Control of Snack Food Manufacturing Systems

Potato chips and micro-chips are more similar than commonly believed

Michael Nikolaou

Chemical Engineering Department, University of Houston

Nikolaou@uh.edu, (713) 743 4309

Introduction

The 1995 Ig Nobel Prize in Physics [1], a highly popular spoof of its true counterpart, was awarded to D.M.R. Georget, R. Parker, and A.C. Smith, of the Institute of Food Research, Norwich, England, for their "rigorous analysis of soggy breakfast cereal" [2]. Apparently, the Prize Committee judged that the analysis of processed food properties warranted little scientific rigor and bordered on the humorous, hence the awarding of the Prize. The authors accepted it with gratitude and offered the following graceful Acceptance Speech [3]: "In our study of compaction of breakfast cereal flakes, we did not leave them turned tongue-in-cheek, or use any other sensory technique. Rather, we set out to relate macro-scale mechanical properties to changes in the scale of constituent food particle molecules. This provides valuable insights into texture. So what does this mean for the manufacturer, and to you, the consumer? Well, it's all about the quest for the ultimate breakfast cereal-eating experience. I hope that the awarding of this prize will stimulate further research in this area."

The above incident epitomizes what is interesting with the technology used in the food industry: On one hand, the finished product is a commodity rarely associated with scientific or engineering know-how, easily recognizable, and broadly available at affordable cost. To wit, the

English vernacular, among others, is widely interspersed with metaphorical colloquialisms borrowed from food and cooking. On the other hand, while there is an abundance of processed food humor [4], [5] – tasteful or not, pun intended – food processing is a serious enterprise in every aspect, including science, technology, business, and public health.

The purpose of this article is to focus on technological issues related to the operation of snack food manufacturing processes [6]. Specifically, we argue that related technology can be unsuspectingly sophisticated. While we elaborate on specific examples, we also stress that it is not our aim to exhaustively cover this diverse and evolving field. Rather, we emphasize cases where we have had hands-on academic or consulting experience. In particular, we emphasize process monitoring and control solutions and challenges of certain (salty) snack food processes. Undoubtedly, there are many other success stories that can be told. We hope that this paper can stimulate enough interest in both the food manufacturing and control communities, so that creative control ideas continue to emerge.

Snack food business

According to the U.S. Census Bureau, "the snack food industry comprises establishments primarily engaged in one or more of the following: (1) salting, roasting, drying, cooking, or canning nuts; (2) processing grains or seeds into snacks; (3) manufacturing peanut butter; and (4) manufacturing potato chips, corn chips, popped popcorn, pretzels (except soft), pork rinds, and similar snacks [7]." The snack food industry sector also includes "consumer-ready packaged chocolate and non-chocolate candies, cookies and crackers, unpopped popcorn and meat snacks [8]." The list of snack food products is growing steadily, as competition, new knowledge in nutrition science [9], [10] regulatory mandate, and self-imposed guidelines for healthful public nutrition force companies to introduce snacks with refined features, such as new raw material basis, improved texture, shape, color, flavor, and nutritional content [11], [12]. The last factor, in particular, has had a significant effect in recent years, as Americans' dietary habits fluctuate, in response to scientific advances, governmental guidelines, commercial offerings, social fads or personal preferences.

The world snack food market reached an estimated $66 billion in 2003, with the United States accounting for about a third of it [8]. As lifestyles in other parts of the world become more westernized, the global demand for snack foods continues to increase and evolve. The market is dominated by a few major companies [13] concentrating on efficiencies in their supply chain, manufacturing, and distribution, as well as on process and product development, market research, and advertising. However, many small companies are also flourishing by concentrating on specialty snacks for which the consumer is willing to pay a premium.

Snack food manufacturing technology

Along with technology for the manufacture of snack foods, food science is obviously of paramount importance for this field. By including elements of physical, chemical and biological sciences, food science is a truly interdisciplinary field of remarkable complexity and considerable breadth, and has frequently contributed, rather than simply benefited from its constitutive scientific fields. Harold McGee [14], [15] offers a palatable introduction to the chemistry and physics of foods and cooking for the scientifically inclined casual reader, which can also be useful for the inquisitive engineer.

The technology for the manufacture of snack foods involves a relatively small number of processes that appear most frequently in snack food manufacturing plants. Following [16], we offer a short description below, along with more details in sidebars.

Extrusion

An extrusion cooker is essentially a high-temperature, short-time plug-flow bioreactor that combines into a single unit multiple unit operations: (a) mixing of raw materials – such as various ground grains and water, (b) shearing/kneading, and (c) heating and/or cooking, using the heat released by friction inside the extruder [17]-[19]. For many extrusion cooking processes, the last function may be followed by puffing (whence the term "puffed snacks"), namely abrupt expansion of high-temperature plasticized and gelatinized starch from a pressurized chamber into the atmosphere [6]. As is usually the case for processes that combine a number of unit operations in a single unit (such as in reactive distillation) control of extrusion cooking processes is an inherently formidable challenge, due to strong coupling of many imprecisely understood phenomena. Additional challenges are posed by variability of raw materials, process modeling difficulties, frequent wear of equipment, and various external and internal disturbances.

