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Industrial Engineering Management – THE key skill for the Digital Age

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ABSTRACT

In this article, concepts and the state-of-the-art of engineering management education and practice with a focus on modern manufacturing are reviewed and discussed. Production is becoming digital, and there is an increasing demand for engineering management, at the interface between the business world and the engineering world, where multi- and interdisciplinary experts in management and technical fields are needed to solve the challenges ahead. A solid university education in engineering and management tools and methods, balanced and integrated, coupled with industrial exposure and experience, will yield well-trained "engineering managers" fit for the changing workplace determined by Industry 4.0. Standardized training can bring out variance needed to excel consistently both from a personal and an organizational perspective in a competitive market place with technical solutions.

KEYWORDS:*Industry 4.0, engineering management, technology, manufacturing, digitization, technical leadership*

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I. INTRODUCTION

"Industrial Engineering" [1], [2], [3], [4], [5], [6] can be described as "engineering that deals with the design, improvement, and installation of integrated systems (as of people, materials, and energy) in industry"[7] or the "discipline of utilizing and coordinating humans, machines, and materials to attain a desired outputrate with the optimumutilization of energy, knowledge, money, and time. It employs certain techniques (such as floor layouts, personnelorganization, time standards, wage rates, incentive payment plans) to control the quantity and quality of goods and services produced"[8], or simply "the use of machines to manufactureproducts, and the study of this"[9], [10].

Engineering is applied science & technology, whereas management can be more seen as an art, though tools exist and scientific approaches have been taken, first known as Taylorism after Frederick Winslow Taylor [11]. Taylor, with his four principles of scientific management, can be seen as the godfather of industrial engineering.

Since the business world and in particular manufacturing is becoming more and more complex, an interdisciplinary approach is needed to optimize processes and manage industrial operations. The reason for the increasing complexity, both with regard to products and processes, is the growth in knowledge, the further evolution of research and development, customer demand, marketing-driven desire-creation and market place aspects such as mature markets with saturation tendencies. From the logistics industry, which has become more and more professional over the last decades [12], the main reasoning behind industrial engineering activities can be inferred: Engineers use their knowledge and tools to optimize the business world, i.e. they enhance manufacturing operations systematically to identify synergies, savings potentials and new opportunities. It was industrial engineering that determined the outcome of World War II [13]. Lean management [14], [15], a game changing concept for global manufacturing, is believed to have been developed out of the industrial engineering approach in Eastern culture [16], [17].

Industrial Engineering has become so much ubiquitous that it is hardly noticed any more. In today's manufacturing, the intelligence resides with the processes, which have been devised by industrial engineers; industrial engineering concepts make both unskilled and knowledge-based workers productive.

An industrial engineer can work in an organization as expert, but likewise as manager. It has become very rare that critical and/or complex tasks are achieved by an individual. Work is hence mostly a team job, and a manager needs to orchestrate either a diverse team, where one or a few engineers are present among other team members of different backgrounds, or the team consists of engineers only. The workplace in a project is often virtual ("virtual teams" [18] can be scattered around the globe), ill-defined or fast-changing. In order to

manage effectively in dynamic, unstructured environments, managers need to understand the interaction of technical, organizational and behavioral aspects to succeed with a team of engineers [19].
In this paper, the most relevant recent literature in the context of industrial engineering management has been compiled and discussed. The relevance of industrial engineering management is elaborated.

II. MANAGEMENT AND THE CHANGING WORKPLACE

There is a plethora on printed and online academic and popular literature on management and leadership. Guidebooks for university graduates, professionals, managers, entrepreneurs, etc., are consistently on bestseller lists.

Management and leadership theories and schools, with specialization of multinational corporations, SME, NPO and other types of organizations are close-to-impossible to enumerate, yet a handful of management techniques has proven universally useful in running "traditional" organizations, see e.g. Peter F. Drucker [20], with tools such as setting targets, or Robert S. Kaplan und David P. Norton [21] with their Balanced Scorecard (BSC). Also, standards such as ISO 9001:2015 are widely used for (quality) management in manufacturing and beyond. Yet the world is changing, and the so-called "knowledge worker" is asking for a different management style than the "old school" unskilled worker as described by John M. Ivancevich and Thomas N. Duening in their classic "Managing Einsteins" [22].

One of the most radical changes in the workplace, which has just begun and will drastically transform the types of jobs in most settings in the coming years and decades, is driven by automation: Dangerous, laborious and repetitive jobs are being transferred to machines, and people can do more intellectual jobs [23], [24], [25], [26], [27]. Managers and teachers are among the groups with lowest risk to become replaced by robots in the near future.

Management skills are taught at universities, and practitioners use self-study from books, e.g. by famous retired executives, well-known popular authors or academics. However, since management and particularly leadership is an art, developing one's style needs practice and time. More often than none, good (or formidable!) engineers are the ones who receive a promotion to become managers. Trainings can ensure a smooth transition into the new role.

