The Need for Introducing System Engineering to Industrial Engineering Students

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***Abstract*—As technical, societal, and economic systems in this modern world become more complex, there is an increasing need to implement systems perspective in engineering. This article aims to provide the brief history of engineering of system, an overview of Systems Engineering, an overview of Industrial Engineering education and the basic consideration for introducing Systems Engineering in Industrial Engineering education in Indonesia. It concludes that Industrial Engineering students need to be introduced Systems Engineering approach and processes to be able to face real problems and real systems which are complex, soon after them graduating.**

Keywords—system;systems engineering; industrial engineering; complexity; education.

I. Introduction

As technical, societal, and economic systems in this modern world become more complex, dynamic, and interconnected, involving more stakeholders, and security and privacy issues, there is an increasing need for integrating views and evaluations, including their mutual interactions and their interaction with the environment.

Here, 'system' is defined as an interacting combination of systems elements which consists of product (hardware, software, and firmware), human resources, information, techniques, facilities, services, and other support elements to accomplish defined objectives that interact with its environment which may include other systems, users, and the natural environment [1].

There is a need for education in this area, and Systems Engineering is an approach, a process and a discipline,which addresses the complex challenges of integrated views of large and small systems in the engineering education [2]. The challenges concern the need to ensure that the system delivered provides a good balance across the range of technical and other characteristics needed to ensure that it provides an appropriate solution to the need which it addresses.

However, traditional education in engineering, including Industrial Engineering, meets that requirement within the specific disciplines, but usually lacks means to address interdisciplinary issues associated with the development and sustainment of systems. The interdisciplinary issues are important for anticipating growing system complexity and forwell-balanced integration of people, processes and technologies.

To bridge this gap in Industrial Engineering education, this paper provides a brief history of engineering of systems, an overview of Systems Engineering, an overview of Industrial Engineering education and the basic consideration for introducing Systems Engineering in Industrial Engineering education in Indonesia.

II. Brief History of Engineering of Systems

The foundations of modern engineering were laid over thousands of years by the rise of cities and the development of urban society in Mesopotamia and Egypt, which occurred sometime before 3000 BC. The growth of these cities stimulated engineering in other ways, especially structural engineering, architecture, transportation, hydraulic and sanitary engineering. Great palaces and great temples were built. Engineers solved the transportation problem by learning how to build roads, bridges and bigger ships which travel over greater distance. Moreover, the cities also produced problems which the evolution of hydraulic and sanitary engineering gradually solved [3]. Early middle eastern writing, for example the *Old Testament* of the *Bible*, has many references to building and agricultural works but always uses entirely matter of fact language, indicating that this knowledge significantly pre-dated that writing.

The Greek achievement in science during sixth to third centuries BC led to dramatic development in engineering. The greatest glory of Greek science was the discovery of abstract geometry (Thales, Euclid), mathematics (Archimedes) and physical science (Aristotle). Although there was little application of natural science to engineering during that time, Greek engineers began to use the new geometry in architectural engineering as soon as it developed. The Greeks sought to apply their scientific knowledge in the pursuit of architecture (e.g. the Parthenon) and war machines (e.g. the Heliopolis).

Although the Romans were the heirs-apparent to the Greek tradition their approach to engineering was markedly different [3, 4]. They were developers rather than originators in their own right [3]. Their greatest contributions were in water engineering and building. Vitruvius, an engineering architect of the Roman period, wrote the case studies of design failures, which are considered the first books on engineering [5]. The Romans produced such engineering marvels as the Roman baths, the first vaulted ceilings, and the Pantheon [4] building structures sufficiently robust as to remain standing and usable to the present.

After the fall of the Roman Empire, when most of Europe fell into the Dark Ages, also called the Middle Ages, the Byzantine Empire and the Islamic Golden Age were in their heyday. During this period, it was new forms of power engineering, which for the first time in human history started to free men from being the principal source of power [3]. This was led by Christian Roman slave owners who increasingly freed their slaves, prior to the fall of the Roman Empire, because of the new Christian attitude that viewed all men as being equal before God [3].

