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A Taxonomy of Industry 4.0 and Related Technologies

Ercan Oztemel and Samet Gursev

Abstract

Industry 4.0 and related technologies will remain at the top agenda of manufacturing systems until respective digital transformation is completed. In order to increase the speed of the transformation and the respective performance, a taxonomy of industry 4.0 is proposed in this chapter. The taxonomy is defined through four aspects including strategic understanding, managerial practices, technological infrastructure and developments, as well as human intervention with respective skills and competencies. Each aspect of these is defined and further sub-categorized in order to reveal the real dynamics of industry 4.0 and respective implementations. Generating the taxonomy would also ease the categorization of the respective efforts and make the assessment processes to be carried out more effectively. It is also believed that the proposed taxonomy will be the source of generating a maturity model of industry 4.0. Note that the proposed taxonomy and respective components are defined by reviewing 620 papers, maturity models, and industry 4.0 projects.

Keywords: industry 4.0, taxonomy of industry 4.0, maturity models, industry 4.0 assessment

1. Introduction

Nowadays many technology providers are spending a great deal of effort for digital transformation through empowering the concept of industry 4.0. Especially, manufacturing companies around the world are now facing substantial challenges due to recent environmental, societal, economic, and technological developments. Aligning this rapidly changing world requires analysis in all areas, not just in manufacturing functions. It is therefore very important to understand scope as well as the structure and the philosophy of industry 4.0. Behind the need for a clear roadmap that will guide the transformation process, the enterprises should comprehend and prioritize basic components of industry 4.0 and identify the ways to cope with the respective challenges which in turn requires new capabilities for managing supplier value chain in an agile and responsive manner.

In order to allow close cooperation and swift adaption along the whole product/process lifecycles from innovation to production and distribution, the companies will need some competencies such as integrating virtual and physical structures (see, e.g., [1]). Manufacturing processes, on the other hand, will be utilizing very limited amount of human intervention. Self-decision-making will be a dominant feature of the implementation plans. Similar to these, several other issues need to be sorted out for having a beneficial transformation. In this respect, the taxonomy of the basic components of industry 4.0 would help designers to better facilitate the change process.

This chapter is devoted to provide such a taxonomy which would allow comprehensive analysis of industry 4.0 from different aspects such as strategic, managerial, technical, and human intervention point of views. As explained below, each view is defined and further sub-categorized to reveal real dynamics of industry 4.0 and respective implementations. Generating the taxonomy would also ease the categorization of the respective efforts and make the assessment processes to be carried out more effectively. This chapter, in this respect, is considered to be one of the main sources for generating the maturity models of the digital transformation.

Current performance in production technologies is mainly driven by the increasing efficiency and effectiveness of the respective manufacturing processes. There are various advancements at various levels such as:

- Organizational-economic level involving methodologies on lean management, process management and strategic management, change management, innovation management, knowledge management, etc.
- Manufacturing technology level including distributed manufacturing, virtual manufacturing, holonic manufacturing, agile manufacturing, additive manufacturing, robotics and laser technologies, etc.
- Material level covering semiconductors, nanomaterials, carbon fibers, thin films, biomaterials, etc.
- Information technology level, examples of which include RFID and embedded systems

All these achievements have led to major but isolated gains in process efficiency and product quality as digital integration of those creates new era of manufacturing. This also increases the possibility of generating intelligent systems enriched by smart sensors, the so-called cyber-physical systems. The integration takes place on both horizontal (across all participants in the entire value chain) and vertical (across all layers of automation) levels of a certain company as a whole. It is fostered by the following driving forces [2]:

- *Vision*: Industry 4.0 is a part of smart networked world, and the philosophy includes novel business, new social infrastructures, and real-time interactions. Transformation process would have to be triggered by a clear vision of the manufacturing. This vision is to be based on “product,” “intelligence,” “IT network,” and “communication.”
- *Strategic approach*: The new era of manufacturing is formed by two main strategies, mainly “leading supplier strategy” and “leading market strategy,” aiming to be the pioneer in supplying and keeping a higher market position.
- *Requirements*: Companies should determine their needs by an in-depth analysis and see their strong and weak points to trigger the strategies accordingly. A comprehensive set of requirements will direct the implementation.
- *Priority areas*: A ranking should be made to strengthen the weak sides of the enterprise. Due to limited amount of resources, the company should generate a prioritized list of requirements and fulfill them accordingly.

Although there are some definition and foresights about the advancements toward future manufacturing systems or industry 4.0 operations, managing complex systems, delivering infrastructure for industry, safety and security factors, regularity framework, etc. are to be the main body of the possible roadmap for implementing practices outlined by industry 4.0. Keeping this in mind, a systematic definition of the future organizations helps both reorganize and advance the existing knowledge. This reorganization can be achieved through the classification of the present knowledge fields toward maturation. There are four main benefits expected as the following:

- Classification of a knowledge field provides a common terminology, which eases the knowledge sharing.
- Classification can provide a better understanding of the interrelationships between the knowledge artifacts in a certain field.
- Classification can help to identify knowledge gaps which can be subject to further improvements.
- Classification can support decision-making processes and facilitate generation of implementation plans.

Additionally, the classification of knowledge can support researchers and practitioners in generalizing, communicating, and applying the findings or advancements to the related fields.

The taxonomy on industry 4.0 presented here in this chapter is generated by reviewing 620 papers as outlined in **Table 1**. The authors benefited mainly from eight publication databases (CiteSeerX, ACM, AISel, EBSCOhost, Emerald Insight, Taylor Francis, Science Direct, Google Academic) for both academic and business areas. Some other literature found on the Internet is also reviewed in accordance with their relevance. Note that the literature review carried out in this study is published in [3]. The methodology for generating the taxonomy is presented below. Following this, the current state of the art on taxonomy studies is given. The proposed industry 4.0 taxonomy is then explained in detail then. Note that the definition of industry 4.0 and respective components are intentionally not covered as the respective information is provided in various chapters of this book.

