were allowed to grow, US companies will no longer able to produce the quantity and quality of food required by the growing population. And there will be a negative trade impact as the US transitions from an exporter to importer of high value finished food products and an exporter only of lower value raw material (corn, soy bean, potatoes, canola, sunflower seed etc.)

In toto, the very safety and stability of the planet depends the availability of adequate agricultural commodities and on transforming the US food industry into one that is highly automated, controlled, efficient, safe and secure. Translating and integrating existing technologies and practices from the automotive, aerospace and electronics industries to food (*i.e.* focusing at TRL 4-7) is essential for making more, better, cheaper, healthier, safer food for an exponentially growing global population. This is a problem well beyond the scope of any one company. It will require a pre-competitive public-private partnership with strong support from federal and state agencies.

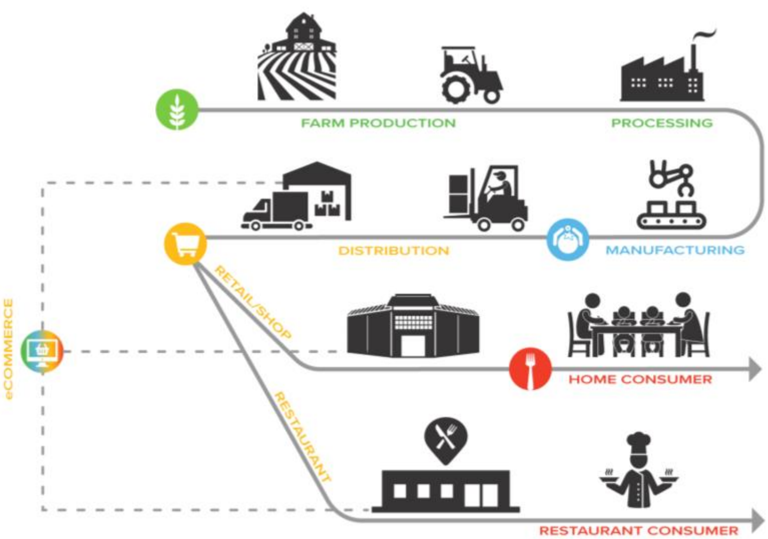
2.4 Consumer Trends and Emerging Disruptors – Pressures on food safety and security are occurring in an environment of rapidly changing consumer perceptions and demand. Led by Amazon and Walmart, there is a rapidly growing on-line retail market that is impacting traditional brick and mortar stores. According to statistics from the U.S. Census Bureau, the percentage of on-line retail sales have increased from 4.2% in Q1 of 2010 to 9.1% in Q4 of 2017[†]. There are projections that on-line retail sales will increase from $409B in 2017 to over $638B by 2022[£].

† US Department of Commerce, US Census Bureau. n.d. *Quarterly share of e-commerce sales of total U.S. retail sales from 1st quarter 2010 to 4th quarter 2017*. Statista. Accessed 3 May, 2018. Available from https://www.statista.com/statistics/187439/share-of-e-commerce-sales-in-total-us-retail-sales-in-2010/.

The potential exists for e-commerce to capture 50% of all retail sales in the future. More than 23% of sales in China are already on-line¥ while on-line purchases of books in the U.S. far exceed the 50% mark. At the same time, signs of a 'gig' economy are emerging in which an increasing percentage of the workforce is self-employed; ride share companies like Lyft and Uber are examples of larger corporate structures built around the independent worker.

How this will play out in the food industry is still to be determined. There are, however, a number of mega-trends that are consistent with broader society expectations and change. Growing anti-mainstream sentiment is driving demand for regionally or locally grown ingredients and consumer identification with the 'farm-to-fork' philosophy. This is driving an accelerating demand for flexibility and change. Consumers want safe, natural, low sugar food with clear, understandable labeling. Animal welfare has become a priority. Ultimately, the ever-increasing importance of the consumer experience in both product and service transactions is particularly true when it comes to food.

An illustration of where and how societal disruptors are impacting the food supply chain is shown below. The traditional supply chain is shown as a solid line. This is a model that has functioned for roughly a century ever since the industrial revolution led to the urbanization of society and altered how food was processed and distributed. As with many of the manufacturing industries throughout the twentieth century, production was (and is) highly linear and centralized. Raw materials/ingredients were aggregated from farms/ranches and delivered to centralized processing plants. From there, finished product is transported to distribution sites from which it goes either to grocery stores or to restaurants.



