Annual Reviews in Control 47 (2019) 214–220

Contents lists available at ScienceDirect

Annual Reviews in Control

journal homepage: www.elsevier.com/locate/arcontrol

Vision article

Fundamentals of smart manufacturing: A multi-thread perspective

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A R T I C L E   I N F O

Article history:
Received 15 June 2018
Revised 29 January 2019
Accepted 3 February 2019
Available online 8 February 2019

Keywords:
smart manufacturing
Industry 4.0
digital manufacturing
manufacturing resiliency
sustainable manufacturing

A B S T R A C T

The paper outlines key characteristics of smart manufacturing, data-driven, networked, connected, resource sharing, resilient, and sustainable. Manufacturing resiliency and sustainability have received limited attention in the literature and they are the focus of this paper. Both are related and offer challenges that may become differentiators of smart manufacturing. Resiliency provides businesses with defenses against natural and human caused adversities. The list of attributes provided in the paper is intended for comprehensive assessment of manufacturing resiliency. Solutions are needed to make businesses more resilient and sustainable. Research on business models equating sustainability with an industrial activity is suggested. A scheme for labeling environmental friendliness of materials makes as a token contribution to sustainability.

Contents

1. Introduction

Manufacturing is undergoing a transformation superseded by the progress in production and artificial intelligence technology. Much of discussion about manufacturing systems focuses around terms such as big data and digital manufacturing (e.g., see NIST, 2018). There is no doubt that the volume of data generated in manufacturing is increasing, however, the volume of the data collected and its usage varies across different industries, their scale, and production areas (Kusiak, 2017). For example, collecting large volumes of data is common in the semiconductor industry. Yet, in majority of discrete manufacturing companies, one would have difficulty identifying a machining center with a dozen sensors installed. In addition, the utilization of data generated in manufacturing tends to be low. Some research organizations have retrofitted machine tools with multiple sensors to study the utility of the generated data, e.g., vibration, oil temperature, pressure. Some manufacturing industries have shown interest in installing sensors on the legacy equipment. Since the research around data-driven modeling has been limited, equipment manufacturers have been reluctant to install sensors. Once benefits from the manufacturing data are fully demonstrated, the mainstream discrete manufacturing industry is likely to follow the data collection practices of other industries. For example, a typical wind turbine that has about the same order of

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https://doi.org/10.1016/j.arcontrol.2019.02.001
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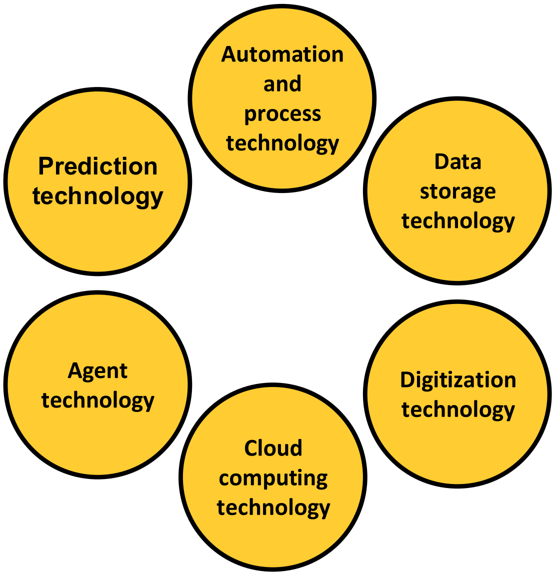

Fig. 1. Sources and consumers of data in smart manufacturing.

complexity as a machine tool, may streams over 100 data points at 0.1 Hz frequency. The data is collected in SCADA (supervisory control and data acquisition) systems that are transaction based. This practice differs from the storage in relational data bases used in many industries.

Much of the developments in smart manufacturing is conditioned by data, and therefore assessment the main sources and usage of data is needed across its technologies. Fig. 1 shows six technologies of importance to smart manufacturing. Details of these and other technologies have been discussed in the literature (e.g., Chen et al., 2018; Wan, Yang, Wang, & Hua, 2018).

Examples of the nature of data, data type, and data volume across the data applications covered by the six technologies in Fig. 1 are presented next.

- *Automation and manufacturing technology*
  - Nature of data: equipment status, production status
  - Data type: numerical, symbolic
  - Data volume: medium.
- *Data storage technology*
  - Nature of data: status and history of production equipment
  - Data type: numerical, symbolic, time series, text
  - Data volume: very large.
- *Digitization technology*
  - Nature of data: artifact characterization, status
  - Data type: numerical, symbolic, text
  - Data volume: large.
- *Cloud computing technology*
  - Nature of data: as-is data, transformed data, integrated data, models, algorithms
  - Data type: potentially data of types determined by the cloud design
  - Data volume: very large.
- *Agent technology*
  - Nature of data: application specific
  - Data type: application specific
  - Data volume: low.
- *Prediction technology*
  - Nature of data: application specific
  - Data type: numerical, categorical, time series
  - Data volume: medium.

