ChE educator

Ignacio Grossmann

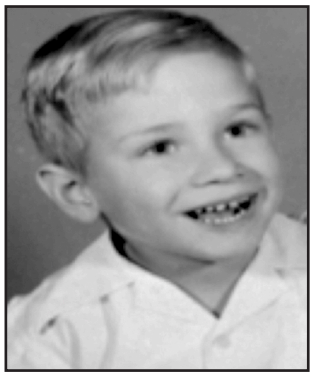
. . . of Carnegie Mellon University

Lorenz Biegler, Chrysanthos Gounaris, Nikolaos V. Sahinidis, and B. Erik Ydstie
Carnegie Mellon University

It is unusual to find a person who, having had a profound impact in his field, is also a truly generous and sincere individual, who is well liked and highly respected by all. It is also rare that a single person's career can be used as a measure in describing an entire research area. This is true in Ignacio Grossmann's case. He has built a foundation that is used as a roadmap for process systems engineering, a dynamic and highly successful area of chemical engineering. Ignacio approaches both life and research with a great sense of high standards, dedication to his students and colleagues and caring for others.

BACKGROUND

Ignacio E. Grossmann was born in Mexico City in 1949, to Swiss parents, Donat and Marie Louise Grossmann, who emigrated to Mexico after the war. His father was a mechanical engineer who ran the Mexican branch of a Swiss manufacturing firm. Growing up in Mexico, he was exposed to a rich multi-cultural community, along with exhilarating interests in music and, of course, *futbol*. Along the way he acquired keen interests in mathematics, science and engineering.



Ignacio growing up in Mexico (1954).

Due to these interests, Ignacio decided to study Chemical Engineering at Universidad Iberoamericana (Ibero), a private Jesuit-run university with a top engineering program, where he would enthusiastically pursue his interests in process simulation and modeling. At the same time, he assisted in several engineering courses and worked as a process design engineer at the Instituto Mexicano del Petroleo (IMP), the research arm of PEMEX. His outstanding undergraduate work included a thesis on multistream heat exchangers, as well as receiving the Medal for Best Student of Mexico from the National Council of Science and Technology.

Ignacio as a student at Ibero (1973).

Ignacio's strong interests in computer aided process engineering led him to pursue graduate study at Imperial College London with a scholarship from the British Council. Working with Prof. Roger W. H. Sargent, a key founder and pioneer of process system engineering (PSE), Ignacio addressed three important problems: optimization of heat exchanger networks, optimization under uncertainty, and optimal design of multipurpose plants. The concepts and solution strategies developed in these papers were instrumental in defining key research directions over the next four decades.

After finishing his PhD in 1977, Ignacio returned to Mexico to lead the Optimization Group at IMP, while at the same time teaching advanced graduate courses at Ibero. During this time, he developed the first mixed-integer optimization approaches for process synthesis as well as an efficient optimization-based strategy for phase and chemical equilibrium.

Needless to say, Ignacio's groundbreaking work at Imperial and IMP was strongly appreciated in the worldwide process systems community. Meanwhile, at Carnegie Mellon University, Dean Herbert Toor (with prudent advice from Nobel laureate Herbert Simon) had started the Design Research Center, which strongly influenced the hiring of a number of faculty in the PSE area. In particular, Prof. Art

Westerberg, then DRC's director, saw the tremendous opportunity to recruit Ignacio to CMU. Ignacio joined in 1979 and has been with CMU ever since.

Ignacio at Imperial College (fourth from the left) with Roger Sargent's group (1975) (including Gerry Sullivan, David Mellefont, Nizar Virani, Rutilio Hernandez-Sosa and Sue Byrne).

IGNACIO'S CONTRIBUTIONS TO PROCESS SYSTEMS ENGINEERING

At Carnegie Mellon, Ignacio rose through the ranks. He was promoted to full Professor in 1986, was awarded the Dean Professorship in 1990 and served as Department Head from 1994-2002. As Department Head, Ignacio hired seven new faculty members. There is ample testimony of the deep, positive mentorship he provided to the then young faculty of our department, who have since grown to become the backbone of our current faculty. In addition, through fundraising for endowed chairs, fellowships and seminar series, he greatly increased the visibility of the department, both on campus and externally. His leadership also strongly impacted the extensive renovation of the research labs in Doherty Hall, carried out under the headship of Prof. Andy Gellman, Ignacio's successor.