Managing both short and long and setting strategic direction are key to successful management at any level and type of organization. Being in the driver's seat of change is a far more comfortable situation than only having to react passively. For a review on pioneering advantage in manufacturing firms, see [28] and [29], and [30] for service firms.

III. INDUSTRIAL ENGINEERING TRAINING

The main purpose of tertiary education is to prepare young adults for the workplace to enable them to take upon responsible roles, which will provide them with satisfying carriers to the benefit of their employing organizations and society at large.
Traditionally, technology and managerial skills were very rarely found in the same curriculum. The needs for industrial engineering training were summarized by [31] as follows:

- Adequate skills in managing technology
- Adequate skills in managing human and financial resources
- Adequate skills in different type of technologies.

The details depend on the economies of the respective countries where the trainings are offered. For Algeria, for instance, the following key areas of knowledge were identified [31]:

- Technology: electrical, mechanical and process engineering, automatic control and computer sciences.
- Management: operation and project management, quality and maintenance management, supply chain management and system engineering.

The industrial engineering curricula of different universities have core traits, with local specialties and sometimes specializations.
Fig. 1 and 2 below show a generic concept for industrial engineering training.

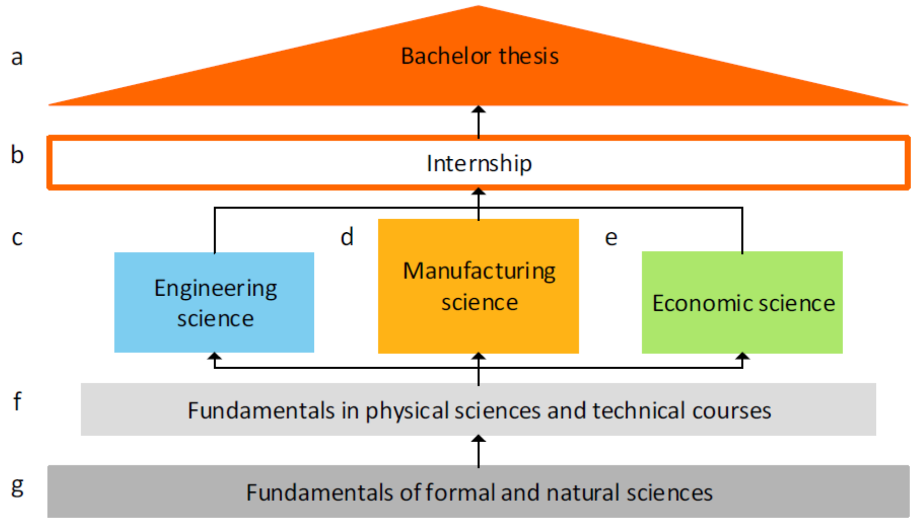

Fig. 1: House of industrial engineering; (a) bachelor thesis; (b) internship; (c) engineering, (d) manufacturing, (e) economic sciences, (f) fundamentals in physical sciences and (g) in formal sciences. Reproduced with permission from [32]

.

A typical bachelor degree programme will last 6 semesters, i.e. 3 years, with 180 ECTS. European Credit Transfer and Accumulation System (ECTS) credits are a standard means for comparing the "volume of learning based on the defined learning outcomes and their associated workload" for higher education in the European Union [33]. A typical master degree programme will last 2 academic years, i.e. have 120 ECTS, with a deepening of bachelor level knowledge.

In industrial engineering programmes, students first study fundaments and then move on to specific courses in engineering, manufacturing and economic science. Typically, in the 5th semester, they carry out an internship, and in the 6th semester finish with their Bachelor thesis, which is their first scientific piece of work.

Fig. 2 shows and improved version for a modern industrial engineering curriculum proposed by [32].