	1987-1990	1996-1999	1999-2002	2005-2008	2008-2011	2011-2014	2014-2018	Total
Cloud						27	25	52
CPS						51	43	94
Data Mining					5	5	34	44
ERP			2	10	5	10	13	40
Industry 4.0	1	1		13	30	31	37	113
IoT			1	9	14	1	23	48
M2M			10	25	2	10	17	64
Smart Factory			10	14	1	23	18	66
Virtual Eng.	1		1	3	5	4	14	28
Augmented Reality					1	10	10	21
Intelligent Robotics					10	10	10	30
Projects						10	10	20
Total	2	1	24	74	73	192	254	620

Table 1.
 Number of literature reviewed for developing the proposed taxonomy.

2. Methodology used for generating the taxonomy

As stated above, the taxonomy is mainly a classification methodology. Enumerative and faceted approaches are used for classification. In enumerative approach, all classes are constant, making a classification plan intuitive and easy to apply. However, it is hard to enumerate all classes in immature or evolving domains. In faceted classification, views of classes that can be combined and extended are described. A true hierarchy ensures the mutual exclusivity, i.e., a presence can only belong to one class. In hierarchical classification, it is compulsory to have good knowledge on the subject or phenomena to be classified. The classes and differentiating criteria between classes must be well defined.

To generate a comprehensive taxonomy for industry 4.0, academic literature, popular media, websites, and Wikipedia as stated above in **Table 1** are first investigated. Attempts to search for respective work indicated that no taxonomy study similar to the one proposed here is available. The literature collected is carefully refined, and those contributing to the taxonomy is selected and put into a database for their contribution.

Similar to the literature review, some of the maturity models such as the one described by [4] and running projects such as MetamoFAB [5] are also reviewed. Together with the literature review, this analysis also showed that the structure of the industry 4.0 is shaped from different aspects, examples of those given in [6–10]. Those are categorized under the so-called common views as shown in **Figure 1**.

After the literature survey and analysis in this manner, attributes and components of industry 4.0 were identified and categorized. Following this, a taxonomy table was created with a wider focus that includes not only the components of industry 4.0 but also all related business functions. The proposed taxonomy is approved by a scientific committee where academics and industrial practitioners took part in this assessment.

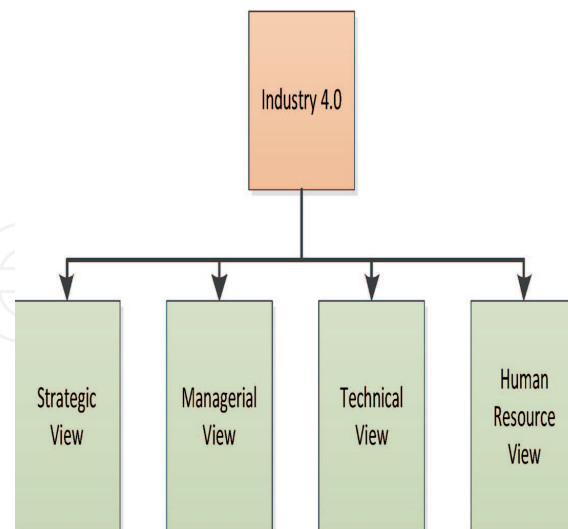


Figure 1.
Main views of industry 4.0, taken as baseline for the taxonomy.

3. Taxonomy of industry 4.0

According to Oxford Dictionary, taxonomy is “a scheme of classification.” It allows for the description of terms and their relationships in the context of any knowledge area. The respective data within the domain is classified into a

hierarchical structure based on their relatedness. As indicated in **Figure 1**, the taxonomy proposed in this chapter is based on four different views which could be considered as four pillars as explained below.

3.1 Strategic view

This indicates strategic aspects of industry 4.0 implementations, believing that the technology by itself is not enough to define the roadmap directing the transformation process as effectively. Some other factors such as strategic approaches should also be taken into account. Accenture investigated the main characteristics of industry 4.0 [11]. Klaus pointed out that new technologies like 3D printing, cloud, or CPS are important for industry 4.0 main goals [6]. But industry 4.0 also grows new strategies and new business models. This would enable to better foresee the future and generate respective assessment models. As shown in **Figure 2**, several sub-categories are defined by focusing on the strategic aspects of industry 4.0.

Corporate culture is an unavoidable part of any transformation in industry. It is elaborated in terms of knowledge sharing, open innovation, mission and vision, innovator and open innovation, etc. Total quality control is found to be important in order to utilize systems developed in an integrated manner. It is believed that these should be taken as the main drivers to restructure the organization. Especially mission and vision of the company should be re-addressed, and innovation culture should be given the prime importance.

Similarly, Kagermann et al. and all other studies explain the importance of *roadmap for strategic evolvement* [12]. Based on the literature analysis, the headings to be followed for the strategic roadmap of industry 4.0 were identified as the following:

- *Investments*: Industry 4.0 includes many new technologies which can be effectively utilized with the right investments empowering the competitive advantage.
- *Strategy*: Enterprise should be determining a correct strategy including industry 4.0 values as described by [13]. It is important to support especially innovation and be open to valuating new ideas.
- *Corporate approach*: Enterprises should develop implementation plan and a corporate approach for the activities to be carried out within and outside the organization. Pre-planned, specific rules, principles, or corporate culture should be established.
- *Resources for realization*: The diminishing amount of natural resources can be a problem especially for manufacturing companies with global supply chains. Industry 4.0 should try to enable the realization of the productivity growth that people need to satisfy the ever-growing consumption behavior, while not actually increasing the demand for resources significantly.
- *Implementation roadmap*: All departments and processes such as procurement, production, sales, marketing, and operations should be in line with the industry 4.0 standards, principles, and specifications which should be implemented in a roadmap manner.
- *Adaption of business models*: The business models in developed markets to generate competitive advantage are often challenged by the environment