The effect of societal and market trends on the food industry are indicated by the dotted lines. Consumer demand for fresh, on-demand food is disrupting the centralized processing - production - distribution model. There is pressure for localized production that leverages the emerging e-commerce paradigm.

At the same time, the current regulatory structure in the U.S. has been criticized for being both too conservative as well as too convoluted to allow the food industry to proactively adapt to the changing society and economy. Multiple agencies maintain standards and regulations that are frequently conflicting and established for processes, practices and a supply chain dating back to the early/mid 20th century. As such, a system intended to ensure food safety and security may in fact be doing just the opposite.

£ Statista. n.d. *Retail e-commerce sales in the United States from 2016 to 2022 (in million U.S. dollars)*. Statista. Accessed 3 May, 2018. Available from https://www.statista.com/statistics/272391/us-retail-e-commerce-sales-forecast/.

¥ eMarketer. n.d. *E-commerce sales as percentage of total retail sales in selected countries in 2017*. Statista. Accessed 3 May, 2018. Available from https://www.statista.com/statistics/255083/online-sales-as-share-of-total-retail-sales-in-selected-countries/.

3. Traceability Across the Supply Chain

***3.1 Traceability at the nexus of food safety and consumer confidence* –** A key problem is the lack of quality data and analytics across the entire supply chain. Over 31,000 food and beverage manufacturing plants located throughout the US are engaged in converting raw agricultural materials into products for intermediate or final consumption. Food processing typically involves extended supply chains with activities common to manufacturing such as transportation, processing, testing, packaging, tracking, and storage. The most important goal of any food supply chain is safety. Traceability is essential to safety. If a potential food safety problem is identified, an effective traceability system can help isolate and prevent contaminated products from reaching consumers (ref).

Consumer confidence in food safety has fallen significantly. Consumer confidence in the safety of the food supply has fallen from 20% in 2012 to 12% in 2016. Researchers are attempting to change this perception through whole chain traceability.

Traceability is the ability to track food products through all stages of harvesting, processing, and distribution. Current traceability regulations rely on being able to track food products one step forward and one step back at any point in the supply chain. This point to point traceback in the event of a food safety event is inherently slow, even with good records at each point in the supply chain. The Food Safety Modernization Act of 2011 (FSMA) requires that records be kept in digital form to improve traceability. However, this is only a small improvement to what would still be a point to point traceback system. A more comprehensive, whole-chain traceability system is needed that facilitates rapid information transfer up and down the supply chain.

***3.2 Restoring confidence with whole chain traceability* –** Whole chain traceability uses advanced technology and information standards to offer visibility into a product's movement from raw ingredients to production to retail. This not only helps improve operations, but also provides a foundation to prevent any product contamination from reaching consumers. Whole chain traceability will also will help organizations comply with new regulations. A whole chain traceability system provides unique opportunities to provide consumers enhanced access to information. Instead of only having access to the traditional product label, any data generated and shared in the supply chain could potentially be viewed by the consumer using any smart device. As more supply chain members are included in the system, information for any product would be available, including those composed of multiple ingredients. Implementation of whole chain traceability can improve food safety, increase consumer confidence in the food supply, promote sustainable production strategies, and reduce food waste.

***3.3 Traceability standards and solutions* –** As food supply chains diversify, more transactions occur across companies and across national borders making tracing products more difficult. Regulatory and technological solutions have been slow to respond. Vertically-integrated, tightly controlled supply chains are able to effectively trace products and ingredients because the information flows within one system. In order to achieve whole-chain traceability across a diverse supply chain, each entity in the chain needs to share their information. The more information that is shared, the better the supply chain coordination. Lack of standards for sharing information and lack of protections for proprietary information are key obstacles to implementing whole-chain traceability systems in diverse supply chains. These obstacles have severely limited participation by firms in whole-chain traceability systems (ref). The principles of traceability are at the core of many of the FSMA regulations manufacturers are implementing now. Standards and new software can help manufacturers improve communication and data sharing across their supply chains and ultimately achieve better visibility. By providing implementation and validation tools to software developers and food manufacturers, we can reduce the cost and increase the adoption of whole-chain traceability.