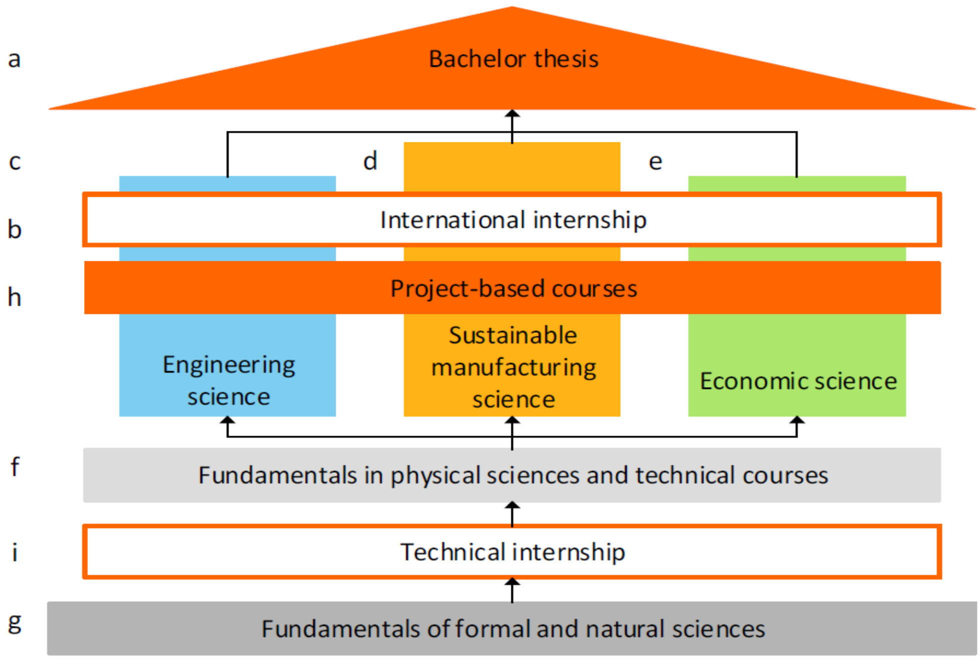

Fig. 2: The reformed new industrial engineering program in form of the house of industrial engineering; (a) bachelor thesis; (b) international internship; (c) engineering, (d) sustainable manufacturing, (e) economic sciences, (f) fundamentals in physical sciences, (g) in formal sciences, (h) project-based courses and (i) technical internship. Reproduced with permission from [32].

In that improved curriculum, the technical internship occurs much earlier, and it is complemented by an international internship towards the end of studies. Most universities have an international office, which supports both incoming and outgoing students, and international experience is a valuable asset for graduates. Engineering, manufacturing and economic science are thought in project-based courses, with modern contents such as sustainability.

The curriculum should be accredited, continuously improved and maintained current to the needs of industry.

There exists today a large offer for university training in industrial engineering, and there is ample literature available on the subject as well. This review article summarizes the current state-of-the-art in industrial engineering management.

An example of engineering management [1] education in emerging regions (Kosovo and Slovakia) is given in [34] and [35], respectively, or in [36] for Peru.

Cooperative education, which combines classroom instructions with work experience in corporations, is discussed in [37] as a best-practice approach for industrial engineering students. The impact was found to be favorable, and comparable on male and female students [37].

A key requirement for university training is transversal knowledge in engineering problems [38], compare also Fig. 2.

The selection of working area for industrial engineering graduates is discussed in [39].

At the Institute of Industrial Engineering, University of Applied Sciences Technikum Wien, Austria, the "Digital Factory" was created to allow state-of-the art training in industrial engineering and related fields, as a teaching factory [40], [41] but also for research, see Fig. 3.

Fig. 3: "Digital Factory" at University of Applied Sciences Technikum Wien, Austria. Picture provided by Erich Markl.

In the Digital Factory, Industry 4.0 [42] solutions are being developed in close collaboration with corporate partners from diverse industries. Industry 4.0 can be seen as the "4th industrial revolution", in which vertical and horizontal manufacturing processes' integration and product connectivity enable (manufacturing) companies to achieve higher performance [43]. Change is more rapid and more disruptive than in the preceding 3 revolutions, starting with the introduction of the steam engine in the 18th century, heralding the first industrial revolution. The 2nd industrial revolution brought electricity and the assembly line; The 3rd industrial revolution started with automation and robot introduction into manufacturing lines. Today, in the 4th industrial revolution, we are seeing the internet of things (IoT), cyber physical systems (CPS), big data [44], artificial intelligence/machine learning, "smart manufacturing" [45] and digital twins [46], literally boosting firms' productivity, consumers' convenience and product individualization. Although called "Industry 4.0", the 4th industrial revolution is not about industry alone, it is transforming our entire lives. For instance, there are is an estimated number of networked devices in use worldwide of 20.8 - 26 billion by 2020 [47], [48], [49]. Cisco expects this number to increase to around 50 billion IoT connections by 2020 [50], and Huawei projects that IoT devices will reach 100 billion units in use by 2025 [51], where cybersecurity issues are becoming increasingly important [52].

The evolution of the industrial revolution is shown schematically in Fig. 4.

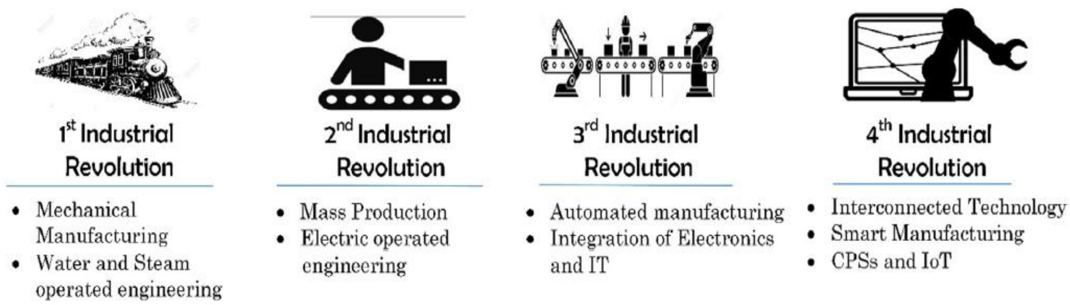

Fig. 4: Evolution of industrial revolution. Reproduced with permission from [53]. IT = information technology; CPS = cyber-physical systems; IoT = internet of things.

