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Challenges and opportunities in food engineering: Modeling, virtualization, open innovation and social responsibility☆

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ABSTRACT

Food engineering should shed its historical mindset, embrace new challenges and opportunities that the 21st century holds. Unabated scientific progress and breakthroughs highlight mounting challenges with some vital paradigm shifts. Four main challenges have been identified: modeling, virtualization, open innovation (OI) and social responsibility (SR). The shift from empirical to physics-based food modeling is paramount to benefit from new sensor technology, proliferation of the 'Internet of Things', and big-data information. An overriding part of modeling continues to be food uniqueness and complexity, consumer needs and expectations, health and wellness, sustainability and SR. Virtualization is to significantly benefit from expanding computational power, dedicated software, cloud computing, big data, and other breakthroughs. Collaboration and partnerships with all innovation ecosystem stakeholders are paramount. Academia's role as a 'startup university' requires revising its intellectual property models, curricula rejuvenating, OI, creativity, employability and SR. Food engineers are at a verge of a very prosperous future.

1. Introduction

Today, food engineering faces numerous challenges while offering many opportunities for its practitioners. This article is based on a plenary session held during the conference "Virtualization of Processes in Food Engineering" at the University of Salerno, Italy (1–3 Oct 2014) and presents the author's views on four main topics: modeling, virtualization, *Enginomics*, OI, SR, as well as on the future of food engineering. These topics and the accompanying challenges and opportunities will play an important part in creating the paradigm shifts required to reshape the food engineering domain.

2. Modeling

A model is an analog of a physical reality, albeit typically more simple and idealized. Models can be physical or mathematical and are created with the goal of gaining insight into reality more conveniently (Datta and Sablani, 2007). An observation made more than three decades ago, which still applies today, stipulated that devising a formal scheme to produce a general kinetic/mathematical model is beyond our knowledge. It outlined the following general steps for structuring a model (Saguy and Karel, 1980): (i) defining the problem; (ii) applying the theory that governs the phenomenon; (iii) expressing that theory in mathematical terms; (iv) writing a suitable computation algorithm; (v) verifying the model by comparing its results with actual experimental data. It is worth noting that fitting a model with no theoretical basis is merely data fitting, and should not be confused with a physics-based approach. Modeling verification is the last step; it is an essential and cardinal part of the modeling process and should not be circumvented. Moreover, the verification step should use a different dataset than that used to construct the model itself. These observations are trivial, but nevertheless bear mentioning.

Despite a very large number of scientific publications on modeling, their applicability to food products and processes is far from straightforward (Bimbenet et al., 2007). Food modeling remains a complicated task due mainly to a lack of knowledge concerning its mechanisms, the difficulty involved in experimentation and obtaining reliable data, and the natural variability and uncertainties surrounding most food properties. For a long time, food processing was mostly dedicated to product safety, stabilization

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and operation scale up in the industry. Process engineers applied concepts from chemical engineering and focused on time–temperature diagrams to predict and limit residual spores or microorganisms in foods (Datta and Sablani, 2007; Trystram, 2012). A new modeling paradigm known as multiscale modeling might alleviate some of these difficulties. Multiscale models are essentially a hierarchy of interconnected submodels that describe a material's behavior on different spatial scales (Ho et al., 2013).

Another topic that needs additional consideration is data availability, reliability and accuracy. In many cases, food engineers lack accurate data for their systems, and consequently use previously reported data with little control of the system used, and/or fit the wrong type of model. A good example is the utilization of Fick law claiming that diffusion is Fickian, and that the diffusion coefficient is a function of concentration. With new tools, methods, monitoring devices, accurate and adequate data collection is becoming feasible. Thus, one should expect to see more benefits of modeling, and even more of multiphysics that would furnish the possibility to test different types of data and deriving the sensitive parameters.

Modeling of foods and food processing are expected to undergo a significant shift due to the widespread proliferation of computers, lower cost, availability of dedicated and sophisticated software (e.g., Comsol, http://www.comsol.com/products), and the enormous potential of big data, microprocessing, sensing devices and connectivity (Saguy et al., 2013). Emerging technologies are already available for the development of a new generation of intelligent sensors for real-time detection and monitoring of changes in a product or process. However, the major shift will occur when experimental or "observation-based" models, where the starting point is the experimental dataset from which the model was built, undergo a significant modification toward physics-based and/or mechanistic models. The latter is based on the universal physical laws that describe the presumed physical phenomena (Datta and Sablani, 2007; Trystram, 2012).

The physics-based approach (also known as deductive, mechanistic, first-principle-based, or 'white box') stems from models of transport phenomena coupled with models describing the physicochemical changes in the product as a function of operating variables (Broyart and Trystram, 2003; Purlis, 2014). The empirical modeling approach (also known as 'black box') ignores the reactions and mechanisms occurring during the process, while aiming to find a relationship between inputs (operating process conditions, product characteristics) and outputs (final quality attributes) using an experimental dataset and mathematical and statistical tools, and linear and/or nonlinear techniques, response surface methodology (RSM), artificial neural networks, etc. A combined model may also be applied (Broyart and Trystram, 2003; Purlis, 2014). While the black-box approach seeks simplified relationships to correlate an output variable with one or more input variables, it ignores and/or circumvents the process's physical and thermodynamic mechanisms, as well as chemical and biochemical reactions. The opposite approach, termed 'white box', takes into consideration the physical changes and other reactions occurring during the process.