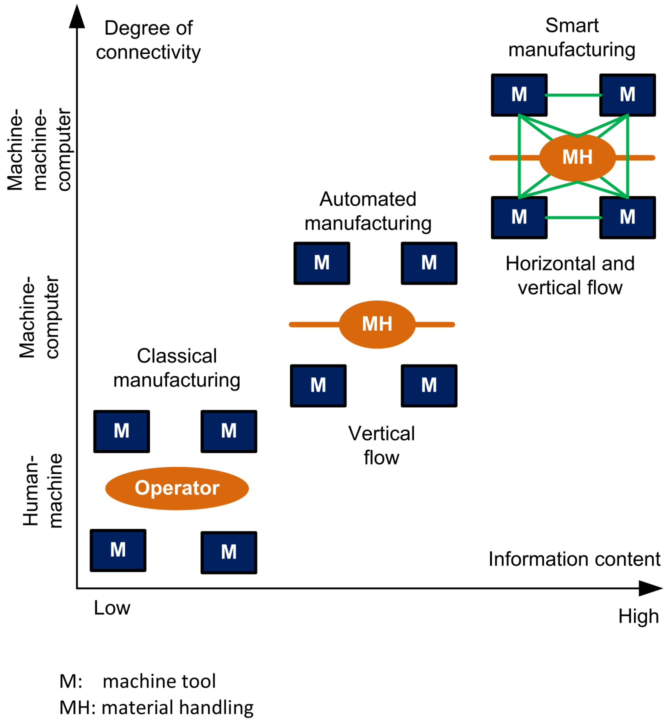

Fig. 2. Evolution of connectivity in manufacturing.

Irrespectively of the degree of implementation of the six technologies, manufacturing is adapting and evolving to meet the market and societal expectations. The characteristics of smart manufacturing such networking, connectivity, resource sharing, resiliency, and sustainability are discussed next. The latter two characteristics remain the focus.

The paper is organized in five sections. Section 1 discussed the digital aspect of manufacturing, including data sources, storage, and uses across applications. Section 2 overviews three characteristics of smart manufacturing, networking, connectivity, and resource sharing. These aspects of smart manufacturing have been covered in the literature. Resiliency and sustainability deserve research attention and they are discussed in Sections 3 and 4, respectively. Section 5 concludes the paper.

2. Networked, connected, and shared manufacturing

In the recent decades, manufacturing industry has become distributed with components and assemblies produced across different regions, countries, and continents. This trend has been largely driven by the search for low labor cost.

Information connectivity in manufacturing has evolved over years, from operators and paper instructions as the information carriers (see Fig. 2) to manufacturing equipment connected to computers (vertical connectivity) and networked equipment and computers (horizontal and vertical connectivity).

In addition to the increased data and information flow, separation between the physical manufacturing asset and systems using data is growing (see Fig. 3). An enterprise model where the physical assets are separated from the cyber assets is likely to emerge (Kusiak, 2018). This digital-physical separation allow sharing resources across different businesses, including the competing ones.

The data and information associated with the technologies of Fig. 1 gradually move to the cloud, thus enabling communication across globally distributed manufacturing assets. This in turn makes the concept of shared economy more practical to implement in manufacturing. The latter has been triggered by the fact that the

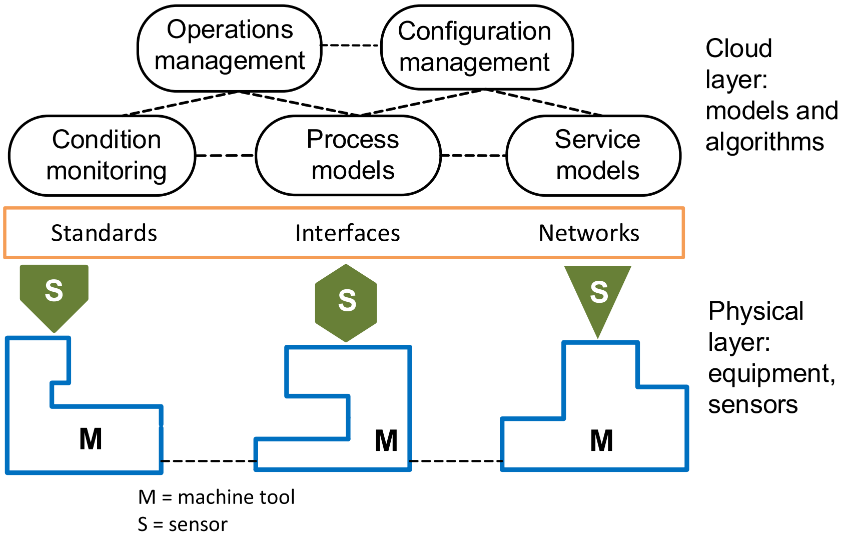

Fig. 3. Physical and cloud layers in smart manufacturing.

utilization of production equipment and other resources (e.g., software) varies across companies.