The time frame for the 4 industrial revolutions is approx. late 18th - early 19th century, late 19th - mid 20th century, second half of 20th century and early 21st century, respectively. When the 4 stages should be described by a keyword, that could be quality of workers' lives, mobility, microcontrollers and ICT.

Vertical integration refers to the integration of ICT systems (information & communication technology) in different hierarchical levels of an organization, i.e. from the shop floor up to the CEO.

Horizontal integration stands for the collaboration between different entities, e.g. production sites and/or suppliers, with an exchange of resources and data in real time.

Different countries and regions have varying degrees of development, see Fig. 5.

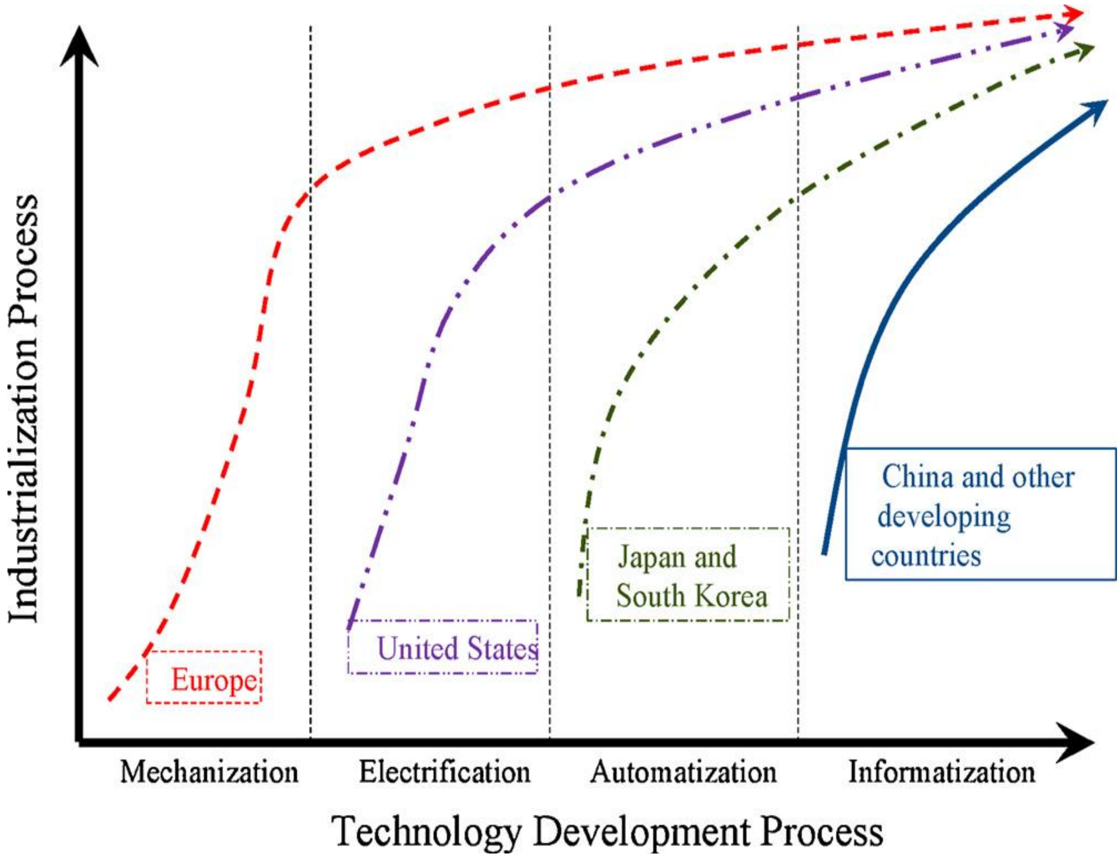

Fig. 5: Industrialization process with technology development processes. Reproduced with permission from [54].

Developing economies are making fast progress, for instance China and other BRICS-countries [55], with lower specific cumulated emissions than "traditional" industrialized countries like Europe and the US [56], [57].

The technology development process depicted in Fig. 5 above shows the 4 steps also highlighted in Fig. 4: Mechanization, electrification, automation and informatization.

Technologies of Industry 4.0 are summarized in Table 1.