Physics-based modeling can be extended by using multi-physics, which involves multiple physical models or multiple simultaneous physical phenomena (e.g., drying, microwaving), and the solving of coupled systems of partial differential equations. This approach holds the potential for generality as no empirical correlations are used at the interfaces. Multi-physics mathematical modeling can drive innovation in very specific applications, and several food applications are already available (e.g., mild drying, devoted to the processing of high-added-value food products, microwaving; Marra, 2012; Marra et al., 2010).

To highlight some of the issues related to empirical modeling, here are two typical examples that are quite frequently used and yet should be considered carefully, if not scrutinized or challenged. They are the Arrhenius model and RSM.

- The Arrhenius equation has been widely used as a model of temperature's effect on the rates of chemical reactions and biological processes in foods (e.g., Clemente et al., 2014; Labuza, 1984; Saguy et al., 2005; van Boekel, 2009). However, the applicability and usefulness of the Arrhenius equation to chemical reactions and biological processes in foods, especially solids, and the relevance of the statistical–mechanical assumptions on which it is based can be challenged on several grounds (Peleg et al., 2012). Furthermore, most, if not all reported rates vs. temperatures traditionally described by the Arrhenius equation can also be described by a simpler exponential model (Peleg et al., 2015, 2014), without sacrificing the fit as judged by statistical criteria. As in the Arrhenius equation, in the exponential model the rate constant is chosen at selected reference temperature. In contrast, however, both temperatures are in degrees Celsius (not Kelvin), and the exponential constant is expressed in degrees Celsius reciprocal. The use of the exponential model eliminates the need to reverse the temperature axis direction and compress its scale. It is important to note that the use of the exponential model also makes it unnecessary to assume that the degradation's energy of activation, is universally temperature-independent, an assumption rarely if ever supported by experimental evidence (Peleg et al., 2015). Worth noting however, that the Arrhenius equation (or model) can be still be used interchangeably, but one should be aware of its several limitations.
- The second example focuses on RSM. This is a statistical technique that uses regression analysis to develop a relationship between the input and output parameters by treating it as an optimization problem (Datta and Sablani, 2007). Although modeling using RSM is very effective and useful for formula optimization in new product development, and in improving processing conditions to obtain a certain objective function and/or quality, it provides no insight into the underlying mechanisms and it is merely an experimental relationship that can be very far from, and in some cases even unrelated to the physics-based model that describes the various phenomena and/or processes. Moreover, changes in formulation and/or the conditions under which the RSM was derived are not possible. It has been previously indicated that physics-based modeling can be an important tool for food product, process, and equipment designers by reducing the amount of experimentation and providing a level of insight that is often not achievable experimentally (Datta, 2008). Hence, RSM should probably be restricted to a handful of practical and limited cases.

The above two typical examples highlight the need for a paradigm shift toward enhancing the utilization of physics-based modeling and simultaneously limiting, as much as possible, the application of empirical models. However, it is quite true that empirical models may be the only feasible and practical approach to coping with food system and process complexity, nonlinearity and natural variability. Cost may be another factor (Pantelides and Renfro, 2013) in the use of empirical modeling. As this issue is of the utmost importance to almost all industrial applications, it highlights the paramount prerequisite for careful consideration.

Utilizing an empirical-based model that is tailor-made for a unique process and industrial applications can deliver some of the benefits of a physics-based approach in a more cost-effective, reliable and sustainable manner. For example, applications for optimization using much simpler models, combined with coordination of linear multivariable controllers, have been found to be less costly to implement while still delivering a significant proportion of the benefits (Pantelides and Renfro, 2013). Nevertheless, striving for the better characterization, understanding and insights gained from physics-based modeling is one of the challenges in food engineering. Another significant challenge for modeling is supporting practitioners with the fundamental understanding and insights required to enhance physics-based model formulation and utilization, and to facilitate the generation of novel tools dealing with the increased amount of real-time information from new sensor technology, improved connectivity and the new and rich big-data resources. A paramount and overriding lingering challenge is to consider food's unique attributes, such as sensory qualities, consumer needs and expectations, health and wellness (H&W) and sustainability.

3. Virtualization

Once a model is established, it opens up a plethora of possibilities, such as computation, simulation, prediction, optimization and process analysis (Datta, 2008; Erdogdu, 2013; Ho et al., 2013; Norton et al., 2013; Saguy and Karel, 1980). These are part of a wider scheme that is described as virtualization. This term is derived from computer engineering, where virtualization is a technique for hiding the physical characteristics of computing resources from the way in which other systems, applications or end users interact with those resources. In practice, getting a Google map on the cell phone or allowing a PC to automatically shop for the lowest price involve the use of virtualization (IBM, 2007). The concept of virtualization is very broad and can be applied to devices, servers, operating systems, applications and even networks with a decreasing regard for geographical and organizational boundaries (Montaigne, 2003).