An enterprise of tomorrow is likely to experience: (1) shortened life-cycle of products; (2) variable demand for products over a short-time horizon. While the product and market horizons are becoming shorter, the life-time of manufacturing equipment is relatively stable. As manufacturing equipment becomes more automated and autonomous, its cost increases. Expanding manufacturing equipment functionality is also noted, e.g., equipment with integrated milling and 3D printing capability is available on the market. The latter trend makes maximization of machine utilization a priority. The cost of manufacturing software and services is also raising. A scenario where the demand for a product may increase *n*-fold in months' time is likely. Meeting such market conditions with a traditional model of manufacturing and service capacity expansion would not be possible. However, a rapid expansion of production capacity with the concept of shared and networked manufacturing resources is feasible. In fact, digital manufacturing facilitates a path towards shared manufacturing (Takahashi, Ogata, & Nonaka, 2017).

The growing need to configure and reconfigure physical and cloud assets to better support the changing product requirements and expanding digitization and standardization will lead to new architectures of manufacturing systems (Kusiak, 2018).

3. Resilient manufacturing

The new wave of automation is likely to impact the web of manufacturing networks. Products and companies could become more vulnerable to the disruptions in supply chains and functioning of physical and cloud assets. Assessment of the vulnerability of an enterprise to the unexpected disruptions in the supply chain and production is important, especially as the manufacturing is evolving. The history has provided sufficient evidence that a failure attributed to one manufacturing company may massively impact the worldwide industry (Sawik, 2018), e.g., the widely publicized earthquake in Taiwan in 2018 and prior years affected semiconductor factories worldwide. The source and severity of factors negatively affecting the industry vary from unintentional (e.g., natural disasters) to intentional (e.g., cyberattacks, trade disputes).

What is resiliency?

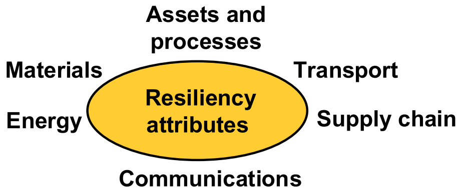

Fig. 4. Traditional manufacturing resiliency attributes.

Resiliency is the ability of a system (here a manufacturing system) to recover from an undesired state and to its desired state (Hollnagel, Woods, & Leveson, 2006; Sheffi, 2005).

Resiliency is gaining attention of the research and practice community in the face of uncertainty attributed to different origins. The resiliency of infrastructure, including buildings, transportation, energy, communication, and water/wastewater has been addressed in the report published by the National Institute of Standard and Technology quoted in Leon and Gao (2016). To recognize the importance of this area, the NIST Center for Risk-Based Community Resilience Planning (http://resilience.colostate.edu/) has been established with the goal of development of open source models for quantitative assessment of resiliency strategies. A holistic approach to resiliency, sustainability, efficiency in transport, land-use planning, energy, water, and waste management is discussed in Kim (2018). Hu, Li, and Holloway (2008) discussed resiliency in manufacturing. In the context of Industry 4.0, Schmitt, Permin, Kerkhoff, Plutz, and Böckmann (2017) defined attributes of resiliency of production systems in such as persistence, adaptability, agility, redundancy, learning capability, and decentralization.

3.1. Resiliency attributes discussed in the literature

Six resiliency attributes (see Fig. 4) that have been discussed in the literature in a broad industrial context are presented next.

√ Energy

Energy is the first level commodity in manufacturing. No meaningful manufacturing activity could take place without a reliable supply of energy, e.g., electricity, heat.

Zhang et al. (2017) identified domain requirements, challenges, and potential solutions in support of resilient outage control of nuclear power plants. The information acquisition and modeling challenges of achieving human-center automation for outage control was established. Resiliency principles in power systems and analysis of risks related to their operations are discussed in Tabatabaei, Ravadanegh, and Bizon (2019). The latter book assembled views and solutions on power systems resiliency provided by many experts. Sokolova and Popov (2019) offered a list of actions for enhancing resiliency of a power grid.