Western civilization remained under the influence of Roman ideals of engineering, where their aims were practical and focused on building [3]. Although there was almost no scientific activity in the West, many of Europe's great cathedrals were built by utilizing Roman knowledge of vaults, arches, and domes to create soaring stone structures during this period [4]. Sometimes there were serious failures but advances were made in knowledge of methods of building as a result of failures.

Meanwhile Eastern civilization was influenced by Greek ideals of science and technology [3]. It was Islam that inherited and maintained the Greek science and technology during the Middle Age. During this time Arabic numbers replaced Roman numerals and prominent Arab artist/engineers published texts on mechanical devices [4].

When the Latin west started to take over the Greek scientific knowledge which Muslims had transmitted and augmented during the 13^{th} century, the two traditions began to fuse, and that launched the Renaissance, a period of great innovation in art and engineering [3].

In the Renaissance period, the printing press enabled greater distribution of ideas, and advances in art enabled richer technical communication, including drawing sketches. The improvements in drawings made by Brunelleschi and Leonardo da Vinci led contemporary inventors to communicate their ideas to others and for ideas to be subsequently improved upon by others [4]. The development of technical drawing during the Renaissance period resulted in effective means to communicate technology concept to both builders of technology and to the buyers of technology [6].

During this period, engineering shifted from an experience based field to learned and studied field. In the three subsequent centuries, advances in design were complemented by striking advances in mechanics and analysis by the likes of Isaac Newton and Joseph-Louis Lagrange, which laid the foundation for the spectacular engineering accomplishments of the industrial revolution [4].

Up to this point in history, it is noteworthy that the great engineering accomplishments came from men trained not as technologists or engineers, but as artists, philosophers, and inventors [4].

As engineering entered the Industrial Revolution, with the invention of the steam engine in the eighteenth century, and later turbines, internal-combustion engines and electric generators, there was the paradigm shift during the 19th century. Engineers craved greater social standing and differentiation from technicians, mechanics, and skilled craftsmen [7]. While science and math training were already essential components of the engineering toolbox[8], engineers sought to align themselves more tightly with science to capitalize upon it's growing respectability within gentrified society [7]. While the shift in emphasis ensured engineers' professional status, this transition came at the neglect of engineers social, political, and non-verbal skill sets [7], [8]. Culturally, “hard thinking" has come to be seen as superior to soft skills because of its objectivity and transparency [4].

As a result, most academic engineering research focuses on furthering analytic tools and capabilities: the science of engineering [8]. Design, once taught through apprenticeships, has become only a small portion of today's engineering curricula, in part because much of design is not easily reduced to words, but is better represented by pictures and visual images: art, not science[8].

For centuries, engineering was both an art and science, and only in the past 200 years has science trumped the role of art and creativity [4].The increasing of systems complexity led the engineering's ability to manage the design process is strained, resulting in miscommunication, team dynamics issues, and new and unanticipated modes of systems failure, often brought about by a failure to consider the social aspects of a system [4]. This is in part because many of the intellectual components of technology are non-scientific and non-literary [8]. Only a small fraction of engineering decisions are based on analytic calculations, the rest requiring consideration of social, political, and environmental issues that are difficult to quantify [7].

Following the historical pattern that great engineering occurs at times when art, science, and design merge, the next generation of engineers must bridge the science-design gap in order to successfully address the difficult and complex problems facing today's engineers [7].

III. Overview of System Engineering

Systems Engineering is the link which has evolved between the art and science of engineering. It is the art and science of developing an appropriate system capable of meeting requirements within imposed constraints [9]. The particular problem in engineering the systems engineering was developed to address was the growing complexity of systems involving integration of elements across a broad range of disciplines [10-12].

The term "systems engineering' was first used by Bell Laboratories in the 1940s and probably the first formal attempt to teach systems engineering was made in 1950 at the Massachusetts Institute of Technology by Mr. G. W. Gilman, then Director of Systems Engineering at Bell Laboratories, Inc [13].