Frying

Frying is a process in which a snack is cooked by floating or being immersed in hot oil. Continuous fryers (Figure 3) are used for large scale operations (~5,000 lb/hr throughput), while batch (kettle-style) fryers are experiencing a comeback among small scale producers (<200 lb/hr) who concentrate on specialty products. In addition to providing heat for cooking, the frying oil becomes a significant component of the end product, varying from as little as 10% by weight in breaded fish sticks to 40% in potato chips [6]. Responding to consumer preferences, the snack food industry is now emphasizing good-tasting low-fat snacks. Although conceptually simple, the design and operation of manufacturing processes for fried snacks poses interesting challenges. The key concern is low-cost production of nutritious snacks at consistent quality and minimum waste.

Baking

In baking processes snacks are cooked by heat transferred through the air by convection, conduction, or radiation. The effectiveness of each of these mechanisms varies with oven and product design, and is generally lower than that of heat transfer based on liquids such as oil. Baking does not contribute any added fat to the finished snack, potentially resulting in more healthful products, which explains the recent surge in popularity of baked snacks.

Drying

Drying is required for several snacks to develop the right crispness. Puffed snacks, for example, must be dried after extrusion in order to obtain moisture content sufficiently low (to ~4%) to insure good texture and storage stability. Because a puffed snack with moisture level above or below normal feels stale or spongy, there is a need for accurate control of the drying process.

Miscellaneous

While the above processes constitute the heart of most snack food manufacturing lines, where practically all cooking occurs, there are additional processes and equipment that are important for the operation of an entire line, such as the following.

(a.) Oil, powder, and granule applicators, including oil and cheese sprayers, powder dispensers, electrostatic salters, and coating tumblers. This equipment is used for snack flavoring, often creating a variety of products from the same basic substrate.

(b.) Transfer and storage equipment. In particular, storage of raw materials is of high importance, given that raw materials are natural products that have limited life and can be seriously affected by storage conditions. For instance, the sugar content of potatoes may be higher than desired when potatoes are stored at low temperature (2-4 C) due to slowing of sugars breakdown to carbon dioxide and water. Sugar content can be lowered back to an acceptable level (<0.2-0.4%) by reconditioning (storage at >13 C for several weeks prior to use). The right sugar content in potatoes ensures that Malliard (browning) reactions and resulting undesirable dark spots on fried potato chips are avoided.

(c.) Measuring and weighing equipment. Such equipment is important for control purposes, among others, providing valuable data for process monitoring and feedback.

(d.) Packaging. A primary concern for packaging is to ensure long shelf life of the finished product. From a process control viewpoint, ensuring that the weight of packaged snacks is as close to but certainly above the value specified on the package has obvious economics implications.

(e.) Nut processing equipment, such as sorters, blanchers, roasters, and coolers.

Control issues in snack food processes

Controllability and process design

As is the case with every process that must be controlled, the nature of the physicochemical phenomena involved and the design of the process greatly impact its controllability characteristics.

Snack food manufacturing processes are generally serial (Figure 5). In that respect, such processes are closer in nature to microelectronics manufacturing processes – which comprise of several tens of elaborate steps that transform silicon and other materials to finished micro-chips – rather than to chemicals production processes, which usually rely on reaction / separation schemes involving recycling of unreacted raw materials. The latter pose significant control challenges, owing to large time lags introduced by recycling streams. Of course, recirculation of heating or cooling media is common in snack food manufacturing (such as recirculation of cooking oil in continuous frying (Figure 4) or cooling water in extrusion cooking (Figure 2)) but is in large part decoupled from product throughput. On the other hand, there is very strong coupling between successive processing steps, owing to the fact that it is virtually impossible to have intermediate storage tanks (the counterpart of surge tanks in chemical industry processes) for tolerance of throughput fluctuations. As a result, throughput control must be tight and reliability must be high, to avoid major process disruptions and product loss [16].

The dynamic behavior of individual processes in snack food manufacturing lines can pose interesting control challenges. For example, the limited capability for intermediate measurements related to product quality in many cooking units that are essentially plug-flow reactors (such as in frying, extrusion cooking, and baking) introduces dead times, typically in the order of 1 minute, which create inherent control limitations [25]. Time-varying behavior is frequently unavoidable, due to both raw and cooking materials variability and process drifting. Interaction between controlled variables is often inevitable (such oil and moisture content or fried snacks, where the former largely replaces the latter). Nonlinearities, arising from the kinetics of many and complex chemical reactions as well as from mass and energy transport at multiple scales and often complex geometries are frequently present. A typical example is process start-up or shut-down. A more exotic example is multiple steady states for the same values of the primary process variables in extrusion cooking [26]. However, control around a steady state can be very effective using multivariable linear control methods [27].

Selection of measured and manipulated variables

Control in snack food manufacturing processes involves both control of process-related variables and control of product-related variables. Obviously, the former affect the latter.

What product-related variables must be controlled to ensure product quality is not trivial. While a consumer can easily determine whether a product is made to their liking, translating this to specifications for a small number of product-related variables that can be measured – preferably in real time or, at least, intermittently in an analytical laboratory – is not obvious. Experience has shown that the connection between product quality and measurable variables is not always clear-cut [28]. Snack food producers rely both on sensory evaluation experts as well as on extensive statistical analysis of consumer test results, to (a) identify variables that are well correlated with overall product quality, and (b) determine optimal values for these variables – which can be strictly confidential. For example, it is well established that moisture content, oil content, and color for many fried snacks capture qualitative features such as crispness, extent of cooking, and taste fairly well [16]. The availability of inexpensive real-time imaging equipment has made quality control possible by means of multivariate image analysis [29], [30]. Crispness is also routinely laboratory-tested by analyzing the frequency spectrum of the sound made when a snack is crushed. Effectively using a blend of laboratory and real-time measurements for process control offers interesting challenges.