Technologies of the Industry 4.0

Technologies	Definition
Computer-Aided Design and Manufacturing [CAD/CAM]	Development of projects and work plans for product and manufacturing based on computerized systems (Scheer, 1994).
Integrated engineering systems [ENG_SYS]	Integration of IT support systems for information exchange in product development and manufacturing (Kagermann et al., 2013; Bruun et al., 2015; Abramovici, 2007).
Digital automation with sensors [SENSORING]	Automation systems with embedded sensor technology for monitoring through data gathering (Saldivar et al., 2015).
Flexible manufacturing lines [FLEXIBLE]	Digital automation with sensor technology in manufacturing processes (e.g. radio frequency identification – RFID – in product components and raw material), to promote Reconfigurable Manufacturing Systems (RMS) and to enable the integration and rearrangement of the product with the industrial environment in a cost-efficient way (Brettel et al., 2014; Abele et al., 2007).
Manufacturing Execution Systems (MES) and Supervisory control and data acquisition (SCADA) [MES/SCADA]	Monitoring of shop floor with real time data collection using SCADA and remote control of production, transforming long-term scheduling in short term orders considering restrictions, with MES (Jeschke et al., 2017).
Simulations/analysis of virtual models [VIRTUAL]	Finite Elements, Computational Fluid Dynamics, etc. for engineering projects and commissioning model-based design of systems, where synthesized models simulates properties of the implemented model (Saldivar et al., 2015; Babiceanu and Seker, 2016).
Big data collection and analysis [BIG_DATA]	Correlation of great quantities of data for applications in predictive analytics, data mining, statistical analysis and others (Gilchrist, 2016).
Digital Product-Service Systems [DIGITAL_SERV]	Incorporation of digital services in products based on IoT platforms, embedded sensors, processors, and software enabling new capabilities (Porter and Heppelmann, 2014).
Additive manufacturing, fast prototyping or 3D impression [ADDITIVE]	Versatile manufacturing machines for flexible manufacturing systems (FMS), transforming digital 3D models into physical products (Weller et al., 2015; Garrett, 2014).
Cloud services for products [CLOUD]	Application of cloud computing in products, extending their capabilities and related services (Porter and Heppelmann, 2014).

Table 1: Technologies of Industry 4.0 Reproduced with permission from [43].

Expected benefits from Industry 4.0, which can be product-related and operational, according to [43], are:

- Improvement of product customization
- Improvement of product quality
- Reduction of operational costs
- Increase productivity
- Reduction of product launch time
- Improving of sustainability (externalities)
- Increase of processes visualization and control
- Reduce of labor claims (worker satisfaction)

What is the industrial engineering approach? University training will provide students with principles, methods and tools, to make them fit for the workplace. Companies want to employ graduates that can basically do a real job from day one, which is why a close link between academia and industry, e.g. through internships and bachelor/master projects, is vital.

Narayana Rao [58], [59] has formulated six basic principles of industrial engineering:
"1. Develop science for each element of a man - machine system's work related to efficiency and productivity.
2. Engineer methods, processes and operations to use the laws related to the work of machines, man, materials and other resources.
3. Select or assign workmen based on predefined aptitudes for various types of man - machine work.
4. Train workmen, supervisors, and engineers in the new methods.
5. Incorporate suggestions of operators, supervisors and engineers in the methods redesign on a continuous basis.
6. Plan and manage productivity at system level".

These principles can be traced back to Taylor's principles of scientific management [11], Harrington Emerson's principles of efficiency [60], Gilbreth's principles of motion economy [61] and Miles' Principles of Value Engineering [62].
Rao has further compiled methods and techniques of industrial engineering [59], a few selected of which are reproduced here:

- Motion study[63]
- Work place design[64]
- Application of ergonomics[65] and biomechanics [66]
- Standardization of methods [45], [67], [68], [69]
- Operator training [70]
- Incentive systems [71], [72], [73]
- Job evaluation [74], [75]

Narayana Rao has further summarized efficiency improvement techniques of Industrial engineering, some of which are listed below [59]:

- Process Analysis [76]
- Operation Analysis [77]
- Value engineering[78], [79]
- Statistical Process Control [80]
- Statistical inventory control [81]
- Six sigma [82]
- Operations research[83]
- Standardization [45], [67], [68], [69]
- Waste reduction or elimination[84]
- Activity based management [85]
- Continuous improvement (e.g. Kaizen [86], [87], Quality circles and suggestion schemes)
- 5S[88]
- Lean systems (e.g. lean six sigma) [89], [90]

More novel tools include virtual reality [91]. Efficiency improvements in industry brought about by industrial engineering are countless, e.g. in healthcare [92], aerospace [93] or with regard to energy efficiency in the shipping industry [94], to name but 3 examples.

IV. INDUSTRIAL ENGINEERING

"Engineering" is "the work of an engineer, for example, designing or buildingmachines, electricalequipment, roads, etc. using scientificprinciples"[95]. There are numerousspecializations, an excerpt of which is given here in Table 2:

chemical engineering	the design and operation of machinery used in industrial chemical processes
civil engineering	the planning and building of things not used for religious or military purposes, such as roads, bridges, and public buildings
electrical engineering	the business or study of designing and building electrical systems, especially those which power and control machines, or are involved in communication
genetic engineering	(the science of) changing the structure of the genes of a living thing in order to make it healthier, stronger, or more useful to humans
mechanical engineering	the study of the design and production of machines
software engineering	the activity of creating computer programs
financial engineering	the work of using mathematical methods to solve problems in finance:
social engineering	the artificial controlling or changing of the groups within society

Table 2: Some disciplines of engineering. Quoted from [95].