In a book on *Virtual Experiments in Food Processing* (Singh and Erdogdu, 2009), computer simulations of selected food processing operations for students to conduct virtual experiments were described. Another book, "*Experiments in Unit Operations and Processing of Foods*" (Vieira and Ho, 2008), experiments were described, experimental results supplied for student work, and videos can be visited at https://www.iseki-food.net/equipment/pilot_plant. Moreover, a database was created to help educational institutions to share their resources. In the future, more reliance on such approaches using digital technology is anticipated. Hence, it is expected that a food practitioners (e.g., food engineers, food scientists and technologists) working on numerous computer tasks (e.g., modeling, kinetics, dynamic simulation, optimization, prediction) to perceive these activities as similar to computer virtualization (i.e., each software functions as if all of the computer's resources are being allocated for its needs). However typically, the 'food virtualizer' community has yet to recognize that each of the aforementioned tasks is part of a more general framework that requires reproducing a virtual environment that mimics real processes, while simultaneously maintaining the characteristic complexity of the phenomena, the product, the process and the outcome. This approach is a real challenge as modeling should depart from the traditional 'black-box' strategy to use a 'white-box' one. This new scheme also calls for a new and different mindset and culture.

By decoupling the physical hardware from the operating system, virtualization provides more operational flexibility and increases the utilization rate of the underlying physical hardware. Consequently, virtualization makes it possible to have a machine (the virtual one) that is totally independent of the hardware (IBM, 2007). Similarly, under virtualization of food engineering topics (e.g., data collection, statistical analyses, modeling, dynamic simulation, prediction, optimization), the researcher is provided with a virtual machine/plant/process/product that maintains the real characteristics and circumvents the need for a physical environment, consequently providing more process flexibility and opening new horizons for understanding, insights and utilization (IBM, 2007; Marra, 2015; Singh and Erdogdu, 2009). It is also clear that foods, and especially the relationship between process and sensory attributes, should be considered. Sensory aspects (tasting, seeing, hearing, smelling, touching, and the overall individual sensations) have already been identified as one of the foremost constructs of process virtualization (Overby, 2008).

While a number of manufacturing sectors (e.g., aerospace, defense, automotive) have been benefiting from modeling activities and process virtualization, the food industry is lagging behind in utilizing the wide potential offered by virtualization as an engineering design tool. The emerging possibilities of this domain are enormous, a few typical examples being a significant reduction in the time and cost of development, design and validation processes and equipment, circumvention of trial-and-error prototypes, reduced overall cost, time to market, risk assessments, etc.

Another major field that is evolving at unabated speed and will have a profound effect on virtualization is the 'Internet of Things' (IoT), used as an umbrella term for various aspects related to the extension of the Internet and the Web into the physical realm, by means of the widespread deployment of spatially distributed devices with embedded identification, sensing and/or actuation capabilities (Miorandi et al., 2012). The IoT, excluding PCs, tablets and smartphones, is predicted to reach 26 billion units installed in 2020 representing an almost 30-fold increase from 0.9 billion in 2009. The IoT product and service suppliers will generate incremental revenue exceeding $300 billion, mostly in services, in 2020. It will result in $1.9 trillion in global economic value added through sales to diverse end markets (Chavie, 2014). In addition to this mind-boggling expansion and proliferation of the IoT, the parallel rise in big data and cloud computing should also be mentioned. Cloud computing is a powerful technology that enables massive-scale and complex computing (Hashem et al., 2015).

Recent developments (e.g., IoT, cloud computing, big data, 3D printing) will drive virtualization development and enhance its potential to address and fulfill the needs of new and sophisticated strategic tools for innovation in the food industry; these should play a significant role in food engineers' future challenges. It is quite evident that proliferation of the beneficial utilization of virtualization could be significantly enhanced by the creation of a four-helix (industry, academia, government and private business) innovation ecosystem that calls for collaborations and partnerships among all stakeholders (Saguy, 2013; Saguy and Sirotinskaya, 2014). The new ecosystem provides a substantial opportunity to move forward effectively. For instance, such a collaboration could reduce the time to market by utilizing virtualization to effectively test numerous new designs, prototypes and novel products, thereby circumventing obstacles, minimizing time and resources and benefiting from the enormous possibilities to test—virtually—performance and novel approaches. Support from all key players of the four-helix innovation ecosystem ensures a smooth transfer from research to implementation and from invention to innovation.

4. Open innovation

Despite the enormous role played by innovation, there is no one acceptable definition that can describe its multifaceted dimensions. One possible description is the application of an idea/invention, technology, process or business model to a product/service that will satisfy a specific need and can be replicated at economical cost. In the face of mounting economic pressure, environmental challenges, diminishing resources, and the ever-growing and accelerating pace of science and knowledge development, innovation offers a significant driving force and a unique opportunity to address these existing and emerging complex topics. Innovation plays a vital role in growth and social well-being. Its application provides new ways of gaining a competitive advantage and creating value, and plays a vital role in all facets of modern life (Saguy, 2011). However, it can become a commodity at unprecedented speed, and consequently, continuous efforts are required to sustain and nourish it (Saguy, 2013).