Historically, product-related variables were controlled by controlling process variables, and ensuring that the food would be processed for a certain time, typically in the order of a minute for a processing step. For example, quality control of fried foods would be ensured by controlling the temperature of the frying oil and residence time of the food in the fryer. Similarly, various studies have connected process variables such as energy release and throughput to the quality of the finished product in extrusion cooking [31]-[34]. Lack of reliable real-time measurements related to product quality prompted this approach. Interestingly, the situation is not different from control of product quality variables in crucial steps of semiconductor chip manufacturing, such as plasma etching of silicon wafers [16]. Indeed, the difficulty in taking real-time measurements of product quality during plasma etching has resulted in the dominant approach of the microelectronics industry being based on "recipes", referring to explicitly prescribed time-profiles of process conditions that need to be precisely controlled (and begging for puns on the subject, such as the one by Michael J. Boskin, chairman of President

Bush's (Sr.) Council of Economic Advisers: "It doesn't make any difference whether a country makes potato chips or computer chips!")

The availability of reliable and inexpensive sensors for direct, real-time measurement of variables related to product quality in the 1980s and 1990s made it possible to control such variables directly by means of computer-aided feedback control (see [25], [27]) and prompted numerous modeling and control studies that elucidated both fundamental concepts and practical aspects. For example, the empirical observation that the oil content of fried chips is proportional to the square root of residence time, used in recipe forming, was clearly attributed to fundamental mechanisms of heat and mass transfer [25].

The selection of manipulated variables is largely dictated by the design of the process to be controlled. For example, the main reason why extrusion cookers (Figure 2) use twin screws or multi-zone continuous fryers (Figure 4) maintain different processing speeds of fried foods by means of different speeds of multiple submergers is precisely the increased controllability afforded by these process configurations.

Control Structures

The control of snack food manufacturing processes is naturally multi-level, not unlike control of chemical processes (Figure 6).

To build manufacturing capacity, one has to seriously consider fluctuations and changes in the appeal of a certain finished product to consumers. Manufacturing multiple products in the same production line offers obvious economies of scale, but creates additional operability and control challenges, not unlike those encountered in the specialty chemicals industry.

Given that the raw material is a natural product, production has to be carefully planned. Supply-chain optimization could provide significant returns. Production scheduling poses interesting challenges, because both the raw material and the finished product have limited storage time, and both supply and demand can have significant fluctuations (for instance, think natural disasters or SuperBowl weekend).

At the predictive control level [35], the availability of pertinent real-time sensors for product quality variables has made it possible to move away from recipe-based control to real-time feedback control, where process conditions are cascaded as setpoints to underlying controllers. Because snack food manufacturing processes are serial, information related to quality of intermediate products (such as sugar content of stored starchy raw materials, thickness of sliced chips to be fried, moisture content of cooked snacks to be dried, cooking rate of products to be eventually packaged) is often passed to subsequent steps for use in feedforward control.

Control objectives, constraints, and control laws

Control of quality characteristics of manufactured snacks offers significant economic incentives. It is reported [36] that tight control and elimination of waste in many snack food manufacturing lines offer a competitive edge that has largely determined the business viability of entire product lines, even though manufacturing costs are in strong competition with advertising and distribution costs, where economies of scale are important. Therefore, a primary objective is to manufacture product at the desired specifications. For example, if the moisture content of a fried snack chip is below specification it imparts a scorched flavor, dark color, and excessive oiliness, while above specification the chip lacks crispness [37]. Meeting quality related constraints that are advertised for the finished product (such as low-fat) is also important.

Because most raw materials for the snack food industry are natural products, they can exhibit substantial variability. Such variability may be due to the variety of a particular crop, location of cultivation, weather conditions during crop growing and harvesting, and storage conditions. Similar concerns exist for other process industries, such as the petroleum, metal, and pulp and paper industries, that rely on the primary production sector for raw materials (that is crude oil, metal ores, and timber, respectively). However, in contrast to industries dealing with fluids that can be blended (such as the chemicals and oil refining industries) the snack food industry deals with products that can be neither blended nor reworked to meet quality specifications, making tight control all the more crucial.

As mentioned above, the availability of real-time sensors, combined with inexpensive real-time computing power (PLC and DCS) has triggered a number of feedback control approaches for various processes. Many of them are model-based, raising important questions about the level of detail at which a process must be modeled, the kind of model used (for example, first-principles or empirical, linear or nonlinear, lumped or distributed parameter), the modeling accuracy that is adequate for feedback control (for example, numeric accuracy, fuzzy relationship accuracy) and the requirements posed by the model for controller development and maintenance [16]. Control-related modeling aspects of extrusion cooking are discussed in [38]-

[40], and an early case of feedback control of moisture in food extrusion is discussed in [41]. A more recent study of model predictive control is discussed in [27]. Modeling of immersion frying is discussed in [42], [43] and a multi-scale model is discussed in [44]. Modeling of a continuous fryer for control is discussed in [25], and modeling and control of continuous frying is discussed in [45]-[48].