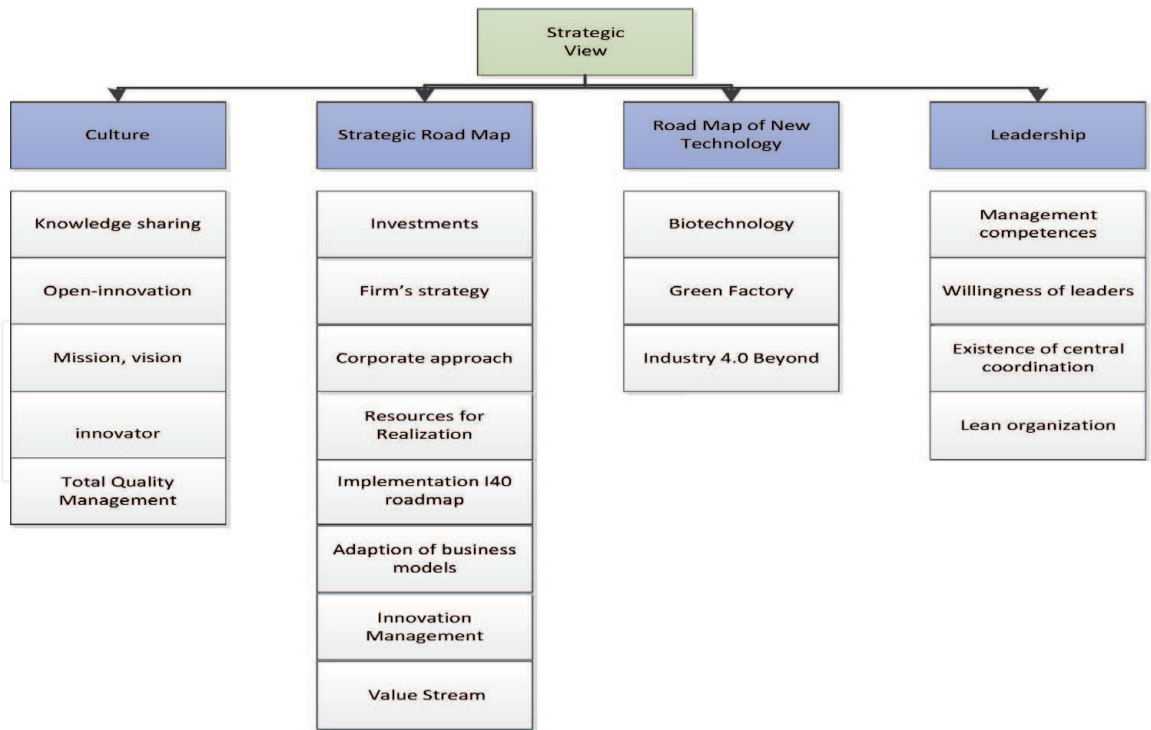


Figure 2.
Strategic View of Industry 4.0.

present in emerging markets. Achieving this change is important for digitizing the processes.

- *Innovation management*: Digital transformation is all about the change, research, and development operations with a systematic implementation process. Innovation management, idea development, conceptualization, feasibility, products, and service development, testing, launching, and marketing are the basic pillars of this process as they can provide their customers with a different perspectives and service understandings.
- *Value stream*: The set of all steps from the start of value creation until the delivery of the end result to customer should be the main focus of industry 4.0.

In the literature, it is hard to see all of these to be covered by any industry 4.0 implementation. Among those, investments, corporate strategy, corporate approach, and resource for realization are challenged in industry 4.0 projects. The rest of those are basically seen in reviews and maturity models (see, e.g., [14–17]).

A road map of new technologies is especially important for technology developing companies. Biotechnology and Green Factories are among those. A basic requirement for a “green factory” is energy-efficient and sustainable production that balances environmental and business interests. Biotechnology is also the technology that utilizes biological systems, living organisms, or part of this in order to develop or create different products. After industry 4.0, it is foreseen that the companies performing Research and Development (R&D) as well as making investments in this field will be successful.

Similarly, the *leadership* is considered to be an important criterion for strategy formulation within the taxonomy. It may include management competencies, willingness of leaders, and existence of central coordination as well as lean organizations. “Competencies” of managers surely can improve management skills and influence the behavior of others—which can have a positive impact on the bottom line.

The competency in this case is defined as the quality of being competent, adequate, and equipped with required skill, knowledge, qualification, or capacity. Organizations should define the competency requirements for their leadership team. This enables the organization to be managed with a consistent competency model. It is important for the leader to believe in the process and to be “willing” to digitize the organization. A leader must have three fundamental characteristics such as knowledge, courage, and compassion with a will to work. Note that in industry 4.0, central coordination and management are important requirements. Besides the leadership, there is also a need to control the whole enterprise and support the leadership with a good business model, especially where the entire factory is remotely controlled and managed.

A *lean organization* understands its customer value and focuses its key processes to continuously increase that. A structure other than lean organization cannot be accepted in competitive and innovative companies. A company with components of industry 4.0 is expected to be free of waste and inefficiency.

3.2 Managerial view

Managerial view is analyzed in terms of three main aspects as the following:

- Products
- Operations
- Business

The products to be produced can be in a variety of forms from ballpoint pens up to robots. However, the product should have some characteristics such as being intelligent enough to help its users to get the maximum benefit of it. Autonomy, self-behavior, being able to communicate with surroundings, generating useful knowledge for the users, etc. are some of the characteristics that have to be considered while transforming the enterprise toward the future. Similarly, industry 4.0 emerged to offer new approaches for dealing with complexity and improving productivity. By deploying the right combination of technologies, manufacturers can boost speed, efficiency, and coordination and even facilitate self-managing factory operations. Several research points out those as the basic benefits to gain in business (see, e.g., [17–19]). Keeping these three aspects into account, the components of managerial view is depicted in **Figure 3**.

As shown in **Figure 3**, the managerial view is categorized by managing the products, operations, and the business as a whole. From the *product* point of view, it is important to generate a *product integration scheme* which would mean something like a form of advertising as placing the specific product in a scene (see, e.g. [20, 21]). Note that, easy and fast integration of products into the market will be one of the main requirements.