During the past four decades, Ignacio made outstanding and long-lasting research contributions to process systems engineering. His trailblazing research has strongly influenced the current practice of process simulation, process modeling environments, process optimization strategies, synthesis of chemical processes, and the modeling of engineering activities. These contributions have also seen widespread application in industry, through numerous application projects, the training of high quality researchers, and the creation and coordination of many initiatives that have spurred strong academic/industrial collaborations and interactions.

On the numerical methods side, Ignacio Grossmann is a pioneer of the area of mixed-integer nonlinear programing (MINLP), the solution of optimization problems with continuous and discrete variables. His development of Outer Approximation in 1986 was the first rigorous decomposition algorithm for solving MINLPs. Since then, numerous other contributions by Ignacio to methodologies such as Generalized Disjunctive Programming, Logic-Based Outer Approximation, Constraint Programming, Convex Hull Relaxation and Branch and Cut algorithms, have led to significant improvements that have made MILP and MINLP strategies a key fundamental paradigm in PSE.

As a follow-up to that work, he developed DICOPT, the first computer code for solving MINLP problems. A powerful extension to this MINLP code techniques is the open-source BONMIN program, which implements the branch and bound, outer-approximation algorithm and the LP/NLP branch and cut methods developed by Ignacio and his team. In addition, the LOGMIP code for solving generalized disjunctive programming problems allows the handling of disjunctions and logic constraints. These codes are in the canon of PSE tools and have also been adopted by countless researchers in operations research, economics and other engineering areas.

Professor Grossmann pioneered a number of optimization models and solution strategies for energy integration and management. In particular, he developed the linear programming transshipment model for determining the minimum energy consumption configuration of an integrated set of hot and cold streams. He introduced the first superstructure optimization model for automatic synthesis of heat exchanger networks that meet specified targets for minimum utility cost and minimum number of units for a given temperature approach. He was also the first to develop a mixed-integer nonlinear model for automatically synthesizing network structures for which energy consumption, number of units and area cost are simultaneously optimized, even without specifying a minimum approach temperature. In addition, Ignacio proposed a model for simultaneous optimization and heat integration that reduces the consumption of feedstock through efficient energy integration. Further examples of optimization-based process synthesis include integrated synthesis of heat exchanger networks and utility plants, optimal distillation sequences as well as synthesis of integrated water treatment systems.

These powerful optimization strategies also extend naturally to logistical optimization in process operations. Ignacio's methods have impacted widespread applications from scheduling of batch processes, strategic and tactical

planning of single- and multi-site plants and optimization of global supply chains. Mixed-integer planning and scheduling models of Ignacio's group have seen extensive applications in industry, and have produced significant savings. The results of his work have reaped significant benefits for the research community as well as in industry. Examples include long range planning of networks of flexible processes, planning and scheduling of offshore gas and oilfields, planning and scheduling of plants with catalyst deactivation, multiperiod planning of utility plants, and scheduling for the following: polymer plants, ethylene feedstocks, plants for manufacturing dyes, rolling mills, consumer products, refinery operations, pharmaceutical plants, and even testing of new products.

Companies that have made use of these techniques include ABB, Atofina, Dow Agrosciences, Dow Chemical, DuPont, EQT, ExxonMobil, Imperial Chemical Industries, Mitsubishi and Unilever, among others. Examples of highly successful projects include refinery and batch scheduling, optimal planning of polymer plants, large-scale supply chain optimization under uncertainty, and gas field development under uncertainty.

Ignacio's broad range of research achievements have led to over 600 scientific articles, which have been cited over 47,000 times (h-index = 115, Google scholar citations). He has supervised over sixty Ph.D. and ten MS students, many of whom have joined major corporations like Dow, ExxonMobil, Shell, BASF and Bayer. Additionally, twelve of Ignacio's PhD students have taken significant academic positions and have generated an academic family tree with over 500 PhDs, one of the largest academic trees in process systems engineering. For the full (and growing) tree, see titan.princeton.edu/tree.