4. Technology Gap Analysis

4.1 Envisioning the future state of the industry – A comprehensive technology roadmap requires articulating characteristics of the industry in its future state. A clear imperative that pervaded discussions was the need for culture change to accompany technological transformation; the future state of the industry must be innovative, proactive and nimble with design, modeling and prototyping far more rapid and flexible to account for and achieve consumer demands for taste, safety and price point. Modernization of equipment and methodologies will be required. However, given the prohibitive cost of overhauling the existing infrastructure, new business models must also be developed where, potentially, that infrastructure could be outsourced.

The food industry of the future must also quickly adopt and integrate data and analytics across the supply chain. Intelligent sensors, artificial intelligence and virtual/augmented reality need to become part of a ubiquitous wireless internet of things (IoT) framework. This not only reduces product design, development and prototyping costs, it allows for greater efficiency of resource consumption, *i.e.* energy and water.

In general, standardization and veracity of data will maximize safety and security. But standardization of machines and processes along the supply chain is equally necessary to ensure seamless data flows. New paradigms are needed to strike the right balance between automation and human labor in terms of efficiency, food safety and security, and a robust skilled work force.

In this future state, then, it is envisioned that product development, production and platforms will be integrated. Production facilities will be smaller and localized with distributed networks of factories rather than the large centralized plants of today. In addition, there will be connectivity of unit operations for safety and efficiency.

Finally, there will be a greater coupling of the underlying science and technology directly into design and production processes. There are needs, for example, to incorporate ontology and engineering properties of food into state-of-the-art computational methodologies for more effective and efficient design and simulation processes. This will have an added benefit of standardization of metrics and nomenclature with impacts on data security, legal liability and IP.

4.2 Broad technology gap areas – Keeping an eye toward the future state of the industry, the next step in the process is to identify technology gap areas that are primary barriers to transformation. In the context of building a pre-competitive public-private partnership, these gaps should be articulated in three broad categories:

- ***supply***: sustainably providing adequate supplies of nutritious food to feed a growing global population of ~10 billion people by 2050,
- ***safety***: ensuring the public safety and trust by preventing illness or injury due to physical, chemical or biological properties of food,
- ***security***: assuring availability of food, integrity of the supply chain and overall viability of the industry.

In the context of ensuring a sustainable food ***supply***, *WATER*, *LABOR* and *PRODUCTION* are critical sub-issues. In many respects, ensuring sufficient clean water to grow the world's food supply is one of the greatest threats to global stability facing mankind. Technology foci need to be on *PURIFICATION*, *CONTAMINANT REMOVAL* and *DETECTION*. And this requires a parallel approach including both developing new technologies as well as technology transfer from other industries.

As noted, consumer trends are pushing for development of technologies and systems that adapt or grow production capacity. This includes increasing demand for strategic regional location to meet local consumer needs. Even with increased automation, the growing population and demand for food will drive expansion of the size and capacity of the *LABOR FORCE*. There will likely be a paradigm shift in the skills required of workers in the future. Growing the *LABOR FORCE* will therefore require a concomitant effort in *EDUCATION* and *TRAINING*.

There is an automation and labor aspect to improving food ***safety*** as well. In addition to enhancing automation increase ***supply***, there is a need to develop *PREDICTIVE ANALYTICS* that can trigger proactive responses to contamination before it disperses throughout the supply chain. This, in turn, requires *ANTIMICROBIAL TECHNOLOGIES* capable of *REAL-TIME CONTAMINATION SENSING*. These capabilities would be accompanied by materials and coatings (including packaging) with *SURFACE DESIGN AND FUNCTIONALITY* to eliminate or significantly inhibit contamination. Embedded sensing in packaging is also a technology gap ripe for exploration.

Antimicrobial materials and coatings will play a significant role in reducing *SANITATION* steps. None-the-less, it is unlikely that the need for separate sanitation processes will be completely eliminated, particularly in the near term. As such, there is a need for emphasis on developing *MOISTURE FREE / DRY SANITATION* creating the potential for *DRAIN-FREE FACILITIES* and, ideally, *CLEANING WITHOUT SHUT-DOWN*.

The third broad technology gap area is food ***security***. This was discussed in part in §3. Physical food security, both availability and protecting the supply chain, are of paramount importance. This is nominally addressed in the context of ***supply*** and ***safety***. However, a major component of ***security*** is *DATA AND ANALYTICS*. Specifically technology needs related to *CYBERSECURITY*, *TRACKING*, *TRACEABILITY*, and *TRANSPARENCY* must be significantly advanced.