While trying to digitize the processes, the way to *digitize the products* (being smarter and having information sharing capability) should also be considered. It should be noted that *big data* and *data analytics* are the main components of industry 4.0. This involves complex applications such as predictive models, statistical algorithms, and what-if analysis powered by high-performance analytic systems.

Similarly, *individualization* or *customization* is another unavoidable progress along digital transformation powered by industry 4.0. This could be reflected by the products as well as the processes. Having the products individualized or customized means generating completely customer-designed specifications which will be of great priority in the market for customer attraction.

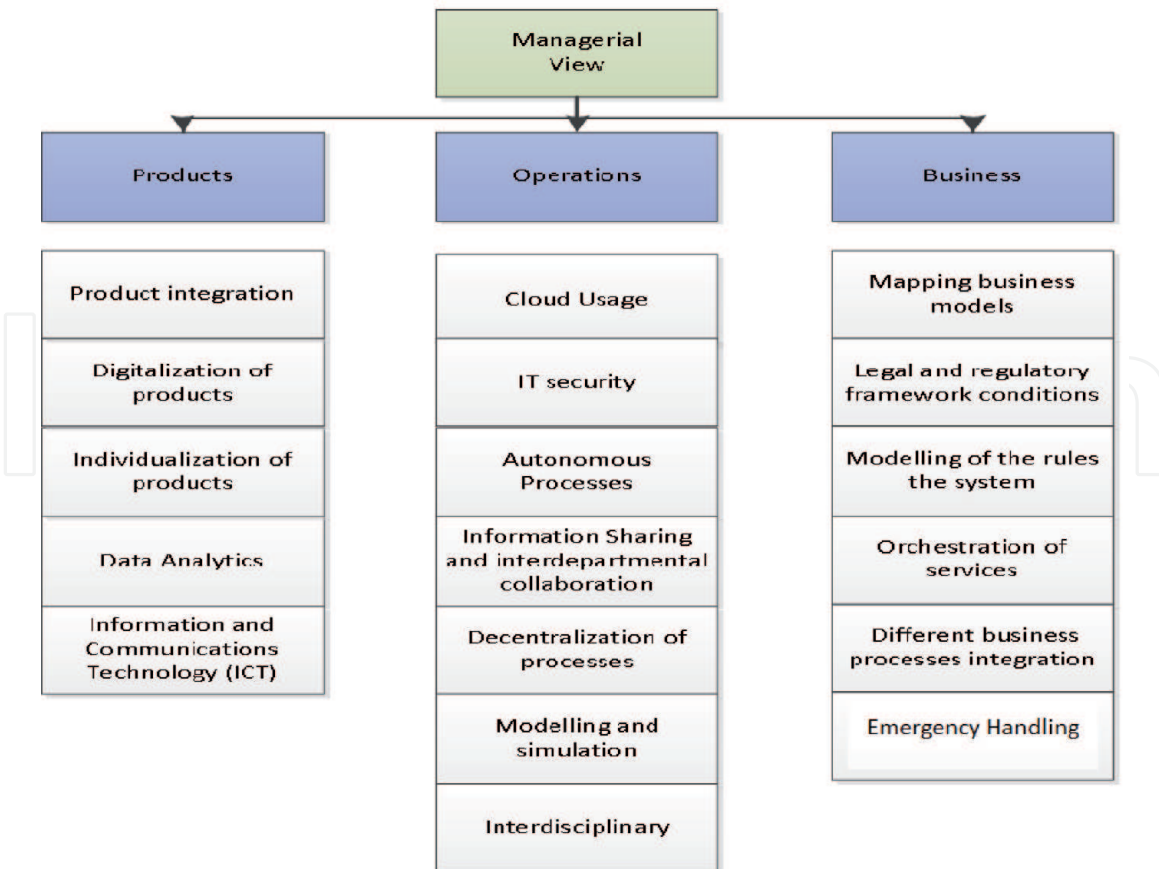


Figure 3.
Managerial View of Industry 4.0.

It is now obvious that industry 4.0 implies that information and communication technology will change human life. This can be considered as leverage for economic, societal, and interpersonal transactions and interactions. Modern information and communication technologies have created a global world, the so-called global village, in which not only the people can communicate with others across the world as if they were living next door but also machines, robots, equipment, and tools can be facilitated along this line. From the *operations* point of view, operations management of future manufacturing systems must have the following characteristics:

- Selecting an appropriate resource is mandatory for operation management. Using efficient process will eliminate the waste of efforts and redundancy. Today, *cloud computing* operations have become very popular and widely employed by many of the organizations just because it allows to perform all business operations over the Internet without spending too much time and money. This technology presents remarkable changes and opportunities especially in computing and communication.
- *Information security* is basically the practice of preventing unauthorized access, use, disclosure, disruption, modification, inspection, recording, or destruction of information. The field of information security has grown and evolved significantly in recent years. It offers many areas for specialization, including secure networks and allied infrastructure, and reliable applications and databases, etc. As foreseen by industry 4.0, future manufacturing systems should pay attention to the progress along this line.

- *Autonomous processes* is another expected behavior of manufacturing systems. This capability triggers the flexibility and adaptability ensuring subsystems and modules with a certain degree of decentralized autonomy and control. In order to manage dynamics, flexible, reconfigurable, and autonomous assembly systems were mainly realized in the last two decades and seem to be required more and more every day. Manufacturing systems taking industry 4.0 as baseline should heavily be engaged with these capabilities.
- Problems with *information sharing* and interdepartmental breaks while practicing industry 4.0 could be the main source of failure as Bello et al. clearly stated [22]. This implies a comprehensive setup of secure communication system. Since machines will be speaking to other machines and perform unmanned decisions, sharing information even knowledge between man to machine and machine to machine, as well as respective software, seem to be inevitable for successful transformation.
- *Decentralization* is the process by which the activities of an organization, particularly those regarding planning and decision-making, are distributed or delegated over an information network. No central system plays the role of control. The overall management of the operational processes is ensured by timely information exchange and requires quality.
- *Modeling and simulation* technology is one of the most popular components of industry 4.0 and revolutionized in the operational processes through augmented reality. As well known, modeling is used for multi-criteria analysis before the new product/process/operations are launched, and simulation is an important tool for the improvement of operation processes.
- Industry 4.0 requires *interdisciplinary operations* which facilitates value engineering, customer-oriented approaches, and customer loyalty. Enterprises aiming to experiment digital transformation should spend a great deal of effort on implementing these.

