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Work-in-Progress: A Delphi Study of Skills and Competencies for the Hydrocarbon Industry

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Abstract

This paper describes an in-progress research study to develop consensus among working industry professionals and chemical engineering faculty on the particular skills and workforce competencies needed in the hydrocarbon industry for the National Science Foundation-sponsored Center for Innovative and Strategic Transformation of Alkane Resources (CISTAR). This study uses a Delphi methodology, which is a systematic solicitation and collection of feedback from a pool of experts (approximately 10-30) on a particular topic through a set of carefully designed sequential surveys. In between survey collection rounds, data are synthesized, summarized, and presented back to the experts for reflection and group consensus building. Once consensus for this study is reached, the list of skills and competencies will be used in the center's graduate courses, summer programs (e.g., Research Experiences for Undergraduates, Research Experiences for Teachers), and K-12 outreach efforts.

Motivation

Chemical engineering evolved in the early to mid-twentieth century mainly based on an abundant supply of fossil resources for chemical production and energy, so process design concepts focused primarily on large tonnage-scale manufacturing facilities [1]. However, the economic use of renewable energy resources such as solar and wind is rising rapidly [2]. Transitioning to these sources of energy is an important endeavor; however, the technology to do so and the costs of this transition indicate that it will happen slowly. The unprecedented revolution in domestic supplies of new light hydrocarbon resources from shale provides a compelling opportunity for the U.S. to become a global leader in fuels and chemicals production. Although this has potential to lower the nation's energy costs, and provide a lower carbon footprint "bridge fuel" to a more sustainable economy, significant challenges exist to realize this revolution.

One of these challenges is the training and development of a workforce prepared to work in the developing light hydrocarbon industry. The fields of engineering education and chemical engineering have agreed upon competencies for engineers generally through reports and standards like The National Academies *The Engineer of 2020* report [3] and ABET student outcomes [4]. While ABET student outcomes have been recently revised, it is now 2020 and no new vision of engineering has been set for engineers beyond 2020. Additionally, sector-specific competencies in chemical engineering have not been defined. This work-in-progress study begins to fill that gap by investigating the skills and competencies needed by chemical engineering graduates to address the pressing issues of energy within the light hydrocarbon industry for the next 30 years.

Process of a Delphi study

This study is a part of a larger effort through the CISTAR NSF Center to develop systems to convert light hydrocarbons from shale resources to chemicals and transportation fuels in smaller, modular, local, and highly networked processing plants. In order to create a list of sector-specific skills and competencies for undergraduate and graduate students, some agreement among stakeholders and experts is needed. Our team has begun the process of a Delphi study to identify these outcomes and develop formal and informal curricula aligned with these outcomes.

The Delphi method, an established and widely used technique in social science research, is used to address complex questions by using a process of iterative surveys given to groups of experts with the goal of obtaining consensus about the problem [5]. Between each round of surveys the anonymized survey data is analyzed by the research team and aggregated around fundamental elements that are the basis of the study. The summary of the analysis is provided to the experts in the next survey round. The subsequent rounds allow the experts to provide feedback on the data and to determine whether they agree with the presentation of the fundamental elements.

The premise of this method is that decisions from a group are more accurate than decisions from individuals. This process also allows for anonymous group interactions and responses to avoid undue bias from a single voice or opinion. The process of data collection, analysis, and reflection is repeated until consensus is reached. There is no agreed upon definition of consensus, and this metric must be defined at the beginning of the study to determine the bounds of the study and when the rounds should end [6].

The Delphi method presents several advantages, such as anonymous feedback, expert opinions, geographically independent, reasoned opinions, and the quantifiable outcomes [7]. Nonetheless, the method presents some caution due to the length of the process until reaching consensus and the confidence of the ability of the experts [8]. Moreover, researcher questions may unintentionally influence responses, assessing expertise bay be difficult due to lack of face-to-face interactions, and attrition may exist [9]. But when appropriately administered, the Delphi method can be an extremely flexible and robust method [10].