4.3 Cross-cutting, science and engineering based technology gap areas – It is immediately apparent that there is significant overlap in safety, security and supply. In terms of 'hard core' science and engineering, the underlying technology gaps are in the areas of automation/control, data/analytics, sensors, and materials:

automation and control

- *FARMING:* While traditional farming would not ordinarily be directly considered part of an advanced manufacturing initiative, there should be some attention paid to automation needs/opportunities in farming, particularly in the context of a critical data and analytics supply chain traceable back to the source and in the context of localized food production.
- *PREPARATION:* Food preparation is generally highly labor intensive, often dangerous and inefficient. From produce to dairy to meat, there are a variety of automation opportunities to explore. Potential for broad impact and universal applicability should undergird the discussions.
- *PROCESSING:* In many sectors of the industry, processing technologies have not advanced significantly since they were developed a century ago. Transformative automation technologies, *e.g.* transitions from batch to continuous processing, and open process automation particularly with regard to safety and security, should be explored.
- *SANITATION:* Given that ~2-3% of gross sales industry-wide is spent on sanitation, this is an area that definitely should be explored. This is, in fact, a coupled challenge including the need for improved, real-time sensing and advanced packaging and food contact materials.

sensors

- *AUTOMATION:* The issues identified above require smart automation, characterized by machine learning and adaptation to variable materials, tasks and conditions. In this regard, embedded sensors must be an integral element of the control algorithms. Best practices and technology transfer from other industries are rich topics for further discussion.

- *CONTAMINANTS:* Rapid, efficient, and low-cost detection of microbial pathogens is a grand challenge facing human food supplies. This is heightened by increasing consumer demand for fresher, minimally processed foods and expanding global production and supply chains. Both sensitivity and automation (of the sensors) are among the topics to be examined.

data and analytics

- *MANUFACTURING:* Ubiquitous introduction of sensors, for automation and microbial detection, necessarily implies large amounts of data to be acquired, processed and used in real time. Coupling the two classes of sensors (*e.g.* using contaminant levels as a manufacturing control parameter) will provide richer diagnostic, prognostic and control capabilities than the base functionality of the sensors.
- *SUPPLY CHAIN:* The transformational power of big data, however, really lies in linking the entire supply chain to create a 'connected enterprise' involving real-time data exchange, and tightly coupled, fault-tolerant connections with end-to-end Ethernet communications. Benefits include: faster time to market, lower total cost of ownership, improved asset utilization and optimization, and enterprise management.

materials and coatings

- *ANTIMICROBIAL SURFACES:* Coating and film technologies that are hostile to microbial contaminants will eliminate or dramatically reduce costly sanitation cycles by creating a safer food production environment. Advancing the science and engineering of antimicrobial surfaces is essential for reducing sanitation costs.
- *PACKAGING:* A major component of food safety and security lies in creating a low cost, biodegradable, liquid, oxygen contaminant barriers, *i.e.* packaging. There are, in addition, tremendous benefits to be derived from integrating sensors into these packaging material to monitor the condition of the contents. Environmental conditions during transport, for instance, is vitally important information for which there is currently little or no systematic monitoring.

The issue of advanced packaging highlights the point that the greatest potential for transformation may well lie at the intersection and overlap of technology areas. The coupling of automation and sensors, sensors with packaging, and data across the entire supply chain are clear examples of the need for systems approaches to the transforming of food manufacturing. Social, economic and political considerations, like emerging consumer trends, and the balance of global resources, enrich the context and conversation. This session, then, will aid in scoping the problem of transforming an entire industry into manageable and impactful steps.

4.4 Technology gaps at the intersection of technology and society – Overcoming technology gaps is only part, albeit an extremely important part, of the transformation. There are equally important, non-technical challenges identified in the workshop. These are:

- ***preparing a skilled, technical workforce:*** Workforce needs, of course, include B.S. through Ph.D. engineers to design and innovate new equipment and processes. But there will be a much greater need for a skilled technical workforce both to make and to operate these systems of the future.