Similar to products and operations, industry 4.0 also reshapes the *business*. The business model to be implemented should describe how the company creates, delivers, and captures the expected value. Business models within the scope of industry 4.0 include a large number of subcomponents as described by [23–25]. The proposed taxonomy includes the following elements:

- *Business model should be mapped* to the manufacturing operations. This mapping involves generating systematic solutions to target market/customer, channels of distribution, revenue streams, effectiveness of operations, intellectual property rights, customer relationship management, etc.
- The legal basis or *regulations* for which the companies are to obey is an important criterion for the system to align business requirements to regulations. That indirectly implies that the business model employed should be digitalized in accordance with the law.
- *Remodeling business rules* are necessary for deciding in which sequence the operations are to be executed. The traditional approach used to implement a business process in today's information systems will no longer be able to cover

the actual needs of the dynamically changing business requirements. New form of rules needs to be developed especially for ensuring machine-software-human information exchange.

- *Orchestration* of services is another basic requirement of industry 4.0. This necessitates loosely coupling interoperable services of small units of software designed that perform discrete tasks. That is to say that the application or service orchestration is the process of integrating two or more applications and/or services together in order to automate a process or synchronize data in real time. Often, point-to-point integration is used. There has to be an integration plan to sustain required level of orchestration.
- Above the application integration, *Business Process Integration* (BPI) is also essential to enable automation of business processes, integration of systems and services, and the secure sharing of data across numerous applications. Overcoming integration challenges makes it easy for the organizations to connect systems internally and externally. Orchestration, process integration, and information sharing capabilities should be aligned to sustain the success of decentralization process.

Business continuity and emergency planning is necessary to assure the performance of industry 4.0 implementations. Since not much human intervention is necessary, it is required to get instant information from the business processes and control them especially under emergencies.

3.3 Technical view

The most detailed and most relevant characteristics of industry 4.0 are the technical aspects and technological approaches. The main reason for this is that the components are structures made up of new technologies. In order to identify related technical issues, the titles, keywords, and findings obtained in all projects, reports, and academic publications have been analyzed. After this extensive analysis, technical view of the proposed taxonomy is defined as shown in **Figure 4**.

The intelligent or **smart factory** is the most popular component of industry 4.0 (see [26–28]) with respective subcomponents.

- *M2M technology* is the main technical requirements for generating intelligent machines fostering smart factories. This technology allows interactions among machines, software, and human operators. Machine-to-machine communication is inevitable. Sensor or cyber-physical systems are used to enable this.
- *Optimization*, also known as mathematical programming, is the collection of mathematical principles and methods used for solving quantitative problems in many disciplines. Optimization is key component allowing information and material flow within the job floor and supporting the product development. The required level of flexibility is a must in order to be able to reconfigure the manufacturing suits for respective purpose.
- Industry 4.0 is all about running the *dynamic organizations* which should engage manufacturing resources, communities, and spaces for its employees and learners to thrive. Dynamic organization is considered as the primary key for the digitalization.