Systems Engineering is rapidly becoming recognized as a key discipline in a number of sectors including Aerospace & Defence, Automotive, Construction, Energy, Transportation, Consumer Electronics, IT, Pharmaceutical & Healthcare, Telecommunications and Manufacturing [14, 15]. It is now gaining international recognition as an effective interdisciplinary engineering approach for bringing human-made systems into being, and for improving existing systems [16]. Therefore, Systems Engineering is more than theory, it is also a process, the process of "bringing the system into being".

The practices of Systems Engineering are believed to have high value in the development of complex systems [17, 18]. It recognized as a key differentiator for the successful architecting, development and deployment of complex systems [14].

Distinguishing features of a complex system include many factors including [14]:

1. A set of components which when combined have additional qualities (emergent properties) over and above those present in any of the individual components themselves.
2. Existence of complex relationships between the components that determine how the system as a whole behaves.
3. Iteration of the design is required to align the customer and other stakeholder expectations of performance and capability.
4. Synthesis of an optimal solution is a trade-off between component performance, cost and risk. Also there might be more than one solution.
5. Modern systems are typically very complex and interact with other systems in a manner that components cannot be optimally designed without consideration of the whole.
6. Requirement to balance requirements against conflicting constraints through the full life of the system.
7. The systems architecture design involves a multidisciplinary approach within a framework that ensures cost, timeframe and delivered system performance can be controlled.

Systems Engineering is defined by The International Council on Systems Engineering (INCOSE), a not-for-profit membership organization founded to develop and disseminate the interdisciplinary principles and practices that enable the realization of successful systems, as an interdisciplinary approach and means to enable the realization of successful systems. This approach focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs during system life cycle [19].

The most important aspect in Systems Engineering is the functional and operational needs analysis of the system to be designed, and the mission, objectives or purpose the system is designed for, as emphasized in the system definition [2]. This involves a definition of the stakeholders and their involvement in the system design and operation [2]. Once the functional and operational needs are analyzed and the mission, objective or purpose of the system is understood and agreed upon, the requirements of the system performance over its mission or lifetime are defined [2]. In this process there may be conflicting requirements or conflicting needs. Any conflicts must be addressed by the stakeholders in negotiations or by some sort of tradeoff [2]. This part of Systems Engineering is closely related to other engineering disciplines, including Industrial Engineering and the design process, be it a product design or a production plant design [2]. Moreover, the process is subject to management and control, just as any other production process [2].

IV. Overview of Industrial Engineering Education in Indonesia

The field of Industrial Engineering grew out of the industrial age as the result of studies popularized by management pioneer Frederick Taylor and the Gilbreths, Lillian and Frank [20]. Taylor, the Father of Scientific Management, proposed work methods designed to increase worker productivity [20]. Frank Gilbreth was known as the Father of Time and Motion Studies while his wife Lillian was a psychologist [20]. The couple believed, like Taylor, that there was "one best way" to accomplish a task, and their work established time and motion studies as a tool of Industrial

Engineering [20]. Both Taylor and the Gilbreths focused their studies on the human side of the machine [20]. Although mechanical engineering was already an established field, but the new science of Industrial Engineering looked at the operators of the machine [20].

The increasing magnitude and complexity of modern industrial plants has demanded the development Industrial Engineering [20]. It was develop into the field that engaged in planning, organizing, improving, managing, and operating various processes for production manufactured products of all kinds and varieties.

Founded in 1948, Institute of Industrial Engineering (IIE) is an international, non-profit association that provides leadership for the application, education, training, research, and development of Industrial Engineering describes "Industrial Engineering is concerned with the design, improvement and installation of integrated systems of people, materials, information, equipment and energy. It draws upon specialized knowledge and skill in the mathematical, physical, and social sciences together with the principles and methods of engineering analysis and design, to specify, predict, and evaluate the results to be obtained from such systems" [21].

Several techniques and approaches developed during recent years became characteristic of Industrial Engineering. These include the analysis of a proposed product with regard to the possible steps and sequences of operations involved in its manufacture, a selection of the most efficient machines to perform these operations, the layout of the plant and shops to provide for the flow of the product from one machine to another, organization of the material supply, avoidance or elimination of bottlenecks, together with the related problems of quality and cost control, testing, inspection, and personnel relations [20].