- ***establishing integrated codes and standards:*** Transforming how food is grown, produced and processed will necessarily be done in an environment of increasing regulation and oversight. While food safety and security indeed demand very present and watchful eyes, food industry leaders identified over regulation, uncoordinated and contradictory requirements from multiple regulatory agencies, and inflexibility as major threats to making the transformations necessary for the industry and the public. The lack of consistent and helpful guidelines is perhaps merely reflects the divergent cacophony of ‘experts’ and the public’s inability to discern fact from rhetoric.

- ***education and public policy:*** It is recognized that any attempt to transform food manufacturing through *less* direct human contact will be doomed to failure in an environment of increasing distrust of ‘processed’ foods. Any transformation must therefore include clear and focused efforts on training, regulation, and public policy and education.

5. Near Term Opportunities

With a focus on the near term, but with an eye toward a long-term vision, a conversation in the April 2018 workshop was framed around the question, 'what would be some of the first high impact projects that would catalyze transformation of the food industry?' The question was also informally rephrased as, 'if you had a million dollars for a project, what would the most impactful thing you could do?' Industry participants were invited to provide input first with academic partners weighing in later.

A central purpose for this exercise was developing a project call by the newly formed Department of Energy funded Clean Energy Smart Manufacturing Innovation Institute (CESMII). This mission of CESMII involves building data and analytics tool sets that can help industry sectors operate more efficiently, *i.e.* with significantly reduced energy consumption. Given that the food industry is the fourth largest energy consuming sector in the nation, it is a natural focal point for CESMII. With this backdrop, the session was concluded by having each participant identify the projects or ideas that resonated to her/him most. This was cross-referenced within the context of relevance to CESMII. The full list of ideas is transcribed in rank order in Appendix II.

In the words of one participant, one of the challenges and benefits of this discussion lay simply in figuring out, or knowing, what to ask. One can see that, at this stage of the process, some proposed topics are quite generic while others are very specific. None-the-less, in looking at the list of projects/topics it is possible to categorize them into five distinct, albeit coupled, groupings.

***Advanced process sensor technologies for food safety and security* –** There was extensive conversation around the need for high resolution, real time sensing, and the associated data and analytics required, for food safety and security. There was a demarcation, however, between in-house sensing during processing and production versus sensors more geared toward consumers. This theme, then, focuses on thoughts related to sensors and data for safety and security within facilities along the supply chain. Specific ideas included:

* deploy real-time, on-line food defense diagnostics on existing safety equipment (10)
* develop and deploy wireless technology for pathogen detection (8)
* advanced food authentication (7)
* data quality and data protection (5)
* collaborative data library (3)
- in-line salt analysis; no silver nitrates (3)

Asterisk bullets denote topics nominally within CESMII scope while hyphenated bullets may be kernels of areas for a separate public-private partnership. Numbers in parentheses behind each topic indicate the number of 'votes' that topic received from the participants. Further, the ideas of data quality/protection and building a collaborative data library are actually ubiquitous and have been included across most of these thematic areas.

It should also be noted that the flow of conversation seemed to imply existence of necessary advanced sensing technologies. Consequently, the tone of the discussion was more about the use of data than the science and technology necessary to generate it. The need for further exploration of the need for enabling diagnostic, controls and materials technologies will be discussed later.

Advanced packaging and sensors for consumer information and awareness – The second grouping focused more on tools and information targeted at the consumer. In a very real sense, the same data are required from the preceding theme. That is, the consumer requires assurance of the absence of pathogens or allergens, that ingredients can be traced to their sources, and information about the environmental history and quality of the food. But this must be presented in ways that are meaningful and understandable to the public. In addition, advanced packaging including embedded sensing are key elements of this theme. Suggested topics comprising this set include:

* consumer food safety detectors (10)
- increased product shelf life ; * if it includes embedding sensors in packaging (7)
- biodegradable, compostable packaging (6)
* 'traceability to source' as a consumer/packaging tool (3)
* data quality and data protection (5)
* collaborative data library (3)

Artificial intelligence and virtual/augmented reality for design and analysis – The common thread of this third grouping of ideas was the untapped potential of technologies employing artificial intelligence (AI), virtual or augmented reality. These are innovations that have been maturing and integrated across other industry sectors. In the context of food, these can be developed across a range of applications from market analysis to process design and modeling for safety, security and efficiency. They have the potential to dramatically increase efficiency, productivity and reduce development time. More importantly, these tools can have a transformative effect on anticipating and mitigating threats long before they become problems. While enhanced sensors would further advance the efficacy of AI and virtual/augmented reality technologies in the food industry, implementation of smart systems can be deployed with existing processes. Specific topics that were raised were:

* organoleptics as a digital AI problem (11)
* virtual and augmented reality (8)
- AI/machine learning for real time market analysis (7)
* data quality and data protection (5)
* collaborative data library (3)

In discussion of relevance to CESMIII, it was posited that development of AI or machine learning tools for real time market analysis at be better aligned with activities within the Digital Manufacturing Design Innovation Institute (DMDII).