With multivariable feedback control coming on-line, the issue of automated controller performance monitoring became important. A thorough experimental study is discussed in [49].

Conclusions

In Part Two of the Pulitzer Prize winning bestseller *Guns, Germs, and Steel* [50] the beginning of the rapid ascent of humankind is attributed to the rise and spread of food production, which capitalized on efficiencies in cultivation, storage, and distribution methods. A few thousand years later, Malthus's grim predictions about an impending global famine were thankfully refuted by a new wave of efficiencies in food production and distribution, spurred by the Industrial Revolution. Nowadays, extreme efficiency in food production has made it sufficient that only a very small percentage of the industrialized world's population is employed in agriculture. However, the food industry as a whole is sizable, offering both employment and much needed products. Efficiencies in all aspects of that industry remain important, both for the benefit of society at large and for the competitiveness of individual companies and businesses, large or small. In this article we argued that automatic control can greatly contribute toward such efficiencies in this multifaceted and interdisciplinary field. We believe that specific examples discussed in this paper, albeit by no means exhaustive, offer the reader a good taste of both challenges and possibilities in the food manufacturing industry, and illustrate the benefits of crossing discipline borders to both benefit from and contribute towards cross-fertilization of ideas. In particular, collaboration between academia and the food manufacturing industry has been proven fertile, and, if nurtured, can certainly be fruitful in the future.

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Sidebar: Extrusion cooking [17]-[20]

Extrusion cookers (Figure 1 and Figure 2) offer significant advantages, including continuous high-throughput processing, energy efficiency, processing of relatively dry viscous materials, improved textural and flavor characteristics of foods, control of the thermal changes of food constituents, and use of unconventional ingredients. Single-screw extrusion cookers were developed in the 1940s to make puffed snacks from cereal flours or grits. As size grew to realize economies of scale, extrusion cookers were used for an increasing array of food products in the 1960s and 1970s. Twin-screw extruders [21], developed in the 1970s and gaining market share in the 1980s, are now widely preferred for their improved conveying and mixing capabilities, interchangeable screw profiles, expanded operational capabilities, and extended range of application. Extrusion cooking is used to manufacture food products such as puffed snacks, macaroni, ready-to-eat breakfast cereals, breadings, croutons, soup bases, drink bases, and pre-gelatinized starch. Interestingly, pet foods are the largest product group manufactured by extrusion cooking, far exceeding the quantity of extruded human food products [22].

Sidebar: Continuous immersion frying

Immersion frying – the cooking of foods by immersion in hot edible oil – is widely used commercially to make fried foods, such as potato chips, French fries, doughnuts, extruded snacks, and fish sticks. Immersion frying offers high heat transfer rates and imparts a characteristic flavor, texture, and color to the final product [23]. Of the more than 2.5 million tons of snacks produced in the U.S. each year, most are immersion-fried. The main phenomena of relevance to control of quality-related variables in immersion frying at the fried food resolution level are:

- heat transfer (from the hot oil to the surface and interior of the food);
- mass transfer (evaporation of moisture from the food, and transfer of oil into the food);
- browning (Maillard reactions between aminoacids and reducing sugars).

Of course, there is a myriad of other biochemical reactions that take place, which constitute a complex system that we are not going to focus on here.

At the process resolution level, a continuous fryer is essentially a plug-flow reactor (Figure 3). A typical continuous frying system involves the following units (Figure 4): (a) A long (~8-15 m) and shallow (~1 m) tank containing the frying oil; (b) A pumping system that pumps and filters the frying oil; (c) A heat exchanger system that transfers heat to the frying oil; (d) a system of conveyors that move the product into, through, and out of the fryer, and (e) a fume exhaust system for removal of hot vapors generated during frying.

Invented as "Saratoga" chips in 1853 [24], potato chips (crisps in the UK) became widely available commercially after the invention of continuous slicing and frying in the 1920s, and grew in popularity during the Depression era, to eventually become the quintessential American snack.

References

[1] M. Abrahams, "The 1995 Ig Nobel Prize Winners," [Online], Available at Available at http://www.improbable.com/ig/ig-pastwinners.html#ig1995.

[2] D. M. R. Georget, R. Parker, and A. C. Smith, "A Study of the Effects of Water-Content in the Compaction Behavior of Breakfast Cereal Flakes," *Powder Technology*, vol. 81, pp. 189-195, 1994.

[3] M. Abrahams, *The Best of Annals of Improbable Research*. New York: W. H. Freeman and Company, 1998.

[4] L. DeLong, "Engineering Bytes. and Bites," [Online], Available at http://www.eweek.org/site/news/Features/chips.shtml.

[5] S. Bains, "Microchips are like potato chips," *Wired*, 2005, Available at http://www.wired.com/wired/archive/13.09/start_pr.html.

[6] S. A. Matz, *Snack food technology*, 3rd ed. New York: Van Nostrand Reinhold, 1993.

[7] U.S. Census Bureau, "2002 Economic Census Industry Series Report," [Online], 2002. Available at http://www.census.gov/epcd/ec97/industry/E311919.HTM.

[8] Anonymous, "Global Snack Food Industry Trends," *Snack Food & Wholesale Bakery*, vol. 93, pp. 64, 2004.