Moreover, Industrial Engineering coordinates men, materials, machines, and methods so as to solve problems met in the conversion, transformation, and fabrication of raw materials into the products of industry [20]. The successfully Industrial Engineer who graduate from Industrial Engineering education must possess special interests and abilities in the analysis of the human, technical, and cost problems of modern manufacturing. In addition,he must possess the personality and attributes of character which will enable him to work with and direct others in the planning and operation of manufacturing enterprises [20].

The specific outcomes of Industrial Engineering education are [22]:

1. To design, develop, implement, and improve integrated systems that include people, material, information, equipment and energy.
2. To accomplish the integration of systems using appropriate analytical, computational, and experimental practice.

In Indonesia, Industrial Engineering Education grows quickly since introduced in Bandung Institute of Technology (ITB) in 1950s. Until 1996, there was about 150 institution offered Industrial Engineering [23]. It was caused by the increasing interest of students to choose to become industrial engineers and the increasing interest of education providers to provide alternative engineering education which considered as easier field compare with other engineering fields. However, mostly in those institutions, Industrial Engineering education was run by people with no background of Industrial Engineering [23]. Moreover, many of the education providers do not their academic activities based on Industrial Engineering field [23]. Therefore, in 1996 BKSTI, a collaborative body of Industrial Engineering providers in Indonesia was formed, and in 2007 Industrial Engineering Core Curriculum was agreed [23]. In 2012, this core curriculum was evaluated, and in 2013 a new Industrial Engineering Core Curriculum was introduced and recommended by BKSTI to be implemented in Industrial Engineering education providers. However, there is no Systems Engineering in this core curriculum.

V. The Consideration of Introducing System Engineering in Industrial Engineering Education in Indonesia

Industrial Engineering learning outcome above emphasize that object that design in this field is an integrated system which include people, material, information, equipment and energy. This integrated system is designed and engineered to achieve its desire performance which consists of efficiency, quality and productivity of designed system.

However, the increasing of complexity of systems nowadays, the increasing effect of social, political and environmental issues in achieving integrated system with its desire performance, demands industrial engineer not only able to use appropriate analytical, computational, and experimental practise, as define in second Industrial Engineering learning outcome above, but also the ability to use systems perspective which underlying Systems Engineering.

The increasing complexity in industrial engineering field which is needed systems perspective is affected by shifting perspective in industrial engineering, which include [22]:

1. The increasing attention on market value or customer requirement.
2. The increasing need to reconfigure the system to deal with change.
3. The attempting to increase efficiency and productivity through the production and supply chain network.
4. Utilization of information technology and knowledge to improve productivity and efficiency.
5. Consideration of resource savings and the impact on environment.

The stressing of using analytical ability, as mention in second learning outcome above, tends to separate problems into smaller part, and trying to solve the problem from parts, interferes with the ability to use a systems perspective. The systems perspective is important for engineers because they need to be able to make appropriate engineering decisions that will have desirable outcomes through the whole of the systems life cycle, from initial design, through development, production, use and finally disposal. Systems Engineering is important to be introduced to Industrial Engineering students, because graduates will face real problems and real systems which are complex, early in their career. The graduates will need to be able to perform industrial engineering work which anticipates the whole system life cycle in order to guide the most appropriate interactions with the system at the current time.

Moreover, a wide range of techniques and approaches which became characteristics of Industrial Engineering including physical and cognitive human factors, manufacturing processes, operations research, engineering management, etc., are learned in Industrial Engineering education separately.

Therefore, although in general, Industrial Engineering students understand that Industrial engineers create a new system or improve an existing system. And the word "system" here is meant to remind the Industrial engineers of three key points which Industrial engineering emphasize more than other engineering disciplines: (1) components (including machines and people) interact with each other to create the overall behaviour of the system; (2) the system being studied is always a subsystem of a larger system and these interactions must also be considered; and (3) systems include humans [24]. However, they often missed the interrelationship between those areas of Industrial engineering. The students also tend to overlook an overarching framework that cans helps students organize their thoughts and select fruitfully from among those techniques [24].