Our Process

Initially, we met with stakeholders and an advisory board for the CISTAR project in Fall 2019 to generate a definition for consensus. This group included faculty in chemical engineering who teach courses related to light hydrocarbon industry processing, industry representatives, engineering education experts, and teacher professional development experts. The group agreed to cease data collection when the standard deviation on individual skills and competencies decreased in subsequent rounds and to complete no more than four rounds. This definition allows for multiple rounds of data collection to ensure as much agreement between experts across vastly different fields, while also avoiding a situation where no stopping point would be reached. Additionally, this definition of consensus used quantitative metrics for agreement without specifying a particular threshold value.

The research team developed the initial list of competencies by synthesizing several documents that spanned from the field of engineering, in general, to the light hydrocarbon industry, in particular. We referred to the *Engineer of 2020* report [3], ABET student outcomes [4], chemical engineering undergraduate course learning outcomes from CISTAR partner universities, current CISTAR course learning outcomes, and relevant job postings related to the light hydrocarbon industry [11], [12], [13]. Once this list was compiled, qualitative content analysis was applied to interpret meaningfully the topics and themes that are evident in the contents of communications when framed against the research objectives of the study [14]. We developed a competency matrix that listed each of the competencies from these documents in a single location. We first reduced near-identical competencies (e.g., problem solving). We then collapsed the remaining competencies into a two-level list of three categories and fifteen competencies. The list includes a working definition of each competency based on the descriptions used in the original documents. The results of our synthesis were checked by other project members, who helped refine word choice related to innovation and understanding the perspective of industry. The initial competency list used to develop the survey is shown below in Table 1. The table contains the competency along with the definition of the knowledge, skills, and abilities (KSAs) for that qualification.

Table 1. Synthesized list of skills and competencies for light hydrocarbon workforce.

Category	**Competency**	**Definition**	**Definition Source***
Engineering fundamentals	Problem Solving	KSAs pertaining to problem identification, scoping, analysis, and solution generation	E1, E2, J7, P1, A1, O45
	Design	KSAs pertaining to the process incorporating problem solving and research through working with stakeholders, developing requirements, iterating on multiple possible solutions to create design solutions to engineering problems	E3, A2
	Research	KSAs pertaining to developing one's own understanding, seeking out new information, and being lifelong learners	A6, A7, O3, O25, O45, O61-63, O76
	Entrepreneurship	KSAs pertaining to bringing about products and processes outside current market offerings	Director of Innovation
	Innovation	KSAs pertaining to the appreciation and implementation of innovation and creativity in engineering work	E2, P6, Director of Innovation
Sociotechnical skills	Communication	KSAs relating to the clear expression of one's ideas with multiple audiences in multiple formats, including oral and written	E4, J5, P3, A3, O20, O64
	Teamwork / Leadership	KSAs pertaining to working with groups, including participation, collaboration, inclusivity, project management, and leadership	E6, J6, P2, A5, O4, O36, O60, O65-67, O73, O75

Category	Competency	Definition	Definition Source*
Sociotechnical skills (*continued)*	Ethics	KSAs pertaining to ethical and professional responsibilities in engineering situations and making informed judgments with high ethical standards	E7, P5, A4, O1
	Business Perspective	KSAs pertaining to understanding and recognizing the practices and perspectives of business and industry. Also includes utilizing these KSAs to bringing about new ideas within a company	E5, P4, O24, O78, Director of Innovation
	Social Awareness	KSAs relating to the context that engineering work resides within, which includes global, cultural, social, environmental, and economic factors	C1, O5, O48
Content knowledge	Unit Operations and Process Design	KSAs pertaining to the understanding and application of energy balances, fluid flow, heat and mass transfer, transport, and separations in process design	C3, O6-19, O26-29, O74
	Reaction Engineering	KSAs pertaining to the understanding and application of kinetics, catalysis, and reaction chemistry	J2, C2
	Process Safety	KSAs pertaining to the recognition and management of hazards and safety concerns in engineering work	C2, O50-58, O68, O77
	Process Controls	KSAs pertaining to the use of control principles to meet safety, economic, environmental, societal, and corporate goals	C2, O69-72
	Additional content knowledge	KSAs pertaining to topics including modeling and materials which ultimately impact process design and control	C2, O21, O30-35, O37, O39-44

* Source details in Appendix

From this list of skills and competencies, we developed a survey to send to our pool of experts. This survey contains a section for participants to report information about their current position (i.e., establishment of role as an expert) including years of experience, area of chemical engineering with which their work is most aligned (gathered from the American Institute for Chemical Engineers [15]), and experience working directly with graduates (bachelor's through Ph.D.) in their position. The second part of the survey asks for an open-ended definition of success in the energy, fuels, and chemical industry and provides the list of skills and competencies from Table 1 for ranking. This section also provides experts an opportunity to list additional skills and competencies they feel are important for success in this area with a short definition. These open-ended responses will be included in subsequent rounds of data collection. The final section of the survey asks general questions about the completeness and accuracy of the list.