Advancing process technologies for safety and efficiency – This theme centers on equipment and processes. There were two sub-groups that emerged. One was around the need for next generation technologies that were smaller, local and highly adaptable. The second focus was ways to make current, large-scale batch operations safer, more secure and more efficient, while at the same time making them more agile to meet rapidly changing consumer demands. Making processes far less resource intensive were also identified as a high priority. Proposed projects/topics were:

- reconfigurable/changeable packaging and processing lines (9)
- process intensification of current large volume equipment (2)
- scalability at the micro-scale (4)
* portion sizing for both nutrient quality and quantity (4)
- increase electro-mechanical efficiency (5)
- motor extensibility (4)
- reduce the cost of electrical components, i.e. pneumatics (3)

- optimization study on automation, labor and co-robotics (6)
- affordable human-free sanitation technologies (10)
- water recycling in-plant (9)
- growing lettuce in salt water (2)

Integrating data and communication across the supply chain – A pervasive topic of conversation was the need for robust, accurate and complete data and analytics across the entire supply chain, *i.e.* from farm to fork. While much of the discussion centered on needs of the manufacturers/processers in the supply chain, there was an understanding that data flow into and out of the plants was critically important. Topics here, then, reflected that awareness and understanding. Suggestions included:

- automated harvesting and handling technologies (9)
* sensors for in-field harvesting; pathogenic and quality (8)
- animal welfare; health and environment (7)
* data quality and data protection (5)
* collaborative data library (3)
- advancing food distribution; i.e. transportation (3)
- build the consortium through communication education and training (3)

In the context of developing a complete picture of the food industry, these topics represent key components of a safe, secure and sustainable supply chain. If one is looking at the industry from an advanced manufacturing perspective, however, these topics may or may not be in scope. Indeed, there are initiatives in the USDA and other federal agencies designed to address, for example, high resolution sensing and automation in agriculture. Clear but coordinated delineation between advanced technology farming and advanced manufacturing of food should be a subject that is explored more deeply in the future.

6. Conclusions and Recommendations

Two seminal workshops on the topic of food as an advanced manufacturing industry were convened in November 2017 and April 2018. The objective of these meetings was to begin building a public-private partnership focused on transforming how food is processed and manufactured into the future. Funding through CESMISS for an initial round of projections is being explored while additional sources including USDA-NIFA and the NSF are also being pursued. Emphasis for the discussions was on capturing the voice of industry leaders in shaping directions and setting priorities. Workshop agendas and participants appear in Appendices I and III, respectively. The key outcomes from these conversations were:

- the initiative must be built around the pre-competitive themes of ***safety***, ***security*** and ***supply*** with recognition that ***nutrition*** is a critical component of the effort,
- technology gaps can be categorized into seven broad areas: ***automation & control***, ***sensors***, ***data & analytics***, ***antimicrobial materials & coatings***, ***codes & standards***, ***workforce***, ***public policy & education***,
- ***traceability*** was identified as a critical cross-cutting data & analytics challenge for the industry,
- five initial areas for early collaborative project development (with significant overlap with CESMII's mission) were identified:
  - ***advanced process sensor technologies*** for food safety and security
  - ***advanced packaging and sensors*** for consumer information and awareness
  - ***artificial intelligence and virtual/augmented reality*** for design and analysis
  - ***advancing process technologies*** for safety and efficiency
  - ***integrating data and communication*** across the supply chain.

The next workshop is scheduled to be held at the General Mills headquarters in Minneapolis, MN on 1 August 2018. This will further explore ideas presented in §5 and lay the groundwork for a project call by CESMII. While collaborative projects develop through 2018 and hopefully start in 2019, additional workshops focused on key technology gap areas articulated in §4 will be planned in the same time period.