In recent years, OI—a relatively young but extremely active domain—has been playing a paramount role in today's innovation ecosystem (Saguy and Sirotinskaya, 2014). Initially, OI was defined as: "valuable ideas can come from inside or outside the company and can go to market from inside or outside the company as well" (Chesbrough, 2003); it was later redefined as: "the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for external use of innovation, respectively" (Chesbrough et al., 2006). Today, OI is essential to surviving and gaining a competitive advantage in most business environments, where companies must use both external and internal ideas, open channels for knowledge access, employ external technology and solutions, and purchase or license inventions (Traitler and Saguy, 2009; Traitler et al., 2011). OI practices were initiated in the software, electronics, telecom, biotechnology and pharma industries before eventually spreading to others, including the food industry (Gassmann et al., 2010). Today's paradigm consists of diverse sets of practices encompassing different dimensions [e.g., open business model, intellectual properties (IP), strategy, collaboration, crowdsourcing, threadless co-creation (Sloane, 2011), and SR (Saguy, 2013; Saguy and Sirotinskaya, 2014)].

To highlight typical OI collaborations, 3-simplified examples are furnished. The first highlights industry-university OI partnership (Syngenta AG and the University of Manchester, UK; Malik et al., 2011). The foremost initial step before OI was launched called for the university to develop its OI strategy for building alliances with industrial partners. Similarly, Syngenta strategy promoted the creation of external alliances and partnership with universities on various research projects, developing and exploiting IP, enhancing human resources skills and expertise. A key benefit of such large-scale efforts is that transaction costs may be reduced by a framework agreement covering research and training needs, negating the need for separate contracts to cover research, training, and other knowledge-transfer activities. Syngenta has developed and established effective mechanism for managing its partnerships by sponsoring university innovation centers (UICs), that furnishes another track for acquiring external technological capabilities, and cutting down the time to market by exploring different routes early in the development process. The main benefits of the UIC for its industrial partner are the development of technology and business model combinations that do not currently exist, enabling to target new markets, facilitating long-term relationships, and bringing unexpected numerous other payoffs. Similarly, academia benefit from this long-term collaboration by gaining a better appreciation of the business environment complexities. IP remains one of the main challenges and both partners need to explore ways to overcome this issue that includes also publications (Malik et al., 2011). It should be noted that innovation would not exist without IP, and new models to approach this issue are needed (e.g., Mimura, 2010; Saguy, 2011).

The next example focuses on OI collaboration between several large companies such as Nestlé and its suppliers (termed Innovation Partnerships; Traitler and Saguy, 2009). This paradigm furnishes new ways to collaborate in all areas of discovery and development with external partners. It brings competences, commitment, and speed to the relationship. Accelerating innovation, lifting the sole burden of resources, finding highly skilled people, shortening the learning curve, and reducing the time to market pressure are some of the key benefits. Sharing a common business model is vital to sustaining OI and enhances the overall ability to survive and to thrive. Nestlé's OI and Innovation Partnerships was very effective and in a quite a short time it contributed to more than $200 million in new businesses ranging for instance from new functional soy ingredients better-tasting soy based drink (with Cargill), and new coating systems for ice cream to new nutritional ingredient solutions in pet food and new dairy-based nutritional functionalities (with Du Pont). It is worth noting that significant success of OI could sometime create also measurable pressure on top management for coordination and alignments and should be carefully considered.

The third example highlights OI collaboration between an Italian food company with several industries and universities in a mutual and orchestrated effort to develop functional foods in Italy (Petroni et al., 2012). The OI partnerships included co-development of biosensors for process and quality monitoring with a Japanese company, collaboration with a company specializing in seeds selection to improve the quality and safety of the products. The functional properties of some the raw ingredients (e.g. herbs, fruits and vegetables little known in the West), the company established another OI collaboration with two Chinese universities. Prior to all these new OI partnerships, the company R&D included only limited external collaboration with two Italian universities on key issues of basic research, thus projecting the major transformation it underwent. It was concluded that adopting OI practices within certain limits facilitated the development and offered effective competitive advantages even to firms that do not have a significant number of R&D personnel, or even none at all. Working with others requires a willingness to integrate, plus managerial skills such as the ability to communicate, assimilate, and understand of the needs of others. Additional numerous examples could be found in a recent book (Noble et al., 2014).

Despite OI's widespread applications, only ca. 10% of all companies are ready for it; another 30% (termed 'contenders') have seen the light and are struggling to make it work, and the remaining 60% (or 'pretenders') do not really know what OI is or why or how it could be relevant to them (Lindegaard, 2010). SMEs and others firms operating in traditional sectors are struggling with its implementation due to their relatively low level of absorptive capacity and management challenges, leading to the perception of OI as unattainable (Lindegaard, 2010; van de Vrande et al., 2009). As elsewhere, SMEs in the food sector are especially struggling with OI implementation (Bianchi et al., 2010; Lee et al., 2010; Saguy and Sirotinskaya, 2014).