Data from each round of the survey will be used to improve the list of competencies. Experts will receive an updated survey along with a short summary of all the expert feedback to read before completing the next round. This process ensures that the collective voice of the group will be shared while also maintaining the anonymity of the process.

The pool of experts to whom the survey will be distributed has been identified through multiple channels. First, we anticipate sending the survey to all faculty within the center. These faculty are experts in teaching and research directly related to the light hydrocarbon industry and shale fuel conversion. Second, we will send the survey to our list of 26 industrial partners. These partners range from multinational oil and gas companies to boutique consulting and advisory firms focusing on oil and gas, energy, and chemicals. This list also includes national laboratories (i.e., Argonne, Oak Ridge, Pacific Northwest, and Sandia), international universities, and foundations. The list will also be distributed through networks of the CISTAR faculty to experts in the field. Together, this list encompasses a wide range of experts across a number of divisions. If the first survey reveals a lack of input from a particular sector, purposeful sampling will be used to solicit participation from individuals in these areas.

Future Work

Our future work involves the completion of this study as well as the dissemination and use of the results of this study. Our Delphi study will provide a prospective view of the changing field of energy and fuels within chemical engineering. The expert feedback will provide a list of skills and competencies aligned with workforce needs beyond basic undergraduate accreditation (i.e., ABET student outcomes) and the current practices in engineering education (i.e., beyond 2020). We envision that this list will be used with CISTAR to develop curricula aligned with these skills in general and special-topics courses at the undergraduate and graduate levels. There are often complaints that current education, which has not dramatically changed in X years, does not prepare students for the workforce. Through this effort, we hope to change that perception.

We plan to use a "backward design" instructional design framework to develop curricula [16]. This approach ensures that student learning focuses on particular actionable learning objectives that are measurable to improve student achievement. This approach involves 1) identifying the desired outcomes and results, 2) determining what constitutes acceptable evidence of competency in the outcomes and results (i.e., assessment), and 3) planning instructional strategies and learning experiences that bring students to these competency levels [17]. The Delphi study addresses the first of these steps, and future work will address the second and third steps.

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Appendix

E: Engineer of 2020

Label	Competency
E1	Strong analytical skills
E2	Practical ingenuity
E3	Creativity
E4	Communication
E5	Principles of business and management
E6	Leadership
E7	High ethical standards
E8	Professionalism
E9	Dynamism, Agility, Resilience, and Flexibility

J: Job Postings

Label	Competency
J1	Course content/knowledge of unit operations (e.g., as kinetics, separations, transport)
J2	Specific skills/knowledge (catalyst evaluation, controlling catalyst deactivation)
J3	Technical skills/knowledge (process modeling)
J4	Safety
J5	Communication
J6	Teamwork
J7	Problem solving

P: NSF Proposal

Label	Competency
P1	Systems-level/Interdisciplinary Technical Skills and Problem Solving
P2	Teamwork
P3	Communication
P4	Industrial Perspective
P5	Ethics
P6	Creativity and Innovation

C: CISTAR Courses

Label	Competency
C1	Contextual knowledge: economy for energy, fuels, materials, energy use in society, different types of energy systems (electricity, LPG/LNG, gasoline, coal, diesel, jet)

C2	Specific skills/knowledge: process intensification, life cycle analysis, modeling, optimization, membrane performance (selectivity, flux, solubility, diffusivity), testing/characterization methods for catalytic materials
C3	Unit operations (reaction chemistry, thermodynamics, catalysis)

A: ABET

Label	Competency
A1	An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
A2	An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors
A3	An ability to communicate effectively with a range of audiences
A4	An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts
A5	An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
A6	An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
A7	An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