All these disciplines are rather specialized. "Industrial Engineering" [1], [2], [3], [4], [5], [6] has been defined as "the integration of machines, staff, production materials, money, and scientific methods"[39]. Thereby, it is a broader, more applied discipline, see Fig. 5 and Fig. 6 which show generic concepts.

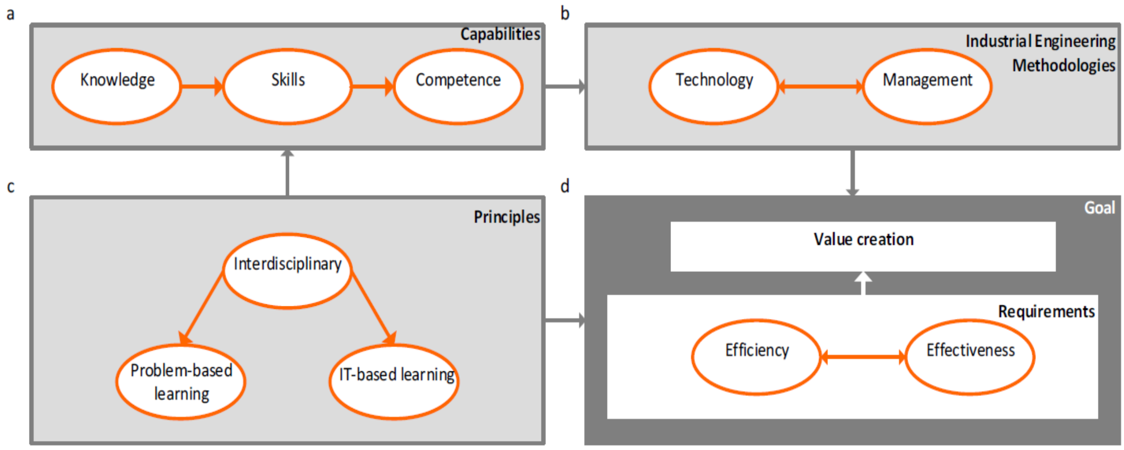

Fig. 5: Industrial engineering (a) capabilities; (b) methodologies; (c) principles; and (d) goal and requirements. Reproduced with permission from [32].

In Fig. 6, practice and education are highlighted:

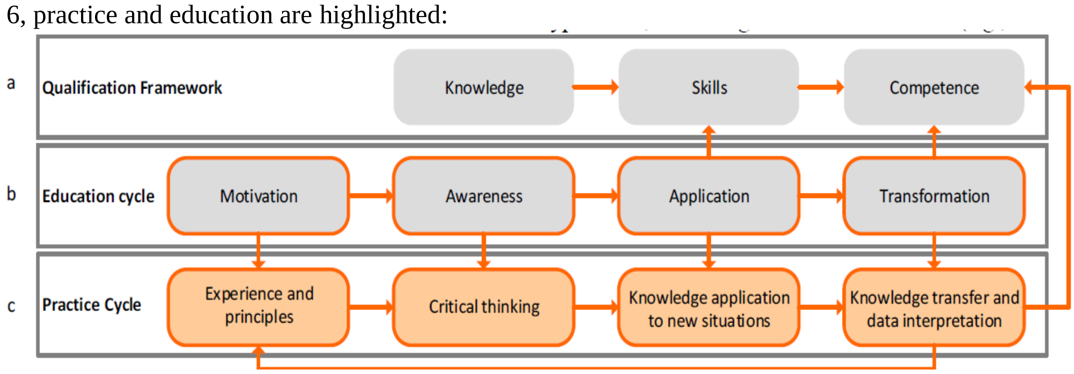

Fig. 6: Capabilities for industrial engineering; (a) Qualifications framework; (b) education; and (c) practice cycles. Reproduced with permission from [32].

Industrial practice coupled with formal training will forge the best-suited industrial engineers for tackling real-world problems.

The history of industrial engineering [96] can be traced back to the 1st industrial revolution. Some of the pioneers worth mentioning are:

• Frederick Taylor, with scientific management and time-and-motion study [11];
• Harrington Emerson, author of "Twelve Principles of Efficiency" [60]
• Henry Laurence Gantt, developer of the Gantt Chart for organizational management;
• Henry Ford, car manufacturer who implemented the assembly line
• Eliyahu M. Goldratt, developer of the Theory of Constraints (TOC) [97]

In the 1940s, the concept of Total Quality Management (TQM) became a core part of industrial engineering [98].

V. ENGINEERING MANAGEMENT

"Engineering management" [1], [99], [100], [101], [102] applies engineering principles for the effective planning and efficient operations of managing manufacturing or other industrial operations. The worlds of engineering and of management are sometimes seen as diametrical. Traditionally, the realms of engineering and management were seen as different and unrelated areas [34].