Professor Grossmann's achievements have been widely recognized and appreciated. He is a member of the US National Academy of Engineering and the Mexican Academy of Engineering, as well as a corresponding member of the Mexican Academy of Sciences. His major awards include the 1994 Computing in Chemical Engineering Award from AIChE, the 1997 William H. Walker Award of AIChE, the 2003 Computing Society Prize of INFORMS, the 2007 Kun Li Award for Excellence in Education at Carnegie Mellon, the 2009 Warren K. Lewis Award of AIChE, and the 2011 Research Excellence in Sustainable Engineering Award from AIChE. He has been awarded honorary doctorates from seven universities (Universidad de Alicante, Universidad Nacional del Litoral in Santa Fe, Kazan National Research Technological University, Universidad de Cantabria, Technical University of Dortmund, University of Maribor in Solvenia, Abo Akademi), is among the Top 15 Most Cited Authors in Computer Science by ISI, and was named one of the 100 Chemical Engineers of the Modern Era by AIChE in 2008. More recently, his achievements have been recognized by the following lifetime awards:

- *Luis Federico Leloir Award for International Cooperation, Argentina, 2012.*
- *Distinguished Professor of Engineering Award, Carnegie Mellon University, 2014.*
- *One of the Most Influential Scientific Minds, Thompson Reuters, 2015.*
- *Chemical Engineering Division's Lectureship Award, ASEE, 2015.*
- *Sargent Medal, Institution of Chemical Engineers, UK, 2015.*
- *Constantin Carathéodory Prize, International Society of Global Optimization, 2015.*

An informal gathering of Ignacio' s research group (2017).

Ignacio receiving an honorary doctorate (his seventh) from the University of Alicante (2019).

- *2017 Award for Long Term Achievements in Computer Aided Process Engineering, CAPE Working Party, European Federation of Chemical Engineering, 2017.*
- *ETH Zurich Chemical Engineering Medal, 2017.*

IGNACIO'S RESEARCH LEADERSHIP

Professor Grossmann was the co-founder and long-time director of the Center for Advanced Process Decision-making (CAPD@CMU), a research consortium of over twenty member companies that support and participate in projects in the area of Process Systems Engineering. Since the CAPD's founding in 1985, Ignacio Grossmann has been its key driver and has led this organization into new research areas and industrial interactions. Providing intellectual leadership on complex design and operational problems faced by process industries, the CAPD produces M.S.- and Ph.D.-level engineers with unique skills in PSE, interacts with industry through mutually beneficial projects and offers a variety of features/services to companies, including short courses and research meetings, access to research software, and collaborative research projects.

About 15 years ago, Ignacio Grossmann initiated a CAPD special interest group on Enterprise-wide Optimization (EWO) (see http://capd.cheme.cmu.edu/ewo.html). This initiative came from the realization that process systems engineering must be applied at larger time and length scales, with logistics and planning across sites throughout the company. As a result, this special interest group was formed to develop novel planning and scheduling models that include consideration of uncertainty, effective integration of production planning, scheduling and real-time optimization, and optimization of entire supply chains. Companies that have contributed to EWO's mission include ABB, Air Liquide, Air Products, Cognizant, Dow Chemical, ExxonMobil, Mitsubishi Electric, P&G, Praxair, Sasol, Total and Unilever. Impressively, EWO deals with a wide range of projects that span a broad segment of the process industries, such as for example strategic planning models for shale gas production, siting of oil production platforms and timing of drilling strategies, assessing the impact of supply chain conditions on consumer product quality, optimization modeling of railcar loading analysis, and design optimization of the packaged gas supply chain.

More importantly, the EWO initiative serves as a forum for industry and academia to exchange ideas and optimization strategies, and to discuss general problem formulations and practical solution strategies. EWO has an active Webinar series that promotes industrial and academic participation, repositories of focused literature case studies, links to available software and resource material for logistics, optimization and problem formulations (see http://www.minlp.org).