Another challenge is to build a bridge over the technology-translation gap, known as the 'valley of death' (VoD), and typically defined as the place where discoveries stemming from basic research are buried due to inadequate commercialization, significant technical obstacles, funding, etc. (Declan, 2008; Markham et al., 2010; Saguy, 2011; Wright et al., 2014). VoD was originally used to refer to the challenges of transferring agricultural technologies to third world countries (Merrifield, 1995). This gap is not unique to food and applies to many other fields that again call for the utilization of the four-helix approach to include all the stakeholders to overcome it. Worth noting that the food industry, probably much more than others, is CapEx (funds used by a company to acquire or upgrade physical assets such as property, industrial buildings or equipment) averse and often consider new plants/equipment very expensive and risky. Hence, prefers to process new products through the same plant (for example, changing the fat composition of spreads still using a margarine line) and consequently circumventing possible innovation.

Addressing the special needs of the food industry and SMEs' unique challenges, OI solution providers, and the roles of academia and IP models, were recently reviewed. Some specific recommendations included: collaboration, creation of a four-helix innovation ecosystem, metrics to quantify academia's SR and revised curricula for promoting innovation with a special emphasis on OI, SME involvement, a new IP model, and management mindsets and strategies. OI was identified as a unique opportunity for all stakeholders to proactively engage in meeting future challenges and opportunities (Bianchi et al., 2010; Lee et al., 2010; Saguy and Sirotinskaya, 2014). Moreover, it provides food engineers with the unique challenge of spearheading new partnerships and collaborations with other domains, and utilizing the most advanced and up-to-date technologies and scientific breakthroughs.

5. Future food engineers and *Enginomics*

Engineers of the future will face bigger and more demanding challenges. Whereas engineers of the past mainly focused on the technical and economic feasibilities of systems design (Alwi et al., 2014), engineers of the future will have the additional responsibility of addressing entirely new topics and dimensions (e.g., innovation, partnerships, creativity, entrepreneurship, sustainability, economic environment, SR, population growth and aging). Furthermore, food engineers will be faced with unique challenges and should play a proactive role in the innovation ecosystem. A multidisciplinary knowledge base, H&W and food security are some of the key and paramount ingredients that should be included. A new term defined as '*Enginomics*' (engineering + nomics) has been coined to depict some of the major topics that combine human internal processes and unit operations. Studying internal transport phenomena, utilization of new techniques, such as microprocessing for modeling and simulation of the digestive system, bioavailability, satiety, DNA predisposition, and nutrigenomics offer unique prospects. *Enginomics* is comprised of these typical main pillars (Saguy et al., 2013):

- Human internal unit operations (digestibility, gastric aspects, targeting, bioavailability, etc.), comprised of H&W (medicine, brain, biology, biota, pro- and prebiotics, nanotechnology, biotechnology, etc.) and nutrition (personalization, prevention, satiety, etc.).
- Food and product engineering (properties, composition, new resources, structure–design, material science, packaging, etc.).
- Manufacturing (processing, waste and water management, environment, compliance, regulations, developing countries, etc.).
- Consumers (safety, acceptability, special needs, sensations, pleasure, etc.).
- SR (food security, feeding the world, sustainability, growing population, water and land scarcity, ethics, values, etc.).

It is worth noting that Google is already working on collecting information that includes: participants' entire genomes and their parents' genetic histories, as well as information on how they metabolize food, nutrients and drugs, how fast their hearts beat under stress and how chemical reactions change their genes' behavior (Barr, 2014).

The above presents some of the rapidly evolving challenges faced by food engineers, for which they need to play a proactive role. It also calls for rethinking and transforming the domain to a vigorous, holistic and dynamic profession, which should strive to go beyond today's vision. Consequently, it highlights the need for new curricula to train both students and professors. This is a very exciting time for food engineers, who can—and should—expand their horizons by offering insights and playing a proactive and significant role in this endeavor.

It is worth noting that engineering at large is faced with similar challenges. For instance, instead of only focusing on the design or improvement of a product or process, the paradigm for 'sustainable engineering' requires dynamic, holistic, integrative analyses of present and future product life cycles, entire supply chains and the ecosystems upon which truly sustainable societies are totally dependent. Consequently, future engineers have to be more innovative, creative and engaged in seeking to ensure that the products/processes/systems they design and use will enhance present and future sustainable societal lifestyles (Alwi et al., 2014).

The cliché that 'you can't compete today with yesterday's technology' is well known; food engineers should adopt new paradigms to avoid even the remote and unfortunate possibility of becoming marginalized and/or non-sustainable. New and innovative approaches are needed, and limiting the rethinking of their roles is not an option. More importantly, planning for the future, and what knowledge should be passed on to students are some of the key driving forces.

To suggest a new perspective, two specific examples are provided: the first is known as 'the dandelion principle' which calls for taking on larger challenges. The world contains many types of underutilized talent—not just people with cognitive, developmental or behavioral differences, but also people who lack access to opportunity for other reasons. Boys in rural India might be headed for lives as subsistence farmers, following in the footsteps of their fathers. Girls in sub-Saharan Africa might be headed for lives of poverty and disease. But if we can adjust the overall contexts of these boys' and girls' lives (for example, by providing access to education and technology), they may be able to do something totally different, and the resulting benefits could flow in multiple directions (Austin and Sonne, 2014). Food engineering is an excellent field in which to fulfill this opportunity.