[9] W. C. Willett and M. J. Stampfer, "Rebuilding the Food Pyramid: Overview / The Food Guide Pyramid (Sidebar)," [Online], 2002. Available at http://www.sciam.com/article.cfm?articleID=000A97BD-80FC-1DF6-9733809EC588EEDF&sc=I100322.

[10] Anonymous, "Snacking, the All-American pastime," *Snack Food & Wholesale Bakery*, vol. 93, pp. SI-34, 2004.

[11] T. P. Shukla, "Future Snacks And Snack Food-Technology," *Cereal Foods World*, vol. 39, pp. 704-705, 1994.

[12] T. P. Shukla, "Modern snack foods," *Cereal Foods World*, vol. 45, pp. 477-477, 2000.

[13] Snack Food Association, "Directory," [Online], Available at http://www.sfa.org/membership/directory.aspx.

[14] H. McGee, *The Curious Cook: More Kitchen Science and Lore*: John Wiley & Sons, 1992.

[15] H. McGee, *On Food and Cooking*: Scribner, a division of Simon and Schuster, 2004.

[16] M. Nikolaou, "Computer-Aided Process Engineering in the Snack Food Industry," in *Fifth International Conference on Chemical Process Control*, vol. 93, *AIChE Symposium Series*, J. C. Kantor, C. E. García, and B. Carnahan, Eds. Tahoe City, CA: CACHE-AIChE, 1997, pp. 61-69.

[17] J. Harper, *Extrusion of Foods*, vol. 1. Boca Raton, FL: CRC Press, 1981.

[18] N. Frame, *The technology of extrusion cooking*, 1st ed: Blackie Academic & Professional, 1994.

[19] J. Harper, "Food extruders and their applications," in *Extrusion Cooking*, C. Mercier, P. Linko, and J. Harper, Eds. St. Paul, MN: American Association of Cereal Chemists, 1989, pp. 1-15.

[20] C. Mercier, P. Linko, and J. Harper, "Extrusion Cooking." St. Paul, MN: American Association of Cereal Chemists, 1998.

[21] F. G. Martelli, *Twin-Screw Extruders: A Basic Understanding*: Van Nostrand Reinhold Company, 1983.

[22] T. Eerikäinen and P. Linko, "Extrusion Cooking Modeling, Control, and Optimization," in *Extrusion Cooking*, C. Mercier, P. Linko, and J. Harper, Eds. St. Paul, MN: American Association of Cereal Chemists, 1989, pp. 157-204.

[23] P. J. Fellows, *Food processing technology - principles and practice*, 2nd ed. Cambridge, England: Woodhead Publishing Limited, 2000.

[24] Wikipedia, "Potato Chip." [Online], Available at http://www.wikipedia.org

[25] W. Y. Feng, M. Shouche, and M. Nikolaou, "Modeling and Predictive Control of a Continuous Fryer," presented at *AIChE Annual Meeting, paper 173j*, Miami Beach, FL, 1995.

[26] S. A. Roberts and R. C. E. Guy, "Metastable states in a food extrusion cooker," *J. Food Eng.*, vol. 6, pp. 103-112, 1987.

[27] H. Sarimveis, H. Genceli, and M. Nikolaou, "Design of Robust Non-Square Constrained Model Predictive Control," *AIChE J.*, vol. 42, pp. 2582-2593, 1996.

[28] Z. Vickers, "Sensory, Acoustical, and Force-Deformation Measurements of Potato-Chip Crispness," *J. Food Sci.*, vol. 52, pp. 138-140, 1987.

[29] H. L. Yu and J. F. MacGregor, "Multivariate image analysis and regression for prediction of coating content and distribution in the production of snack foods," *Chemometrics and Intelligent Laboratory Systems*, vol. 67, pp. 125-144, 2003.

[30] H. L. Yu, J. F. MacGregor, G. Haarsma, and W. Bourg, "Digital imaging for online monitoring and control of industrial snack food processes," *Industrial & Engineering Chemistry Research*, vol. 42, pp. 3036-3044, 2003.

[31] G. Roudaut, C. Dacremont, B. V. Pamies, B. Colas, and M. Le Meste, "Crispness: a critical review on sensory and material science approaches," *Trends in Food Science & Technology*, vol. 13, pp. 217-227, 2002.

[32] B. Bhandari, B. D'Arcy, and G. Young, "Flavour retention during high temperature short time extrusion cooking process: a review," *International Journal of Food Science and Technology*, vol. 36, pp. 453-461, 2001.

[33] W. E. Riha and C. T. Ho, "Flavor generation during extrusion cooking," in *Process-Induced Chemical Changes in Food*, vol. 434, *Advances in Experimental Medicine and Biology*, 1998, pp. 297-306.

[34] W. E. Riha and C. T. Ho, "Formation of flavors during extrusion cooking," *Food Reviews International*, vol. 12, pp. 351-373, 1996.

[35] M. Nikolaou, "Model Predictive Controllers: A Critical Synthesis of Theory and Industrial Needs," in *Advances in Chemical Engineering Series*, G. Stephanopoulos, Ed.: Academic Press, 2001.

[36] A. Brooks, "Personal Communication," 1995.

[37] G. Mottur, "A Scientific Look at Potato Chips - The Original Savory Snack," *Cereal Foods World*, vol. 34, pp. 620-626, 1989.