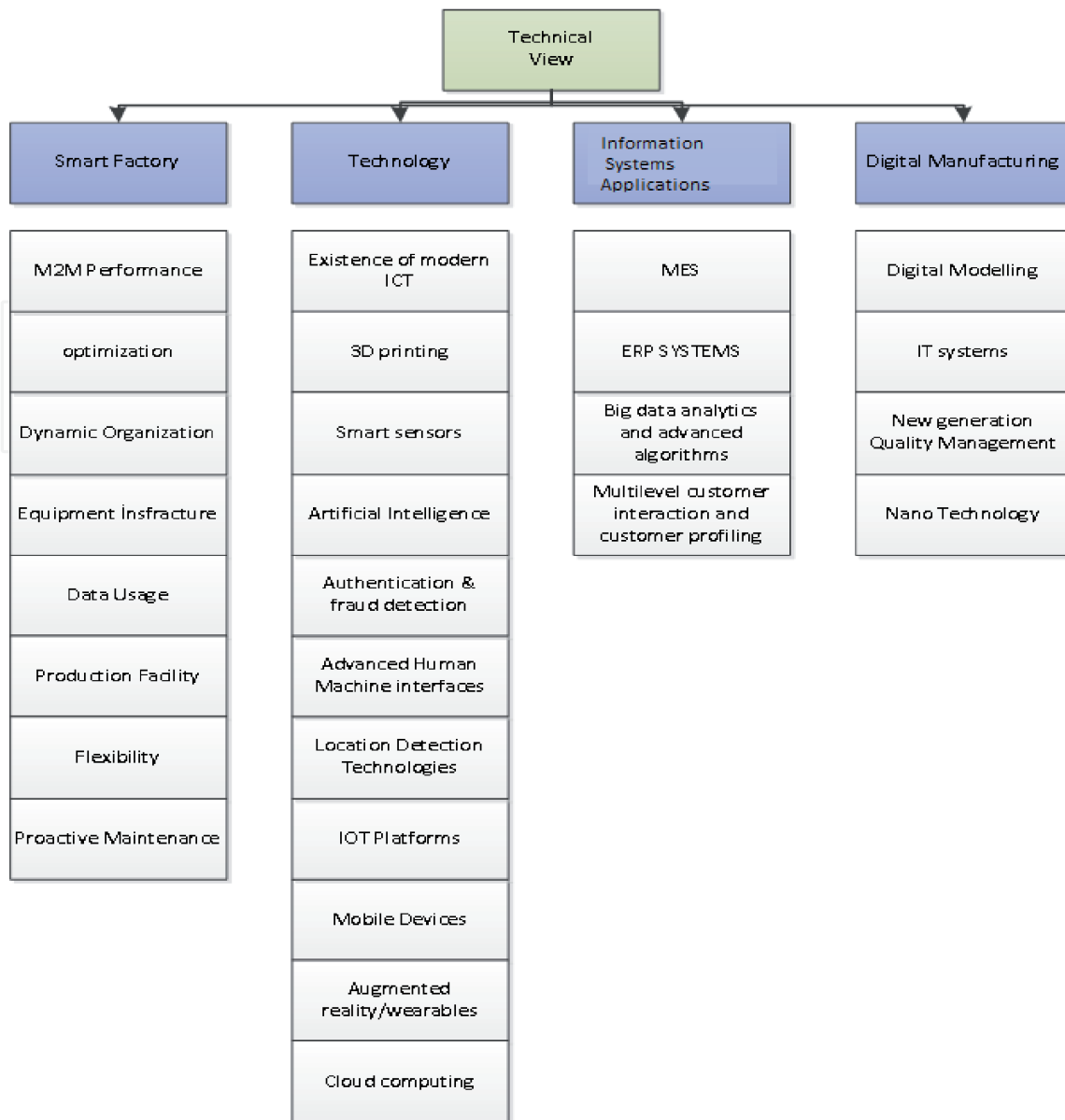


Figure 4.
 Technical View of Industry 4.0.

- *Equipment infrastructure* is also important for ensuring business continuity and performance increase under dynamicity. Keeping interfaces set properly enable integrated functions to run without any shortcomings. Some of the applications such as equipment maintenance, optimization, and flexibility provide the link between the intelligent factory and industry 4.0. Machine maintenance is important as not much human involvement will be possible, and the machines are going to take control of themselves for continuously working.
- Similarly, the system would not be successful without *effective use of data*. Note that in industry 4.0, an extensive set of data is required to make the right decisions, understand and manage the processes, and perform improvement. Data is also necessary to define the required autonomy as it is an essential part of the process to provide sufficient capability for the enterprise to manage production facility for criteria of smart factory.
- *Production facilities* such as handling, separating, treating, and processing have to be fully under control of the system by itself. Respective equipment and

facilities need to be in operation on time. Since assuring effective and efficient operations are a must for industry 4.0, the production facilities should be configured in such a way that the basic requirements are fulfilled.

- Another important feature to consider within industry 4.0 environment is the *flexibility*, meaning to produce reasonably priced customized products of high quality. The need for flexible processes is to permit rapid low-cost switching from one product line to another. This requires both machines to have multi-functionality and the operators to develop multiple skills in order to switch easily from one kind of task to another.
- *Proactive maintenance* should not be discarded from this taxonomy. This can be defined as implementing a preventive maintenance strategy that works to correct the root causes of failure and avoid breakdowns caused by underlying equipment conditions. The purpose of proactive maintenance should be identifying, anticipating, and eliminating before they actually occur. Creating a proactive maintenance program characterized by industry 4.0 helps organizations find hidden inefficiencies as described by [29].

The second pillar of the technology view presented in this taxonomy is the **technology** employed. It should have some characteristics prone to industry 4.0 as explained below.

- *Information and communications technology* refers to respective technology used to handle telecommunications, broadcast media, intelligent building management systems, audiovisual processing and transmission systems, network-based control and monitoring functions, etc. Converging technologies that exemplify ICT should also include the merging of audiovisual, telephone, and computer networks through a common cabling system.
- *3D printing or additive manufacturing* is the process of making three-dimensional solid objects from a digital file. The creation of a 3D printed object which is achieved using additive processes is considered to be an important aspect of industry 4.0. In an additive process, an object is created by laying down successive layers of material until the object is formed. Adapting industry 4.0 to any enterprise should have this capability not just for producing the products but also for understanding the respective product behavior.
- A *smart sensor* is a device that takes input from the physical environment and uses built-in compute resources to perform predefined functions upon detection of specific input and then process data before passing it on. Since they operate interactively over an IT network, they are called cyber-physical systems. Industry 4.0 is heavily based on these sensors and respective Internet of Things.
- *Artificial intelligence* is, on the other hand, one of the pioneering technologies facilitated by industry 4.0, especially for ensuring required autonomy and self-behaving capability. Research associated with artificial intelligence is highly technical and specialized. Knowledge engineering is a core part of AI research. Machines can often act and react like humans only if they have abundant information relating to the world. Artificial intelligence must have access to objects, categories, properties, and relationship among those.

- *Fraud detection* technology, especially those utilizing machine learning systems, is expected to become one of the top priorities of industry 4.0 implementations. Fraud detection problems are known for being extremely imbalanced. Boosting is one technique that usually works well with suspicious data sets. It iteratively creates weak classifiers (decision trees) by weighting the instances in order to increase the respective performance.
- *Human-machine interface* (HMI) technologies enable people to interact with computers. It is important to employ right set of equipment and related technologies to have continuous operations of manufacturing systems. It is known to IT technology specialists that the archaic user interfaces can reduce productivity on the machines which are commonly among the most expensive in the facilities. That encourages the industry 4.0 specialist pay attention to this technology.
- There are various technologies that can provide real-time information processing to the devices located apart. Those devices may include mobile telephones, laptop computers, personal digital assistants, and gaming consoles. *Location detection technologies*, such as the global positioning system (GPS), are included as a standard feature in many new mobile telephones. Similar technologies have to be utilized where manufacturing units are located.
- An *IoT platform* is an indispensable technology for industry 4.0. A multilayer structure that enables straightforward provisioning, management, and automation of connected devices within the universe of Internet of Things (IoT) is set up. IoT platforms were originated in the form of IoT middleware, whose purpose was to function as a mediator between the hardware and application layers. Its primary tasks include data collection from the devices over different protocols and network topologies, remote device configuration and control, device management, and over-the-air firmware updates. There is a need to employ the platform for easy implementation of these.
- Similar to those listed above, *mobile devices* are to be used within the manufacturing suits in industry 4.0 more and more everyday. New data storage, processing, and display technologies have allowed these small devices to do nearly anything that had previously been traditionally done with larger personal computers. These devices should be configured in accordance with the purpose of the manufacturing system.
- *Augmented reality* (AR) is an interactive experience of a real-world environment whose elements are augmented by perceptual information generated by computer simulation. Integrating real and synthetic worlds is also the basic requirement of industry 4.0. Since augmented reality is the ability to integrate digital information into real-time experiences, this technology will remain at the top of the agenda in implementation projects.
- *Cloud computing* is the delivery of computing services—servers, storage, databases, networking, software, analytics, intelligence, and more—over the Internet (the cloud) to offer faster innovation, flexible resources, and economies of scale. As mentioned above, cloud computing technology is to be empowered within manufacturing and respective management activities.