The second example comes from a recent book that highlights the principle that innovation happens at the interface, and we should not be looking only for incremental innovation; rather, we should consider the new and ever-growing requirements of breakthroughs in the whole innovation ecosystem, including startups. This calls for a different way of thinking, incorporating and promoting disruptive (as opposed to incremental) OI. The term 'startup corporation' was introduced to indicate that established companies succeed mainly in incremental innovation. Major breakthroughs and disruptive innovation are achieved when firms combine the philosophy of the startup with the experience, resources and network of an established company (Davila and Epstein, 2014).

To prepare for the new roles of food engineers of the future, it is therefore critical, first and foremost, to rethink and revise the curricula, *Enginomics*, enhance collaboration, support open networks, promote SR and consider ethics and employability. The latter becomes feasible when a 'startup university' paradigm is implemented where, in addition to basic science, applied research and innovation also play an important role.

The startup university term is a parallel description of a 'startup corporation' as coined recently (Davila and Epstein, 2014). A probably more adequate definition seems to be '*Innoversity*' that combines innovation and university into one integrated term. It depicts the new shift required for universities to fully leverage their strength in conducting basic research towards becoming simultaneously a proactive player and a catalyst in the four-helix OI ecosystem, embracing, sustaining and driving breakthrough innovations. A new and innovation-driven mindset built on the university foundation of basic science should be a very powerful combination to address all aspects of the future.

6. Social responsibility

A critical, but often omitted element of the innovation process is SR, which should be a part of every stakeholder's duties and concerns. Aside from creating value for the business, innovation must also bring value to society. The creation of societal benefits should become an important dimension in academia and industry collaborations. A genuine concern for society should be the norm, and an integral part of such partnerships and of the innovation process itself (Saguy, 2011, 2013). For academia to play a proactive role, criteria to assess its contributions, as well as reward them, should become an integral part of academic life. Accepted metrics are therefore required to assess and quantify SR and academia's role in disseminating knowledge, promoting innovation and finding the proper approaches for circumventing issue becoming impassable barriers (Saguy and Sirotinskaya, 2014).

For a business to create value for its shareholders in the long term, it must also bring value to society. Recent studies have shown a strong positive relationship between corporate SR and financial performance. However, the impact of the former on the latter is an evolving topic, mainly due to different metrics, methodologies, R&D budget, company size, etc. Academia should also develop the necessary tools, curricula and metrics for studying, teaching, measuring and assessing the contributions and relevance of its SR programs.

Although the need to alert young scientists of their SR has been widely acknowledged, the question of how to actually do this has so far garnered only limited attention (Borsen et al., 2013). This clearly indicates that academia should place more importance on the SR challenge. Food engineers have additional challenges centered on food security, feeding an expanding and aging population, and sustainability, to name only a few.

7. Conclusions

The food engineering domain is faced with numerous significant challenges and opportunities as it strides toward the future. The fierce competition with adjacent fields, innovation, new technologies and unabated scientific progress highlight the need to assess those challenges and opportunities and the required paradigm shifts. The main challenges and opportunities are:

- **Modeling** – Transforming the empirical 'black-box' approach into physics-based modeling and striving for better characterization, fundamental understanding and insights are paramount. This will open new avenues to gaining benefits from the increased amount of real-time information, new sensor technology, proliferation of IoT, improved connectivity and new and rich big-data resources. A special and overriding part of the modeling continues to be the uniqueness and complexity of food-quality aspects, such as sensory attributes, consumer needs and expectations, health and wellness, sustainability and SR.
- **Virtualization** – Recent developments, such as IoT, cloud computing, sophisticated software and big data highlight the unique need to develop virtualization in order to benefit from enhanced modeling and computational power and address and fulfill the needs of new and sophisticated strategic tools for innovation in the food industry. Initial efforts in this field should take advantage of the vast potential offered by *Enginomics*.
- **Innovation** – OI and the creation of a four-helix innovation ecosystem offers numerous benefits, but its implementation calls for a different mindset for all stakeholders. To proactively promote innovation, academia should strive to become a 'startup university' by revising its IP models and curricula, and enhancing its focus on innovation, creativity, employability, relevance and applied research.
- **Startup University and *Innoversity*** - Calls for a universities to fully leverage their strength in conducting basic research while simultaneously becoming a proactive player, a catalyst, embracing, sustaining and driving breakthrough innovations.
- **Social responsibility** – SR is not just good business; it should become part and cornerstone of the food engineer's practice. Academia needs to proactively engage in developing and adapting new metrics to quantify its relevance, contributions, performance and implementation.

These 21st century challenges offer food engineers of the future unique opportunities to spearhead new partnerships and collaborations with other domains by focusing on and assimilating the most advanced and recent technologies and scientific breakthroughs. This is a very exciting time for food engineers, with a bright future and great potential. The road forward requires a proactive approach that can be described, in a nutshell, by the following quote: *"To accomplish great things, we must not only act, but also dream; not only plan, but also believe"* (Anatole France, 1921 Nobel Prize for Literature; http://en.wikiquote.org/wiki/Anatole_France; accessed 13.01.2015).