APPENDIX I: WORKSHOP AGENDAS

WORKSHOP PROGRAM

8 – 9 NOVEMBER 2017
ADVANCED MEASUREMENT LABORATORY CONFERENCE ROOM
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
GAITHERSBURG, MARYLAND

TUESDAY 7 NOVEMBER 2017

19:30 – 21:30	**Welcome reception and networking** ***(Homewood Suites Ballroom)***

WEDNESDAY 8 NOVEMBER 2017

7:30 – 8:25	**Breakfast** ***(NIST Advanced Measurement Lab Conference Room)***
8:25 – 8:45	**Welcome and Overview** *Simon Frechette; NIST* *Tim Wei; UNL)*
8:45 – 12:00	**Session 1: The Future of Food Safety and Security; Integrating Advanced Manufacturing into the Food Industry**
8:45 – 9:45	*Overview / Case Studies* *Matt Chang; Chang Industrial* *Jim Costa; Sneakz* *Tim Amlaw; Pure Harvests*
9:45 – 10:45	*Round Table Discussions: Participants reflect on the plenary talk, expanding on and adding to the broad challenges already identified.*
10:45 – 11:00	*Break*
11:00 – 11:30	*Report Outs: Each round table group reports on key outcomes from their discussions.*
11:30 – 12:00	*Open Discussion*
12:00 – 12:45	**Lunch** ***(sponsored by ADM)***
12:45 – 16:00	**Session 2: Traceability Along the Supply Chain**
12:45 - 13:45	*Overview / Case Studies* *Simon Frechette; NIST* *Pablo Coronel; CRB* *Jim Wetzel; CESMII / General Mills* *Brad Elrod; Secure Concepts*
13:45 – 14:45	*Round Table Discussions: Participants reflect on the plenary talk, expanding on and adding to the technology gaps already identified.*
14:45 – 15:00	*Break*
15:00 – 15:30	*Report Outs: Each round table group reports on key outcomes from their discussions.*
15:30 – 16:00	*Open Discussion*

16:00 – 17:00 **NIST Tour**

18:30 – 20:00 **Dinner *(Homewood Suites Ballroom)***

THURSDAY 9 NOVEMBER 2017

7:45 – 8:45	**Breakfast *(NIST Advanced Measurement Lab Conference Room)***
8:45 – 12:00	**Session 3: An Integrated Look at Key Technology Gap Areas; Automation / Sensors / Materials / Data**
8:45 – 9:45	*Overview / Case Studies* *Theo Lioutas; LGG Consulting / UNL* *Jose Leboreiro - Hernandez; ADM* *Dave Lundgren; Rubicon Labs*
9:45 – 10:45	*Round Table Discussions: Participants reflect on the plenary talk, expanding on and adding to the broad challenges already identified.*
10:45 – 11:00	*Break*
11:00 – 11:30	*Report Outs: Each round table group reports on key outcomes from their discussions.*
11:30 – 12:00	*Open Discussion*
12:00 – 13:30	**Lunch**
13:30 – 15:45	**Session 4: Synthesis and Next Steps**
13:30 – 14:15	*Overview of Opportunities* *Tim Wei; UNL* *Dean Schneider; CESMII*
14:15 – 15:00	*Round Table Discussions: Participants break into round table discussions to identify and prioritize technology gaps and suggested next steps.*
15:00 – 15:45	*Report Outs and Discussion: Each round table group reports on key outcomes from their discussions.*
15:45 – 16:00	**Closure**

WORKSHOP PROGRAM

18 – APRIL 2018
GEORGIA TECH RESEARCH INSTITUTE CONFERENCE ROOM
GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA

WEDNESDAY 18 APRIL 2018

09:00 Welcome; Introductions; Objectives

09:20 Overview of CESMII and the Project Funding Opportunity

10:30 Break

10:45 Questions for Industry:

I1) If you could magically transform your company today, what would you do? How would your company be different?

I2) If you still had the authority, but couldn't just wave a wand, what steps would be needed to make the transformation?

12:00 Input from Academics:

A1) Based on the responses to *Questions 1) & 2)*, what is feasible with current science and technology? What could be developed in the near-term (1-5 years), mid-term (5-10 years), long-term (10+ years).

12:30 Lunch

13:00 Question for Industry:

I3) If you had access to some of the best minds, facilities and up to ~$1M in external (*i.e.* CESMII) funding, what would be your first step(s)?