[38] T. A. Haley and S. J. Mulvaney, "On-line system identification and control design of an extrusion cooking process: Part I. System identification," *Food Control*, vol. 11, pp. 103-120, 2000.

[39] T. A. Haley and S. J. Mulvaney, "On-line system identification and control design of an extrusion cooking process. Part II. Model predictive and inferential control design," *Food Control*, vol. 11, pp. 121-129, 2000.

[40] C. H. Li, "Modelling extrusion cooking," *Food and Bioproducts Processing*, vol. 77, pp. 55-63, 1999.

[41] L. Levine, S. Symes, and S. Weimer, "Automatic control of moisture in food extruders," *J. Food Eng.*, vol. 6, pp. 97-115, 1986.

[42] B. E. Farkas, R. P. Singh, and T. R. Rumsey, "Modeling heat and mass transfer in immersion frying.1. Model development," *Journal of Food Engineering*, vol. 29, pp. 211-226, 1996.

[43] B. E. Farkas, R. P. Singh, and T. R. Rumsey, "Modeling heat and mass transfer in immersion frying.2. Model solution and verification," *Journal of Food Engineering*, vol. 29, pp. 227-248, 1996.

[44] N. Mittelman, S. Mizrahi, and Z. Berk, "Heat and Mass Transfer in Frying," in *Engineering and Food, Chapter 12*, B. M. McKenna, Ed.: Elsevier Applied Science Publishers, 1984, pp. 109-116.

[45] Y. Huang, A. D. Whittaker, and R. E. Lacey, "Neural network prediction modeling for a continuous, snack food frying process," *Transactions of the ASAE*, vol. 41, pp. 1511-1517, 1998.

[46] Y. Huang, A. D. Whittaker, and R. E. Lacey, "Internal model control for a continuous, snack food frying process using neural networks," *Transactions of the ASAE*, vol. 41, pp. 1519-1525, 1998.

[47] L. Brescia and R. G. Moreira, "Modelling and control of a continuous frying process: A simulation study.1. Dynamic analysis and system identification," *Food and Bioproducts Processing*, vol. 75, pp. 3-11, 1997.

[48] L. Brescia and R. G. Moreira, "Modelling and control of a continuous frying process: A simulation study.2. Control development," *Food and Bioproducts Processing*, vol. 75, pp. 12-16, 1997.

[49] G. J. Haarsma and M. Nikolaou, "Multivariate Controller Performance Monitoring: Lessons from an Application to a Snack Food Process," presented at *AIChE Annual Meeting*, 1999.

[50] J. Diamond, *Guns, Germs, and Steel*: Norton, 1999.

[51] M. Battacharya and M. A. Hanna, "Influence of process and product variables on extrusion energy and pressure requirements," *J. Food Eng.*, vol. 6, pp. 153-163, 1987.

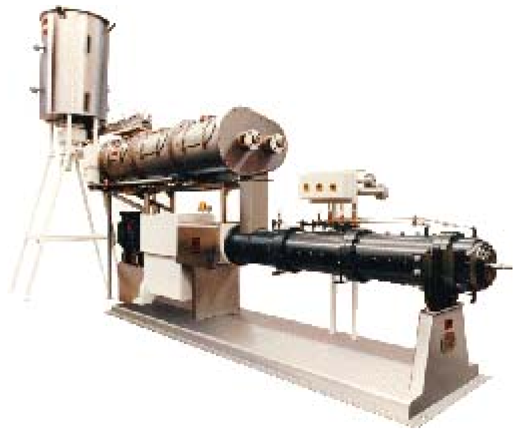

Figure 1 – Twin-screw extrusion cooking system, courtesy of Wenger. The first barrel is a pre-conditioner, used in conjunction with the extruder to increase residence time, reduce mechanical power consumption, and/or increase capacity. A cooling jacket around the extruder, instrumented with thermocouples in various places provides temperature control

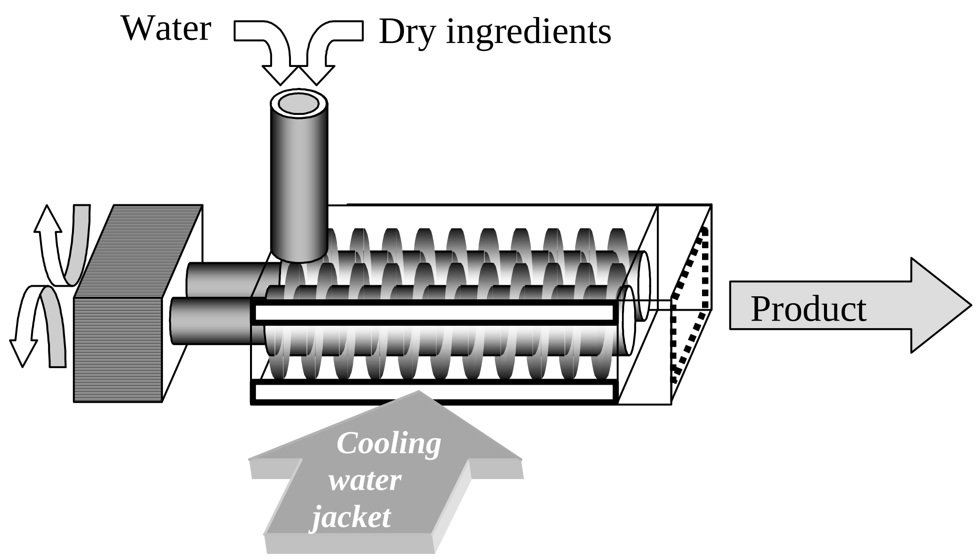

Figure 2 – Simplified schematic of twin-screw extrusion cooker. In food extrusion, the most effective manipulated variables are mass feed rate, moisture content of mass feed, mass and barrel temperatures, and screw speed [51].