References

Alwi, S.R.W., Manan, Z.A., Klemes, J.J., Huisingh, D., 2014. Sustainability engineering for the future. J. Cleaner Prod. 71, 1–10.
Austin, R.D., Sonne, T., 2014. The dandelion principle: redesigning work for the innovation economy. MIT Sloan Manage. Rev. 55 (4), 67–72.
Barr, A., 2014. Google's New Moonshot Project: The Human Body, WSJ, July 25 ed., New York, NY, pp. B1–B2.
Bianchi, M., Campodall'Orto, S., Frattini, F., Vercesi, P., 2010. Enabling open innovation in small- and medium-sized enterprises: how to find alternative applications for your technologies. R & D Manage. 40 (4), 414–431.
Bimbenet, J.J., Schubert, H., Trystram, G., 2007. Advances in research in food process engineering as presented at ICEF 9. J. Food Eng. 78 (2), 390–404.
Borsen, T., Antia, A.N., Glessmer, M.S., 2013. A case study of teaching social responsibility to doctoral students in the climate sciences. Sci. Eng. Ethics 19 (4), 1491–1504.
Broyart, B., Trystram, G., 2003. Modelling of heat and mass transfer phenomena and quality changes during continuous biscuit baking using both deductive and inductive (neural network) modelling principles. Food Bioprod. Process. 81 (4), 316–326.
Chavie, R., 2014. Can the internet of things eliminate machinery failure for food manufacturers? Food Manufacturing. http://www.foodmanufacturing.com/articles/2014/03/can-internet-things-eliminate-machinery-failure-food-manufacturers; accessed 13.01.2015.
Chesbrough, H., 2003. Open Innovation: The New Imperative for Creating and Profiting from Technology. Harvard Business School Publishing, Cambridge, MA.
Chesbrough, H., Vanhaverbeke, W., West, J., 2006. Open Innovation: Researching a New Paradigm. Oxford University Press, Oxford, UK.
Clemente, G., Sanjuan, N., Andres Carcel, J., Mulet, A., 2014. Influence of temperature, air velocity, and ultrasound application on drying kinetics of grape seeds. Drying Technol. 32 (1), 68–76.
Datta, A.K., 2008. Status of physics-based models in the design of food products, processes, and equipment. Comprehens. Rev. Food Sci. Food Safety 7 (1), 121–129.
Datta, A.K., Sablani, S.S., 2007. Mathematical modeling techniques in food and bioprocesses: an overview. In: Sablani, S.S., Datta, A.K., Rahman, M.S., Mujumdar, A.S. (Eds.), Handbook of Food and Bioprocess Modelling Techniques. CRC Press, Bocca Raton, FL, pp. 1–12.
Davila, T., Epstein, M.J., 2014. The Innovation Paradox Why Good Businesses Kill Breakthroughs and how they can Change. Berrett-Koehler, San Francisco, CA.
Declan, B., 2008. Translational Research: Crossing the Valley of Death, Nature, June 11 ed., pp. 840–842.
Erdogdu, F., 2013. Mathematical modeling of transport phenomena for simulation and optimization of food processing operations. In: Yanniotis, S., Taoukis, P., Stoforos, N.G., Karathanos, V.T. (Eds.), Advances in Food Process Engineering Research and Applications. Springer, New York, NY, pp. 473–487.