O: Course Objectives from partner universities

Label	Course	Competency
O1	CHE 200 (Sophomore seminar)	Demonstrate an understanding of the need for academic and professional integrity and ethical behavior.
O2		Demonstrate an understanding of contemporary issues encountered in the professional practice of chemical engineering including business practices, environmental, health, and safety issues and other public interests
O3		Demonstrate an appreciation of the need for engaging in life-long learning and using appropriate learning strategies to maintain and enhance the professional practice of chemical engineering
O4	CHE 205 (Intro to energy and mass balances)	Work professionally and ethically as a member of a chemical engineering team.
O5		State and describe the diverse social, economic, and environmental issues associated with being a chemical engineer.
O6		Apply the law of conservation of mass and conservation of atomic species in order to solve mass balances in unit operations with and without chemical reactions and with and without recycle streams.

O7		Determine, using first principles and well-established correlations, the relations between thermodynamic equilibria and multiphase systems.
O8		Integrate the first law of thermodynamics with the concept of energy balances in unit operations with and without chemical reactions and with and without recycle streams.
O9		Apply the laws of conservation of mass and energy and thermodynamic equilibrium data in order to formulate solutions for mass and energy flow rates in multi-unit systems.
O10		Utilize the concepts of transient mass balance problems in order to develop a basis for non-steady state applications.
O11		Design multiunit chemical processes using steady-state and transient mass and energy balances in order to create multi-unit operations similar to those in future courses and applications in industry.
O12	CHE 211 (Thermo)	Understand the interconnection between work and heat.
O13		Use the First Law of thermodynamics and energy balances in the analysis of closed and open systems.
O14		Use the Second Law of thermodynamics and the application of the concept of entropy in the analysis of reversible and irreversible processes.
O15		Derive and apply thermodynamic relations and relationships between thermodynamic potentials.
O16		Analyze thermodynamic power and refrigeration cycles.
O17		Predict, understand and apply the properties and phase equilibrium behavior of ideal and non-ideal fluids.
O18		Understand the concepts of fugacity and chemical potential.
O19		Apply thermodynamic principles to chemical reactions and equilibrium.
O20		Practice clear, effective and concise written and oral communication of problem solutions.
O21		Use computational tools in the solution of thermodynamics problems
O22	CHE 300 (Junior Seminar)	Identify the wide range of career opportunities offered by the Bachelor in Chemical Engineering degree
O23		Demonstrate an understanding of the need for developing leadership skills, professional integrity and ethical decision making in the professional practice of chemical engineering
O24		Demonstrate an understanding of contemporary issues encountered in the professional practice of chemical engineering including

		business practices, environmental, health, and safety issues and other public interests
O25		Demonstrate an appreciation of the need for engaging in life-long learning and using appropriate learning strategies to maintain and enhance the professional practice of chemical engineering
O26	CHE 306 (Separations)	Design flash distillation by hand and computer calculations;
O27		Design distillation systems by hand and computer calculations;
O28		Do preliminary design of crystallizers;
O29		Design membrane separation systems by hand and computer calculations.
O30	CHE 320 (Statistics and Modeling)	Understand and use the concepts of probability for use with the normal and t-distributions, confidence intervals, and hypothesis testing.
O31		Understand and apply least squares fitting of data by use of linear algebra with computers.
O32		Understand and apply regression and model building from data with experimental error obtained with replicates to establish an adequate model.
O33		Design experiments for single and multiple factors and apply regression to model the results.
O34		Understand and apply propagation of error and sources of variation or variance components.
O35		Understand and apply statistical quality control and improvement with various charts such as average, range, and cusum (concepts of consumer and producer risk and capability index are included).
O36		Work professionally and ethically in teams.
O37	CHE 330 (Materials)	Develop a very basic fundamental understanding regarding structure-property relationships of materials that are commonly used in our daily life and industry. We will emphasize on organic and polymer materials slightly more.
O38	CHE 377 (Transport)	Perform macroscopic and differential mass, momentum, and mechanical energy balances.
O39		Apply momentum balances to fluid statics.
O40		Apply mass, momentum, and energy balances to laminar and turbulent flow of incompressible fluids in conduits and past submerged bodies.
O41		Understand and apply dimensional analysis and kinematic similarity to engineering design.
O42		Design of fluid transfer equipment (pipelines, agitated vessels, pumps, etc.) and analysis of its operation.