To bridge this, Systems Engineering provides the framework to enable the realization of successful system, by forming a structured development process that proceeds from concept to production to operation by utilizing a set of techniques that work for a system with multiple entities working together to provide a quality product or service that meets the user needs. Not only the entity of systems but, the interaction of those system's entities also needs to be focused on. The nature of techniques to be adopted can range from operations research, human factor through supply chain management to project management along system life cycle.

Furthermore, Industrial engineers are trained to design and analyse the components of which man-machine systems are composed [1]. They bring together individual elements that are designed via other engineering disciplines and properly synergize these subsystems together with the people components for a completely integrated man-machine system [1].

By adopting systems engineering principles, industrial engineer can play an important role as brokers of information and knowledge and technical directory order to provide a more realistic view of the efforts needed to accomplish the actual realization of physical industrial systems.

For example, by adopting systems engineering principles, when designing or improving a specific an integrated man-machine systems to achieve its desire performance, industrial engineers can take into account [25] :

- Preliminary conceptual design and functional architecting;
- Logical design or physical system architecting; and
- Detailed design or implementation architecting

A number of questions may be posed with respect to formulation, analysis, and interpretation that clearly indicate the role of values in every portion of a systems-engineering effort, including [25]:

- What is the problem? The needs? The constraints? The alterable?
- How do the client and the analyst bound the issue?
- What objectives are to be fulfilled?
- What alternative options are appropriate?
- How are the alternatives described?
- What alternative state of nature scenarios are relevant to the issue?

Analysis questions of importance are the following [25].

- How are pertinent state variables selected?
- How is the issue formulation disaggregated for analysis?
- What generic outcomes or impacts are relevant?
- How are outcomes and impacts described across various societal sectors?
- How are uncertainties described?
- How are ambiguities and other information imperfections described?
- How are questions of planning period and planning horizon dealt with?

By leveraging Systems Engineering knowledge, it helps industrial engineers in providing production planning and analysis, systems integration, lifecycle planning and estimating, change analysis and management, continuous process improvement, quality assurance, business case analysis/return on investment, engineering management and systems integration [1]. It also complements industrial engineers' knowledge in supply chain management, budgeting and economic analysis, production line preparation, production, production control, testing, staffing, organizing, directing, cost, schedule, and performance monitoring, risk monitoring and control, operations planning and preparation and operations management [1]. Those knowledge areas cover the overarching aspects of Industrial Engineering and describe the synergies between Industrial Engineering and Systems Engineering [1].

As time goes by, Industrial Engineering observed that its alumni and its approaches can be applied into non-manufacturing based industries, such as the service industries which includes banking, hospitals, transportations and consulting [22, 26]. These systems need industrial engineers to optimize their performance, efficiency and productivity as objects of integral systems. The systems life introduce as the overarching approach that can encompass many different variations of Industrial Engineering at this time[26].

This is why many Industrial Engineering Programs are evolving their names into Industrial and Systems Engineering programs, especially in US universities [26]. Currently there are 20 universities in the US that offer degrees combining Industrial and Systems Engineering out of the 90 Universities which offer Industrial Engineering programs.

While Systems Engineering education has grown since the 1960s, any many universities now offer SE at bachelor, masters and PhD levels around the world. In the US in the past decade, the number of institutions and programs offering SE has nearly tripled in the last decade [27].

In 2010, Fabrycky identified 80 institutions offering a total of 165 SE education focused programs [27]. Fabrycky identified 56 Systems Centric SE (SCSE) programs, where SE is the intended major area of study and 109 Domain Centric SE (DCSE) programs, where the programs integrated mostly with Industrial Engineering.

Moreover, the majority of the department which offer Industrial and Systems Engineering degree is called Department of Industrial and Systems Engineering. The university list and degree offered can be found in Table 1 below.