14:00 Input from Academics:

A2) Based on the responses to *Question I3)*, where could your university contribute? Are there better/higher impact starting points that would provide greater ROI for industry?

14:45 Break

15:00 Combined Discussion

C1) Are there pre-competitive, cross-cutting synergies that might emerge from *Questions 1) - 3)* that might combine into a compelling collaborative effort?

C2) Which of these areas align with CESMII mission and objectives?

15:45 Closure

APPENDIX II: NOTES

CONSUMER MEGATRENDS
- transformation of commerce from bricks and mortar to e-commerce; project 50%/50% split across all markets
- emergence of the 'gig' economy
- increased importance of the consumer experience in both product and service transactions

FOOD MEGATRENDS
- accelerating pace of change
- anti-mainstream
- consumer identification with 'farm to fork'
- regional / local
- natural
- low sugar
- flexibility
- safety
- labeling
- consumer concern with animal welfare

FOOD INDUSTRY OF THE FUTURE
- proactive and nimble
- innovation and incubation (?)
- streamlining of codes and standards in the context of IP, to attract more capital at a higher rate
- integration of data analytics along the supply chain
- deployment of artificial intelligence for prototyping and commissioning
- rapid, flexible modeling and prototyping to achieve consumer demands for taste, safety and price point
  transformation of industry culture and mindset to be innovative, proactive and transformative
- product development and production are integrated
- product platforms are integrated for increased efficiency
- smaller localized production facilities
- distributed factory networks
- connectivity of unit operations for safety and efficiency
- standardization of metrics and nomenclature
- a common understanding of what is mean by 'standards' and 'guidelines'
- clear standards and guidelines for data security, legal liability and IP
- modernized equipment and methodologies for enhanced safety and security
- new paradigms in the balance of automation and human labor in terms of efficiency, food safety and security, and a robust skilled work force
- ubiquitous wireless IoT
- intelligent sensors
- deploying technology to enable flexibility in sensing, integrating data flow across
- integration of modeling portfolios into a comprehensive design space
- virtual reality is an integral part of the modeling and design process
- new business models where infrastructure can be outsourced
- machines and standardizing equipment to make that seamless data flow possible
- a new business paradigm in which connectivity enables / drives simulation for rapid response
- integration of science, e.g. ontology, and state-of-the-art computational methodologies into modeling, simulation and development processes
- incorporating engineering properties of food into design and simulation processes

- distributed test beds
- capabilities to monitor resource consumption (e.g. energy and water) as an efficiency and sustainability metric/tool
- commonality of data models
- veracity (accuracy) of data

FIRST STEPS
- knowing what to ask
* organoleptics as a digital AI problem (11)
* deploy real-time, on-line food defense diagnostics on existing safety equipment (10)
* consumer food safety detectors (10)
- affordable human-free sanitation technologies (10)
- water recycling in-plant (9)
- automated harvesting and handling technologies (9)
- reconfigurable/changeable packaging and processing lines (9)
* virtual and augmented reality (8)
* develop and deploy wireless technology for pathogen detection (8)
* sensors for in-field harvesting; pathogenic and quality (8)
* advanced food authentication (7)
- animal welfare; health and environment (7)
- increased product shelf life ; * if it includes embedding sensors in packaging (7)
- AI/machine learning for realtime market analysis; perhaps better for DMDII? (7)
- biodegradable, compostable packaging (6)
- optimization study on automation, labor and co-robotics (6)
* data quality and data protection (5)
- increase electro-mechanical efficiency (5)
- motor extensibility (4)
- scalability at the micro-scale (4)
* portion sizing for both nutrient quality and quantity (4)* 'traceability to source' as a consumer/packaging tool (3)
- reduce the cost of electrical components, i.e. pneumatics (3)
- advancing food distribution (3)
* collaborative data library (3)
- build the consortium through communication education and training (3)
- in-line salt analysis; no silver nitrates (3)
- process intensification of current large volume equipment (2)
- growing lettuce in salt water (2)

NEXT STEPS
- USDA/NIFA FACT initiative: what are the data needs of the food industry?
- 1 August workshop hosted by General Mills in Minneapolis
- sub-groups to flesh out 'first steps' ideas
- additional conversations specifically around the automation, sensors and advanced materials needed to integrate data and analytics across the supply chain

APPENDIX II: WORKSHOP PARTICIPANTS

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 # attended the 8-9 November 2017 workshop
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