Figure 3 – (a) A high-capacity (4200 lb/hr) continuous frying system, shown with the oil circulation and heat-exchanger. (b) A compact (400 lb/hr) continuous fryer with the top raised for cleaning and maintenance (courtesy of Heat and Control). The quality of fried chips is quantified by specifications on moisture content, oil content, and color. Quality is mainly controlled by manipulating the residence time and frying temperature of the chips in the fryer. A common disturbance is product load changes. To manipulate residence time, the submerger speed is adjusted, so that submerged chips travel at the same speed as the submerger paddles. To manipulate the frying temperature, oil circulates continuously between the fryer and heat exchanger. Multiple injection points of hot oil are used, to ensure the desired temperature profile along the fryer, according to cooking preferences. Because part of the frying oil leaves with the chips, it has to be continuously replenished. In addition to creating fast process dynamics, low oil volume and rapid oil turnover assure fresh product with a long shelf life. A level controller maintains oil level at its optimum.

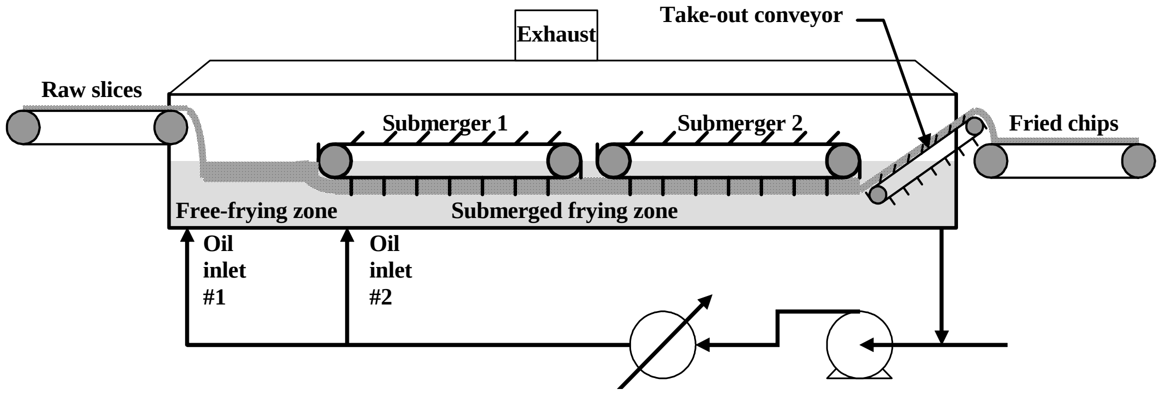

Figure 4 – Schematic of a multi-zone continuous fryer. The dual submergers and oil inlets provide improved controllability. Key variables associated with product quality are moisture content, oil content, and color, all of which can be measured in real time at the outlet. Key manipulated variables are oil temperature, submerger speed, and take-out conveyor speed. Secondary loops ensure that process variables such as oil-bath level, oil temperature, and oil flow are maintained at desired values [16]. Because part of the oil leaves the fryer with the fried chips, it is continuously replenished with fresh oil at controlled amounts, thus simultaneously suppressing oil rancidity in the fryer.