Gassmann, O., Enkel, E., Chesbrough, H., 2010. The future of open innovation. R & D Manage. 40 (3), 213–221.
Hashem, I.A.T., Yaqoob, I., Anuar, N.B., Mokhtar, S., Gani, A., Ullah Khan, S., 2015. The rise of "big data" on cloud computing: review and open research issues. Inform. Syst. 47, 98–115.
Ho, Q.T., Carmeliet, J., Datta, A.K., Defraeye, T., Delele, M.A., Herremans, E., Opara, L., Ramon, H., Tijskens, E., van der Sman, R., Van Liedekerke, P., Verboven, P., Nicolai, B.M., 2013. Multiscale modeling in food engineering. J. Food Eng. 114 (3), 279–291.
IBM, 2007. Virtualization in Education. http://www-07.ibm.com/solutions/in/education/download/Virtualization%20in%20Education.pdf; assessed 10.01.2015.
Labuza, T.P., 1984. Application of chemical kinetics to deterioration of foods. J. Chem. Educ. 61 (4), 348–358.
Lee, S., Park, G., Yoon, B., Park, J., 2010. Open innovation in SMEs – an intermediated network model. Res. Policy 39 (2), 290–300.
Lindegaard, S., 2010. The Open Innovation Revolution: Essentials, Roadblocks, and Leadership Skills. John Wiley & Sons Inc., Hoboken, NJ.
Malik, K., Georghiou, L., Grieve, B., 2011. Developing new technology platforms for new business models: Syngenta's partnership with the University of Manchester. Res.–Technol. Manage. 54 (1), 24–31.
Markham, S.K., Ward, S.J., Aiman-Smith, L., Kingon, A.I., 2010. The valley of death as context for role theory in product innovation. J. Prod. Innov. Manage. 27 (3), 402–417.
Marra, F., 2012. Multi-physics modeling as a design tool: advances and prospects. In: Institute of Food Technologists Annual Meeting, Las Vegas, NV.
Marra, F., 2015. White Page on Virtualization of Processes in Food Engineering. http://www.virprofood.unisa.it/thewhitepage; assessed 18.05.2015.
Marra, F., De Bonis, M.V., Ruocco, G., 2010. Combined microwaves and convection heating: a conjugate approach. J. Food Eng. 97 (1), 31–39.
Merrifield, B.D., 1995. Obsolescence of core competencies versus corporate renewal. Technol. Manage. 2 (2), 73–83.
Mimura, C., 2010. Nuanced management of IP rights: shaping industry–university relationships to promote social impact. In: Dreyfuss, R.C., Zimmerman, D.L., First, H. (Eds.), Working within the Boundaries of Intellectual Property Innovation Policy for the Knowledge Society. Oxford University Press, Oxford, UK.
Miorandi, D., Sicari, S., De Pellegrini, F., Chlamtac, I., 2012. Internet of things: vision, applications and research challenges. Ad Hoc Netw. 10 (7), 1497–1516.
Montaigne, M., 2003. Rational Virtualization Opens E&P Eyes. http://www.epmag.com/rational-virtualization-opens-ep-eyes-731381; assessed 08.01.2015.
Noble, C.H., Durmusoglu, S.S., Griffin, A. (Eds.), 2014. Open Innovation New Product Development Essentials from the PDMA. John Wiley & Sons Inc., Hoboken, NJ.
Norton, T., Tiwari, B., Sun, D.W., 2013. Computational fluid dynamics in the design and analysis of thermal processes: a review of recent advances. Crit. Rev. Food Sci. Nutr. 53 (3), 251–275.
Overby, E.M., 2008. Process virtualization theory and the impact of information technology. Organ. Sci. 19 (2), 277–291.
Pantelides, C., Renfro, J., 2013. The online use of first-principles models in process operations: review, current status and future needs. Comput. Chem. Eng. 51, 136–148.
Peleg, M., Normand, M.D., Corradini, M.G., 2012. The Arrhenius equation revisited. Crit. Rev. Food Sci. Nutr. 52, 830–851.
Peleg, M., Normand, M.D., Kim, A.D., 2014. Estimating thermal degradation kinetics parameters from the endpoints of non-isothermal heat processes or storage. Food Res. Int. 66, 313–324.
Peleg, M., Kim, A.D., Normand, M.D., 2015. Predicting anthocyanins' isothermal and non-isothermal degradation with the endpoints method. Food Chem. 187, 537–544.
Petroni, G., Venturini, K., Verbano, C., 2012. Open innovation and new issues in R&D organization and personnel management. Int. J. Human Resource Manage. 23 (1), 147–173.
Purlis, E., 2014. Optimal design of bread baking: numerical investigation on combined convective and infrared heating. J. Food Eng. 137, 39–50.
Saguy, I., Karel, M., 1980. Modeling of quality deterioration during food-processing and storage. Food Technol. 34 (2), 78–85.
Saguy, I.S., 2011. Paradigm shifts in academia and the food industry required to meet innovation challenges. Trends Food Sci. Technol. 22 (9), 467–475.
Saguy, I.S., 2013. Academia-industry innovation interaction: paradigm shifts and avenues for the future. In: Yanniotis, S., Taoukis, P., Stoforos, N.G., Karathanos, V.T. (Eds.), Advances in Food Process Engineering Research and Applications. Springer, New York, NY, pp. 645–656.
Saguy, I.S., Marabi, A., Wallach, R., 2005. Liquid imbibition during rehydration of dry porous foods. Innovat. Food Sci. Emerging Technol. 6 (1), 37–43.
Saguy, I.S., Singh, R., Johnson, T., Fryer, P.J., Sastry, S.K., 2013. Challenges facing food engineering. J. Food Eng. 119 (2), 332–342.
Saguy, I.S., Sirotinskaya, V., 2014. Challenges in exploiting open innovation's full potential in the food industry with a focus on small and medium enterprises (SMEs). Trends Food Sci. Technol. 38 (2), 136–148.
Singh, R.P., Erdogdu, F., 2009. Virtual Experiments in Food Processing, second ed. RAR Press, Davis, CA.
Sloane, P., 2011. A Guide to Open Innovation and Crowdsourcing. Kogan Page Ltd., London, UK.
Traitler, H., Saguy, I.S., 2009. Creating successful innovation partnerships. Food Technol. 63 (3), 23–35.
Traitler, H., Watzke, H.J., Saguy, I.S., 2011. Reinventing R&D in an open innovation ecosystem. J. Food Sci. 76 (2), R62–R68.
Trystram, G., 2012. Modelling of food and food processes. J. Food Eng. 110 (2), 269–277.
van Boekel, M.A.J.S., 2009. Kinetic Modeling of Reactions in Foods. CRC Press, Boca Raton, FL.
van de Vrande, V., de Jong, J.P., Vanhaverbeke, W., de Rochemont, M., 2009. Open innovation in SMEs: trends, motives and management challenges. Technovation 29 (6–7), 423–437.
Vieira, M., Ho, P., 2008. Experiments in Unit Operations and Processing of Foods. Springer Science + Business Media LLC, New York, NY.
Wright, B.D., Drivas, K., Lei, Z., Merrill, S.A., 2014. Industry-funded academic inventions boost innovation. Nature 507 (7492), 297–299.