In order to utilize the technologies listed above over the IT, network requires a set of information processing technologies to be embedded into the system. That is why enterprise resource planning (ERP) related to work has a remarkable impact on industry 4.0 [30–32]. In manufacturing suits equipped by industry 4.0 components, the following *information processing systems* need to be equipped and operated.

- A *manufacturing execution system (MES)* which is a software system connecting monitors and respective control devices to manufacturing systems and handling data flows that take place on a factory or shop floor. The overall goal of MES is to make certain that manufacturing operations are effectively executed and improve production output. This is essential when there is not much human involved in the operations as implied by industry 4.0.
- The basic software framework to support information processing could be *ERP systems*. They should be obliged to take into account innovations such as the industrial Internet of Things (IIoT), which is revolutionizing manufacturing by leveraging intelligent, connected devices in factories. Better data and process analysis capability ensures even more opportunities to fine-tune their operations.
- The fourth industrial revolution and the rise of things such as IoT, robotics, and sensors could in turn create a system which can produce things much more efficiently. *Big data* and *analytics* such as machine learning methodologies can be utilized in order to dig relevant information out of the data collected. This may make predictions and spotting right knowledge easy.
- *Customer profiling* is a way to create a portrait of customers to help in making design decisions concerning service. This facilitates customizations and support customer satisfaction.

Digital manufacturing which is also an indispensable component of industry 4.0 is roughly the application of digital technologies to manufacturing. It is all about having the right information, at the right place, at the right time. The goal is to link disparate systems and span processes across all departments and functions within the value chain.

- Digital modeling and fabrication is a design and production process that combines *3-D modeling* or computing-aided design (CAD) with additive and subtractive manufacturing. It is therefore considered to be one of the essential parts of the proposed taxonomy.
- As stated earlier *IT systems* with respective sub-technologies should be utilized within manufacturing units. Mobile devices will be used as the main applications in order to manage so called remote systems. Today mobility already provides solutions that allow an employee or manager perform vital management functions from a phone or tablet, and do so from wherever they work or stay.
- Additive manufacturing provides some extra opportunities for manufacturing society. These include more inspections with fewer devices, reliable measurement, and detection of challenging target, cost savings, IO-link communication, real-time remote monitoring and diagnostics, and

predictive maintenance. All of these new technologies necessitates the definition of new *quality control processes*. Traditional quality practices will not be sufficient enough to assure the required level of quality.

- *Nanotechnology* is an area that can change the whole world independently of all other criteria. It is expected to benefit greatly from the production stage in the near future. Industry 4.0 applications should not disregard the progress on nanotechnologies.

3.4 Human resource view

There is a strong relationship between industry 4.0 and human life or society. When industry 4.0 is effective all over the world, business life, human resources, and the social lives of people are foreseen to have complete change. Although much of the operational processes are carried out by robots and machines, industry 4.0 will lead to major changes on people abilities which is highlighted in **Figure 5**. In this taxonomy, four aspects of human resources are considered to be worth mentioning as explained below.

The first component of these categorizations is the *people* pointing out mainly the required skill and competencies of the employees from the following points of view.

- *Employee autonomy* can have positive benefits for both the individuals and the company as a whole. When staff members have the freedom to approach their jobs in a way that suits their personalities and skill sets, business that can flourish from all aspects are covered. As planning a way to strike the right balance of autonomy in the company, it is important to define how employees can work within the structure of the business in the most effective way.
- *Employee openness*, trust, and transparency also ensure that people are kept informed of issues as they arise and that everyone receives current knowledge about an ever-changing situation. Lack of openness can create distrust, lead to hidden agendas, and be detrimental to the team, attitude, work, and productivity. Company and business owners who value the thoughts and opinions of their staff stand much better chance of being successful. In the future this openness will be more required than today.
- Employers want effective and *competent employees*, regardless of the position of their job. There are ways to evaluate prospective employees for specific types of jobs. Machine autonomy will surely be empowered by staff competency in computing, programming, behavior modeling, simulation, real-time information processing, etc.
- A *skill set* is a particular category of knowledge, abilities, and experience necessary to perform a certain type of a job. Industry 4.0 practitioners should also identify the required set of skills to perform daily operations where human is involved.
- Similarly, required skills may not be found right-hand. There may be a need for *skill acquisition* theory which is not just a theory of the development of language, rather it is a general theory of learning ranging from cognitive to psychomotor skills. This theory, which is based on, for example, adaptive