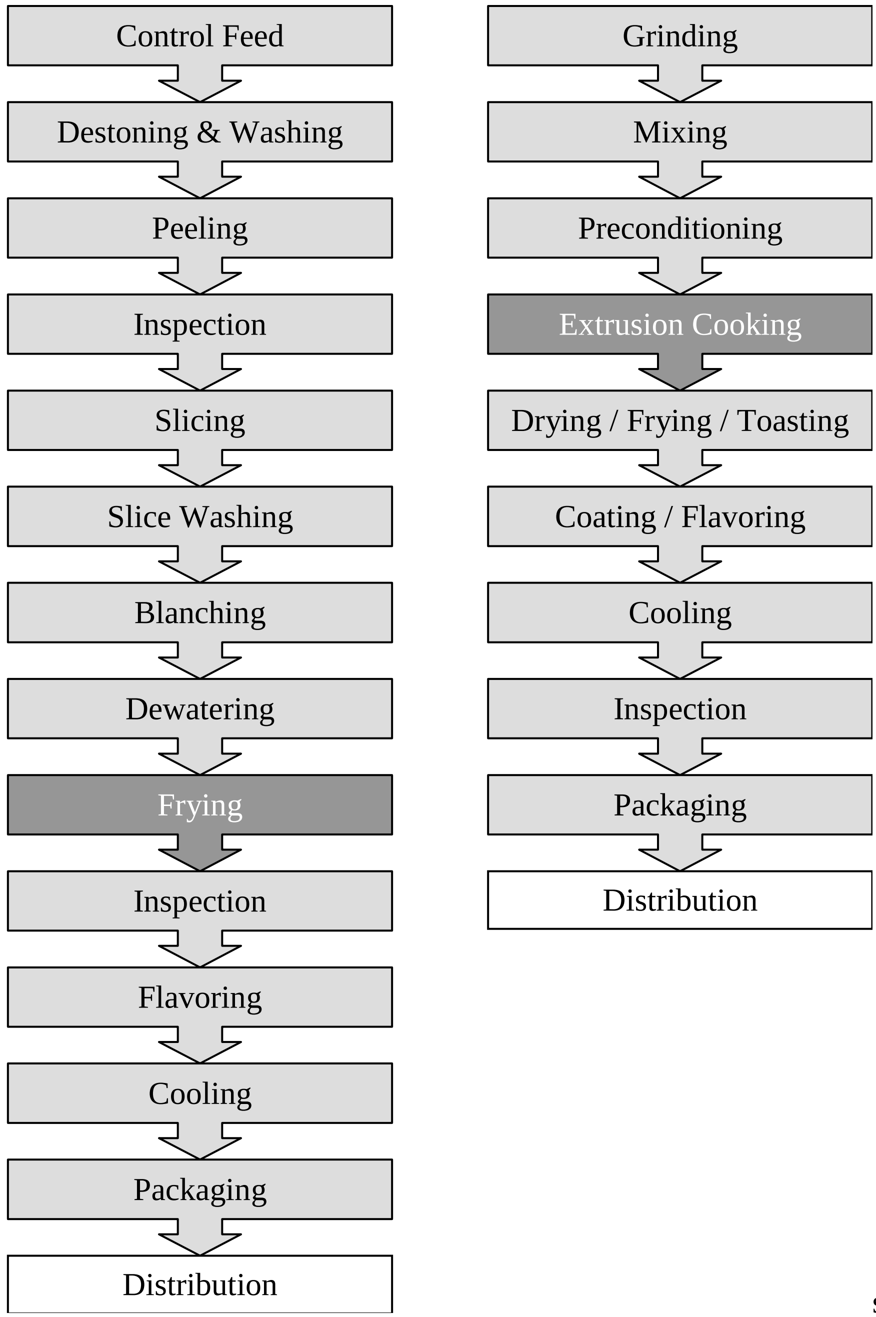

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Figure 5 – Examples of snack food manufacturing lines. (a) Components of a potato-chip production line. The inspection blocks involve visual inspection of peeled raw potatoes or finished chips. Until recently, inspection was done manually, a strenuous, labor-intensive task that also entailed cutting-off of unwanted raw potato parts or removal of off-spec chips. (b) Components of an extruded snack production line. In both lines, the heart of the system is the “reactor”, that is the fryer or extrusion cooker.

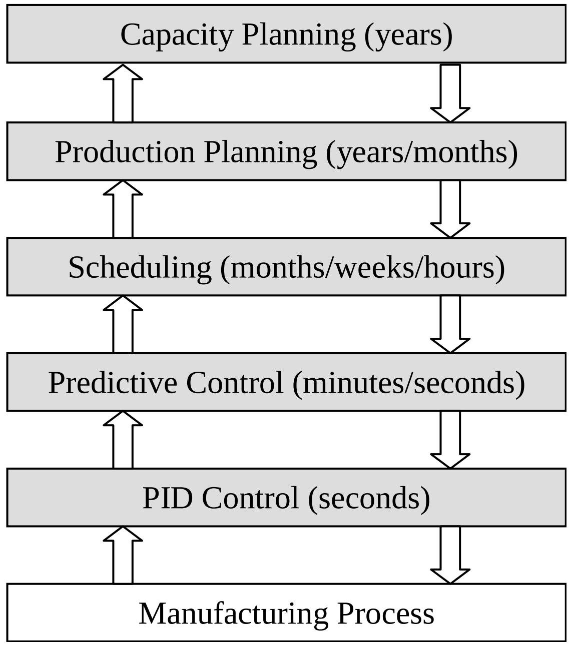

Figure 6 – The multi-level control hierarchy of snack food manufacturing processes at multiple time scales is fairly similar to the hierarchy in other process industries. Decisions from upper levels are passed to lower levels, whereas information from lower levels is passed upwards. Because time scale decreases as one moves downwards, decisions made at each level are supposed to be "instantly" followed by the underlying level. Various modeling and decision making paradigms are used at different levels. For example, explicit stochastic models, first-principles models, and dynamic programming may be used at the planning and scheduling levels, whereas empirical models and on-line optimization or explicit control algorithms are used at the predictive control and PID levels.

Author’s Bio

Michael Nikolaou received his Diploma from the National Technical University, Athens, Greece, in 1984, and his Ph.D. from the University of California, Los Angeles, in 1989, both in chemical engineering. From 1989 to 1997 he was initially Assistant Professor and then Associate Professor in the Chemical Engineering Department at Texas A&M University. After receiving tenure at Texas A&M, he held a Visiting Scientist position at MIT in 1995, before moving to the University of Houston in 1997 where he is presently Associate Professor. Dr. Nikolaou's research interests are in computer-aided process engineering, with current emphasis on process modeling, identification, monitoring, and control, and their applications to the chemical, petroleum, microelectronics and biomedical industries. His research has been externally funded by both government and industry, and over 15 Ph.D. graduates from his group are now successfully holding positions in industry or academia in the U.S. and overseas. His industrial experience includes consulting to a number of companies in diverse fields. His academic and consulting experience on snack food manufacturing provided the basis for this article.