O43	CHE 378 (Heat and Mass Transfer)	Develop a sound fundamental understanding of heat and mass transfer through theoretical analyses and consideration of the physical phenomena.
O44		Integrate the concepts of momentum, heat and mass transfer to acquire an understanding of the interrelation of these physical phenomena.
O45		Apply these concepts to solve problems of practical importance in chemical engineering and allied fields. Continue the development of problem-solving and self-learning skills.
O46	CHE 400 (Senior Seminar)	Demonstrate an understanding of the need for developing leadership skills, professional integrity and ethical decision making in the professional practice of chemical engineering
O47		Demonstrate an understanding of contemporary issues encountered in the professional practice of chemical engineering including business practices, environmental, health, and safety issues and other public interests
O48		Identify the wide-reaching effects that engineering decisions have on society, our global community and our natural environment
O49		Demonstrate an appreciation of for engaging in life-long learning and using appropriate learning strategies to maintain and enhance the professional practice of chemical engineering
O50	CHE 420 (Design -- Process Safety Management and Analysis)	Understand and appreciate the need for professional integrity and ethical decision making in the professional practice of chemical engineering (4).
O51		Identify government agencies, regulatory bodies, codes, and standards that govern the global, societal, and environmental impact of plant design projects. (4)
O52		Identify & apply OSHA PSM & EPA RMP in the chemical process industries. (4)
O53		Identify the potential hazards and hazardous conditions associated with the processes and equipment involved in the chemical process industries, design shortcomings, and steps to eliminate or mitigate them, including learnings from significant industrial incidents. (2)
O54		Describe and apply the principles and approach of inherently safer design to reduce and eliminate hazards and thereby lower the risk of new or existing chemical systems. (2)
O55		Be able to utilize the techniques, analytical skills, and modern computational tools necessary for successful chemical engineering practice (1).
O56		Perform quantitative engineering analysis based upon the applications of mass and energy balances, fluid mechanics of liquid / gas / two-phase flow, heat transfer & the conservation of

		energy, mass transfer, reaction kinetics, process control, statistics and diffusion & dispersion under highly variable conditions. (1)
O57		Be able to design a system, component, or process to meet desired technical, economic, safety, and environmental criteria. (1)
O58		Demonstrate knowledge and understanding of risk assessment and management tools, programs and processes associated with process safety. (2)
O59		Demonstrate an understanding of contemporary issues encountered in the professional practice of chemical engineering including business practices, environmental, health, and safety issues and other public interests. Our graduate will be aware of the wide-reaching effects that engineering decisions have on society, our global community and our natural environment. (7)
O60		Work effectively in teams and develop / enhance problem solving skills. Prepare a professional project report.
O61	CHE 435 (Design -- Chemical Engineering Laboratory)	Determine the performance data required to complete the design for a process or process equipment.
O62		Design and conduct an experimental program to determine the required performance data.
O63		Use the requisite performance data to obtain a technically feasible design.
O64		Effectively report the results of their work in written form and communicate the results to their peers in an oral presentation.
O65		Function as a member of a technically diverse team.
O66		Understand different personality types, how these types respond, and how they can function effectively on teams.
O67		Develop an understanding of the professional responsibilities of the engineer as a member of a team.
O68		Understand and practice appropriate safety measures.
O69	CHE 456 (Controls)	Identify a process, understand the problems physics, develop a mathematical model as a surrogate for the process, and solve the problem analytically or numerically using computer packages.
O70		Design, model, and test a hierarchical control system on a complex process.
O71		Understand the role of process control in meeting stringent safety, economic, environmental, societal, and corporate goals.
O72		Understand the building blocks of process control and synthesize them to provide complete process control solutions.
O73		Work effectively in a team to execute process control computer laboratories in a professional and ethical manner

O74	CHE 463 (Application of Chemical Engineering Principles)	Apply principles of chemical engineering to design practical systems.
O75		Participate in team-based projects to understand team operation and decision-making.
O76		Gain experience in and appreciation of the need for individual learning about new systems, equipment, etc.
O77		Understand the role of the engineer in promoting safe operation and consideration of environmental issues in technical decisions.
O78		Develop an appreciation of current issues and challenges which you may well be addressing as professionals