IGNACIO'S CONTRIBUTIONS TO CHEMICAL ENGINEERING EDUCATION

Through the publication of their textbook *Systematic Methods of Chemical Process Design*, Prof. Grossmann has made unique contributions with Profs. Art Westerberg and Larry Biegler to undergraduate and graduate education. This text is highly significant because it reflects the dramatic changes that process design and process systems engineering have undergone over the past thirty years. In addition, Ignacio prepared several CAChE Design Case Studies that have been used extensively by many universities http://www.che.utexas.edu/cache/casestudy.html.

For international education and outreach, Prof. Grossmann was the key driving force in establishing the Chemical Engineering PanAmerican Collaboration Organization (CEPAC) (http://www.cepac.cmu.edu). This organization was established to promote collaboration between Pan-American countries in chemical engineering research. Ignacio has been the main driver in linking researchers in process systems engineering (PSE) in the western hemisphere. Through sponsorship of the National Science Foundation and the PanAmerican Advanced Studies Institute (PASI), he co-organized three major PASI workshops: PASI-PSE in 2005; Emerging Trends in PSE in 2008; and Process Modeling for Energy and Sustainability in 2011. In addition, he developed and continues to maintain the CEPAC website to serve as a forum to discuss trends in PSE, a repository for educational materials for PSE education, and to promote and publicize PSE meetings and organizations. Notable on this website are links to all PSE researchers in Latin America and

North America. He also created the Virtual Library of Process Systems Engineering http://cepac.cheme.cmu.edu/pasilectures.htm that provides a collection of state-of-the-art lecture notes by PSE leading researchers in North and South America.

Professor Grossmann also served as a Director of AIChE from 2007-2009 and Chair of the International Committee, where he continues to be very active. The AIChE International Committee develops and implements strategic and tactical activities related to the international component of AIChE's mission. He has promoted activities and academic exchanges with groups in Latin America, Spain, India, China and Russia. Moreover, for *Chemical Engineering Progress*, he edited a series of feature articles on the international chemical industry, including growth and surveys in Argentina, Chile, Italy, Mexico, Russia, Saudi Arabia and Spain.

Ignacio at Home with Andrew, Claudia, Blanca and Thomas.

IGNACIO AT HOME

While a graduate student in London Ignacio met Blanca Espinal, a native of Navarra province in northern Spain. As Ignacio wound up his graduate studies, they married in 1977 and moved to Mexico to start a family. Now with three grown children (with families of their own) Blanca and Ignacio fondly remember countless school committees, many soccer coaching sessions, and numerous hockey practices. Claudia, their oldest, received her Ph.D. in biological sciences from UC-San Francisco and is now Program Officer with the Research Infrastructure team at the Patient-Centered Outcomes Research Institute (PCORI) in Washington, DC. Andrew, who studied Communications Design at CMU, is an independent graphic designer and developer whose projects span web-based educational designs to traditional print design. Thomas, the youngest, studied Industrial Engineering at the University of Wisconsin and now works for Apple in Cupertino, CA.

With the arrival of six grandchildren, the Grossmann family has become even closer as the next generation grows up. Moreover, Blanca and Ignacio continue to share their love of music and travel, particularly to Europe and Latin America, with regular trips to Spain and Mexico to visit family and friends.

The Grossmann grandchildren during soccer practice orchestrated by Ignacio. From left to right: Elena, Oscar, Joaquin, Lucas, James, and Alex.

OUTLOOK

Despite his long track record in research and education, Ignacio shows no signs of slowing down and he continues to run an active PSE group with broad research portfolios in enterprise-wide optimization, optimization of power and energy systems and PSE applications in the pharma industry. His research legacy and continuing research contributions were recognized at his 65th birthday, where over 100 former students, colleagues and friends met to celebrate his many accomplishments. A similar event is being planned for Ignacio's 70th birthday celebration during the 2019 Annual Meeting of the AIChE.

As he continues to open new vistas for the PSE community, all of us look forward to many more successes for Ignacio to celebrate. ❐