No	University Name	Degree
1	Auburn University, Industrial and Systems Engineering Program	Bachelor of Science (BS) in Industrial and Systems Engineering
2	Binghamton University, Systems Science and Industrial Engineering Department	Bachelor of Science in Industrial and Systems Engineering (BSISE)
3	North Carolina State University, Edward P. Fitts Department of Industrial and Systems Engineering	Bachelor of Science in Industrial and Systems Engineering
4	Northern Illinois University, Department of Industrial and Systems Engineering	Bachelor of Science in Industrial and Systems Engineering
5	Oakland University, Department of Industrial and Systems Engineering	Bachelor of Science in Industrial and Systems Engineering
6	Ohio State University, Integrated Systems Engineering Department	Bachelor of Science in Industrial and Systems Engineering
7	Ohio University, Department of Industrial and Systems Engineering	Bachelor of Science in Industrial and Systems Engineering
8	Philadelphia University, Industrial and Systems Engineering Minor Track	Bachelor of Science in Engineering (BSE)
9	Rutgers University, Department of Industrial and Systems Engineering	Bachelor of Science in Industrial and Systems Engineering
10	San Jose State University, Department of Industrial and Systems Engineering	Bachelor of Science in Industrial and Systems Engineering
11	University of Alabama - Huntsville, Industrial and Systems Engineering and Engineering Management Department	Bachelor of Science in Industrial and Systems Engineering
12	University of Arizona, Department of Systems and Industrial Engineering and Engineering Management	Bachelor of Science in Systems Engineering; Industrial Engineering; Engineering Management
13	University of Florida, Department of Industrial and Systems Engineering	Bachelor of Science in Industrial and Systems Engineering
14	University of Michigan - Dearborn, Department of Industrial and Manufacturing Systems Engineering	Bachelor of Science in Engineering (BSE) in Industrial and Systems Engineering
15	University of Oklahoma, School of Industrial and Systems Engineering	Bachelor of Science (BS) in Industrial and Systems Engineering
16	University of Rhode Island, Department of Mechanical, Industrial and Systems Engineering	Bachelor of Science (BS) in Industrial and Systems Engineering
17	University of San Diego, Industrial and Systems Engineering Program	Bachelor of Science/Bachelor of Arts in Industrial and Systems Engineering
18	Virginia Tech, Department of Industrial and Systems Engineering	Bachelor of Science in Industrial and Systems Engineering (BSISE)
19	Wright State University, Department of Biomedical, Industrial and Human Factors Engineering	Bachelor of Science in Industrial and Systems Engineering
20	Youngstown State University, Department of Industrial and Systems Engineering	Bachelor of Engineering (BE) in Industrial and Systems Engineering

TABLE I. US UNIVERSITIES WHICH OFFER COMBINATION OF INDUSTRIAL AND SYSTEMS ENGINEERING

VI. CONCLUSION

As the complexity of technical, societal, and economic systems increases there is a need for integrated views and evaluations in Industrial Engineering, not only of the systems themselves but also of their mutual interactions and their interaction with the environment in which they are placed into service. This integrated view of the system and the system in its context is what is distinctively offered by systems engineering.

Moreover, the stressing of using analytical ability in Industrial Engineering education which tends to separate problems into smaller part, and trying to solve the problem from parts and wide range of techniques and approaches which became characteristics of Industrial Engineering including physical and cognitive human factors, manufacturing processes, operations research, engineering management, etc., which are learned by students in Industrial Engineering education separately, interferes with the ability to use a systems perspective.

Systems Engineering provide the framework to enable the realization of successful system, by forming a structured development process that proceeds from concept to production to operation by utilizing a set of techniques, including Industrial engineering techniques that work for a system with multiple entities working together to provide a quality product or service that meets the user needs during system life cycle.

There is a need to educate Industrial Engineering students in this area, and Systems Engineering is an approach, a process and a discipline, which addresses the complex challenges of integrated views of large and small systems in Industrial Engineering and will advance the graduates' competencies beyond those of industrial engineering to those that incorporate the additional skills to address the issues presented by the whole life cycle of the system in its context.

Therefore, Industrial Engineering students need to be introduced to the Systems Engineering approach and processes to be able to face real problems and real systems which are complex, not only in manufacturing based industries, but also in the service industries, soon after graduation.

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