[16] contrasts professional engineering technology to industrial engineering, with a bucket and its 2 ears as a metaphor, where the authors state that "If want to bring up full of water, you must make the best of the two ears of professional technology and industrial engineering technology."[16]

A production system can be expressed as a board truck, see Fig. 7.

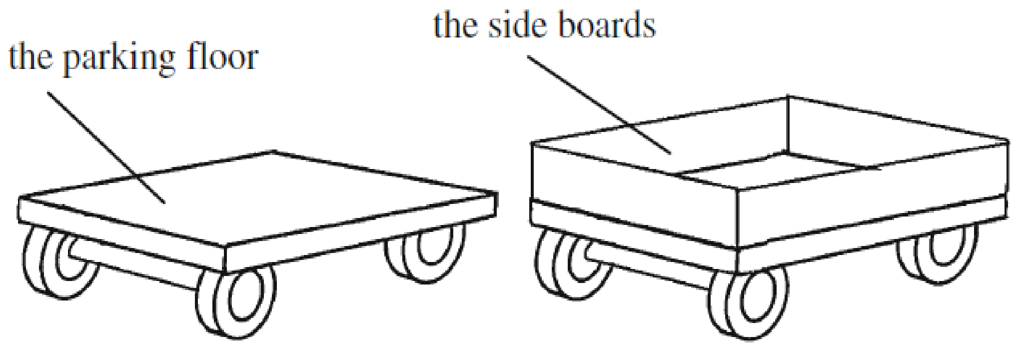

Figure 7: Relationship between industrial engineering (right) and professional engineering technology (left). See text for details. Reproduced with permission from [16].

Professional engineering technology has produced the solution on the left in Fig. 1: The truck or platform can carry goods, it is fit for purpose. However, the solution on the right, with side boards provided by industrial engineering technology, is more practical, and it can give a better (economic) value, i.e. more goods can be transported in the same time than with the pure engineering technology solution.

Industrial engineering can be said to be concerned with the optimization of engineered systems [103], [104]. According to [16], industrial engineering can also be termed "efficiency engineering".

In business, leaders need to communicate across all levels and with different personalities. Likewise, an engineer can only successfully get his/her ideas implemented when he/she speaks the language of "business people". At the interface between engineering and management, the interdisciplinary field of "engineering management" is located. It can be defined as the application of management practice to the area of engineering. Engineering management can be studied at universities and universities of applied sciences. Graduates, and practitioners, can combine the problem-solving expertise of pure engineers with the skills of a manager for organization, planning and running a business and its stakeholders. Engineering management becomes more and more important as our enterprises and organizations turn towards complex, knowledge-based entities, where the age-old debate of whether a leader needs to have technical understanding becomes a no-brainer. An engineer without business acumen is as dangerous and as difficult to integrate in a modern organization as a trained business person without technical understanding. In the digital age, where speed and innovation have become more important that fixed assets, professionals, whether working as experts or as managers, need both technical and economic knowledge and skills in order to succeed, personally and with their organizations. According to [105], engineering management should be based on an ecological concept. For more details on engineering management, see e.g. [99], [100].

VI. INDUSTRIAL ENGINEERING MANAGEMENT

What sets industrial operations apart from services and small-scale trade and crafting organizations is a large lever: Significant investments, a high number of employees, high turnovers and profits, and a large impact on society, be it the local community or the state/government. Stakes are high, and maintaining success is of paramount importance. Industrial engineering management has exactly this task to solve.

Managing in a technical setting can be termed "industrial management" [106]. As early as 1962, the importance of technical education in industrial management has been highlighted [107]. The literature discusses numerous aspects of industrial management, e.g. [108], [109], [110], [111], [112], [113]. For "technical leadership", managers need to be well-trained not only in managerial competence, but also in engineering details in general and in their specific industries.

As the pertinent business literature holds, leadership occurs at all levels of organizations, and with matrix setups, it becomes important to be able to influence 360° in one's organization to get one's job done. Literacy of technology in order to be able to communicate well with expert engineers from different disciplines and to take the right decisions for innovation and long-term organizational success.

Industrial Engineering Management can be considered the most important skill today's digital age. Industrial

Engineering education is the basis, and the shortage of skilled labor in STEM (science, technology, engineering & mathematics) [114], [115], [116] needs to be alleviated, e.g. though early engagement of pupils to arouse their excitement for technical disciplines [117].

VII. CONCLUSION

The half-life of knowledge has become very short, on the order of years, and it is not so much facts but rather methods and tools which are key to being successful in modern professional life.

The majority of jobs has shifted to the services sector, however, there will always be a need for physical goods, and manufacturing is the basis for these. The main trend in manufacturing is digitization [118], [119], [120], [121], [122], coupled with product individualization and the need for short time and low cost production, which happens increasingly in flexible industrial settings.