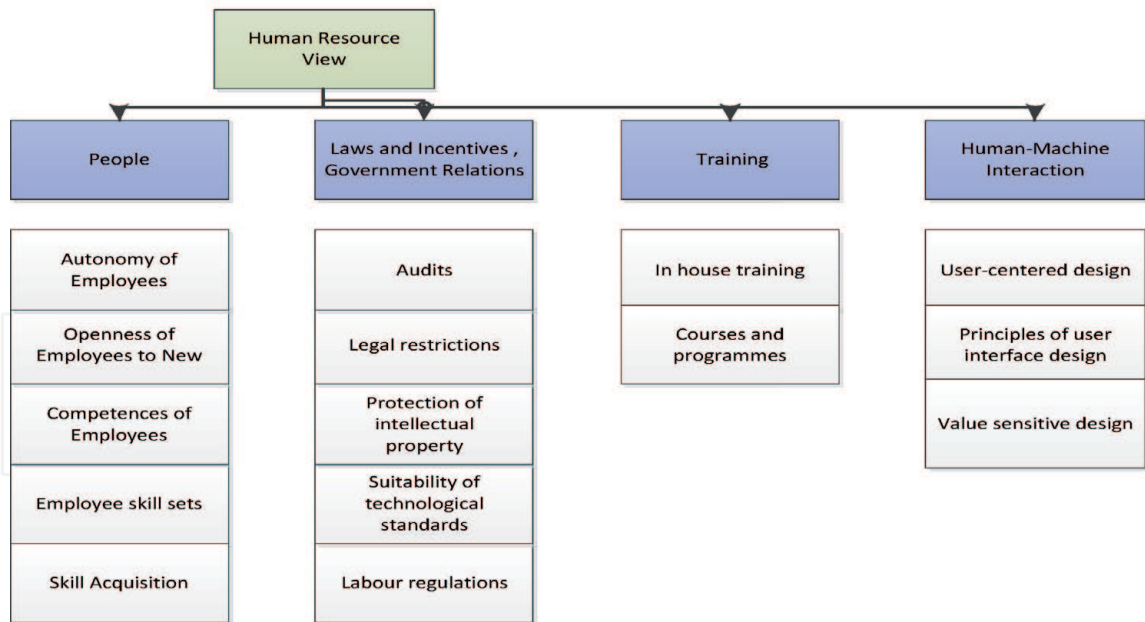


Figure 5.
Human Resource View of Industry 4.0.

control of thought model, claims that adults commence learning something through mainly explicit processes and, through subsequent sufficient practice and exposure, proceed to implicit processes.

Laws, legal restrictions, protection rules, employee rights, and audits will change rapidly in the near future. Decentralized business processes will have to be examined in audits as opposed to centralized audits of today. “Auditing” procedures should be redefined to cope with industry 4.0 baselines. Similarly, “legal restrictions” and employee rights will be revised taking the man-machine interfaces into account. There must be a change in the perception of classical management and the possibility of working more freely. As the production speed and capacity will increase, the competition should go much more controlled. The protection of the environment, human, and society will be essential. Intellectual property rights (IPR) systems can be critical in helping new ventures transform their innovation potential and creativity into market value and competitiveness. Efforts should be continued to ensure that “technological standards” are sustainable, and technology audits should be increased while keeping respective IPR on hand. This will definitely yield “labor regulations.”

It is now certain that in industry 4.0, single-level operational jobs, low-quality jobs that do not require qualification, and jobs that require physical power will be carried out by robots. Simulation and similar studies will heavily be used for staff training and maintenance. Virtual reality will make a great contribution to training in this regard. It is expected that the education and training system will totally change. New topics within the scope of industry 4.0 will have to be covered. Education system will not be enough to create the required level of competency and skills which in turn will necessitate “in-house training.” On-site training is believed to increase rapidly in the near future. Technical knowledge and specialization will gain more importance than today. Programs and trainings will also be multifaceted.

While training is one of the valuable tools to support industry 4.0 in terms of mobility and access, *man-machine interaction* enables more flexible operation from the following aspects.

- Today, many processes are carried out by people. However, they will be replaced by machines. People already started to work with chatbots and digital assistants. Online shopping, online banking, and after-sales processes are now changing rapidly. It is important that people have *user-oriented design* features to be satisfied with their experience. Industry 4.0 will enforce designers to perform customized design as much as possible.
- Since customers will be more concerned with user-oriented design features, designing interfaces that everyone can use will then easily contribute to competition, that is to say that the user-friendly products will typically be more successful than those with complex, convoluted interfaces. Additionally, customers often avoid unreliable products, such as software programs that are full of bugs. In order to ensure a good user experience, companies often thoroughly test their products before releasing them to the public. Especially, software products will be designed obeying the principles of user interfaces attracting the attention of users to important points and issues.
- Similar to user centric design and user interface design, *value sensitive design (VSD)* will also be the point of attention in industry 4.0 implementations. VSD is a theoretically grounded approach in order to make the design of technology that accounts for human values in a principled and comprehensive manner. Accurate analysis is needed to rapidly adapt to user expectations. Interfaces must be interchangeable and renewable according to the individual's wishes. Customized processes and products of industry 4.0 will definitely require VSD to be at the top agenda item of designers.

4. Conclusion

Being able to cope with digital transformation requirements, the companies should pay attention to certain phenomena interrelated to one another. It is now obvious that future manufacturing will be more intelligent, more flexible, more adaptive, more autonomous, more unmanned, and more sensor based (industry 4.0 standards). More and more augmented reality will take place in production suits. This will naturally change the man power profile as well. There is a need to carry some research along this line. Moreover, future manufacturing systems will not only be based upon industry 4.0 standards but will be more extended toward generating fully automated and unmanned systems with having robots enriched with humanlike behaviors. The correct use of real-time information is expected to lead not only today but also the next industrial revolution.

This new trend will not only affect the economy and manufacturing industries but the whole society, education, health, and law. It can be considered a well-accepted start that will guide the human life toward the future societies. Today, all of the components considered in this research are assembled to some degree one way or another to serve economies. In order to facilitate this transformation, the taxonomy of industry 4.0 is developed and presented in this chapter. Change management process along this line could be effectively managed by concentrating and utilizing the components of the defined taxonomy which consider strategic, managerial, technological, and human interactions from various aspects.

The taxonomy presented could obviously be expanded and aligned to specific field with some sector-specific needs. The impacts of biotechnology and nanotechnology applications could be elaborated in more detail. Since industry 4.0 will have a

severe effect on politics, trade, and the legal systems, there could be a need to extend the taxonomy in the light of the developments for better reflecting the reality.

On the other hand, industry 4.0 will change working life and business processes of people as well. For this reason, studies on labor economics and labor rights could be considered in terms of their effect on manufacturing and service providing systems. The taxonomy will help improve those, and the achievements in turn will help improve the taxonomy.

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