GE executive Jack Welch [123], [124] is known for his stringent six sigma approach [82]. He said that "In manufacturing, we try to stamp out variance. With people, variance is everything." Conferred to industrial engineering management, university training should be standardized, providing graduates with the necessary tools and knowledge both in managerial and engineering areas. It is then in their business environments where they can make a difference, by applying scientific methods and following a results-oriented approach for real life problem solving.

VIII. OUTLOOK

With digitization spreading, the 4th Industrial Revolution, for which the term "Industry 4.0" has been coined, is happening at the moment and truly transforming manufacturing.

Engineers as interface managers between the two worlds of technical experts and business people are faced with increasing challenges, and there is a necessity for a paradigm shift in industrial engineering training and education. The "megatrends" [125], [126] will contribute to a changing environment for industrial engineering.

What are the major trends in industrial engineering management? In [127], branding has been identified as a trend with high relevance for engineering management, since building, maintaining and managing a brand is one of the most important, but also one of the most complex and most subtle tasks in the modern business environment.

The closing of ranks between theory and practice will become more important, too. This is why collaborative education [37], [128], [129], [130] will gain importance.

Open source [131], [132] and open innovation [133], [134] are likewise expected to become more prominent in industrial engineering, as well as individualization, subsumed by the credo for "lot size one" [135], [136]. Other trends with high relevance are life-long learning [137], automation/system integration/miniaturization, (see mechatronics development) [138] and further agility and acceleration [139], [140] e.g. resulting in shorter product life cycles, in general. Another important trend fully underway is modelling and simulation [141].

Probably the most fundamental trend in industrial engineering is multi- and interdisciplinary work and development, as can be seen e.g. in [142] and [38].

Flexibility [143] is at the center of industry 4.0 [43] concepts. Manufacturing will become intelligent/smart [45], [144], [145]. Cloud manufacturing [146], [147] could become a reality.

Hopefully, sustainability [32],[148], [149], [150] is another trends of the future, as well as "zero waste" manufacturing [84]. Another important trend is the use of novel materials and manufacturing processes, see e.g. [151] and [152], as well as electromobility[153], [154].

Additive manufacturing [155] is receiving considerable attention, however, its production costs often offset flexibility, compare Fig. 8.

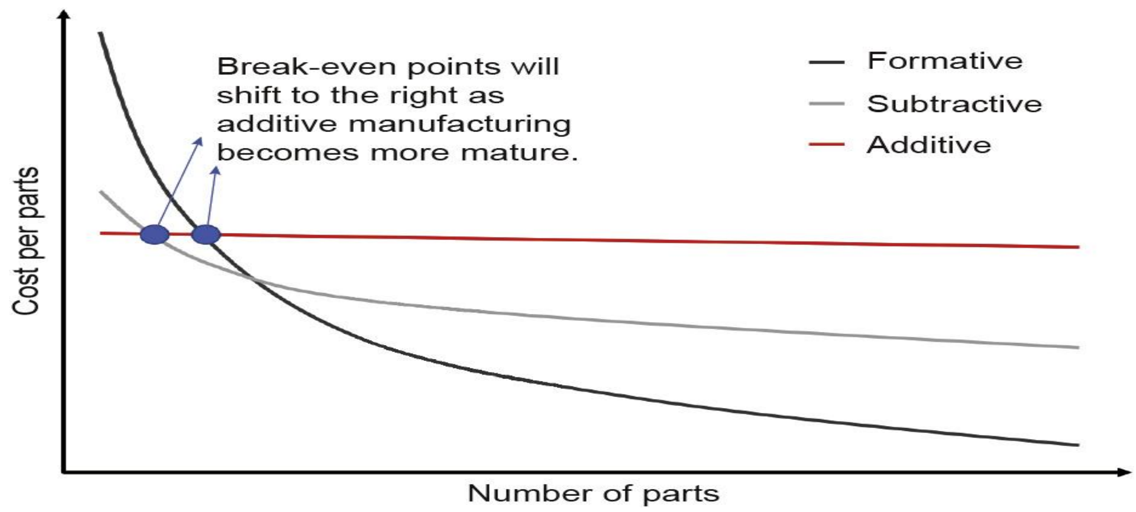

Figure 8: Plot of unit cost versus lot size. Reproduced with permission from [156].

That challenge needs to be solved. For the application of additive manufacturing in robotics, see e.g. [157] and [158].
Managers in industry 4.0 are more „management engineers", and industrial engineers are predestined for that role.
Let us conclude with thoughts on a citation ascribed to Henry Ford [159], that for improving transportation, people would have asked for faster horses instead of cars.

Pure engineers would probably have optimized Edison's incandescent light bulb, but not invented a totally new lighting concept such as LED. It is scientists that come up with new ideas. Similar is the situation in business: Pure managers would administer the present, because they do not understand technology and technological change deeply enough, and pure engineers would, too, optimize what they know. It needs out-of-the box thinkers, innovators, interface managers – the industrial engineering managers – who can blend information from both worlds into scenarios and paths for action into the digital age, shaping manufacturing 4.0.

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