√ Materials

The mix of manufacturing materials is changing over time due to the diminishing availability of raw components (e.g., neodymium, platinum), shrinking mining sites, design of new materials such as powders for 3D printing with the properties needed, and development of organic materials (e.g., agave-based composites).

Gardner and Colwill (2016) offered a three-phase framework for resilient use of critical materials in manufacturing. It involves identification of a link in the supply chain where this material is used, determination of the risk level, and assessment of the severity of supply disruption. Gaustad, Krystofik, Bustamante, and Badamia (2018) presented the principles of circular economy to mitigate the shortage risk of critical materials. The vulnerability assessments across 16 recent criticality studies was summarized in Helbig, Wietschel, Thorenz, and Tuma (2016). He has listed 18 vulnerability indicators, including six indicators that were most frequently used.

√ Assets and processes

The manufacturing process dictionary is becoming more diverse and complex resulting from the developments in technology. There is also a need to maintain the legacy equipment as new technologies enter the market.

Komljenovic, Gaha, Abdul-Nour, Langheit, and Bourgeois (2016) offered a decision-making framework considering extreme risks and rare events in asset management. The framework was intended to support resiliency and robustness of organizations facing uncertainty of unknown origin and severity.

√ Transport

The transport of the future is emerging. Besides autonomy, it is likely that it will become more three-dimensional with air transport corridors established. Xu, Wang, Huang, and Chen (2018) presented a data-driven solution for resilient fleet management in flood-affected areas. Murray-Tuite (2006) defined ten characteristics of a resilient transportation system: redundancy, diversity, efficiency, strength, adaptability, collaboration, safety, mobility, autonomous components, and recovery ability. Attempts to quantify resilience of transportation systems were presented in Cox, Prager, and Rose (2011) and Serulle, Heaslip, Brady, Louisell, and Collura (2011).

√ Supply chain

Industries are not likely to progress along the same trajectory. Transitioning to new configurations and modes of supply chains needs to be addressed. Due to the exposure to natural disasters, some companies have improved the reliability of supply chains (Hamdi, Ghorbel, Masmoudi, & Dupont, 2018; Wakolbinger & Cruz, 2011), however, the internal and system-wide disruptions have not received sufficient attention (Liu, Shang, Lirn, Lai, & Venus Lun, 2018; Tsao, Linh, Lu, & Yu, 2018). Radhakrishnan, Harris, and Kamarthi (2018) provided a detailed overview of overview of supply chain resiliency. Components contributing to the resiliency of a supply chain such as flexibility, velocity, visibility, and collaboration were defined. Processes used to build resilient supply chains were outlined. Rajesh (2018) investigated evolution of resilient and sustainable supply chains. Aligning the sustainability and resilience objectives in a supply network was illustrated with case studies.

√ Communications

A modern manufacturing company could not sustain operations if the communication system would be affected by an unintentional or intentional (e.g., cybercrime) disruption.

One aspect of resiliency of data centers when the unpredictable workload would exceed capacity of service providers to handle this workload while maximizing the revenue was addressed by Al-Ayyoub, Al-Quraan, Jararweh, Benkhelifa, and Hariri (2018). A mixed-integer linear-programming model was developed that considered incidents affecting the user traffic and/or the data center service capacity. Fisher et al. (2018) presented benefits of cloud solutions in sustainable manufacturing, in food, pharmaceutical, and chemical industry. These benefits are derived from: collaborative design, automation, improved process resilience, and enhanced waste reduction, reuse and recovery.

Efforts to standardize methods to assess performance and characterize environmental aspects of manufacturing processes have been undertaken by NIST (ASTM 2016; Barnard Feeney, Frechette, & Srinivasan, 2017).

3.2. Extended resiliency attributes

Each of the attributes in Fig. 4 relates to manufacturing resiliency either directly or indirectly, and on a different time scale. Additional attributes potentially impacting manufacturing resiliency are presented next. A brief justification for inclusion of each attribute on the manufacturing resiliency list is provided.

√ Logistics

Cloud-like solutions may absorb large portions of the logistics functions and make them highly portable which makes them vulnerable to disruptions.

√ Efficiency

Efficiency of manufacturing and its supply chain (including energy efficiency) directly impacts productivity and sustainability. Eroding efficiency increases the risk of a business failure.

√ Productivity

To remain competitive, companies pay attention to productivity. Technology and the appropriate skill set drive productivity. Diminishing productivity lowers business resiliency.

√ Capacity

Manufacturing operations and its capacity are globally distributed. Shared manufacturing will increase complexity of capacity management. A resilient system needs to consider various configurations of manufacturing capacity.

√ Dependability

The dependability attribute has many dimensions, including trust as well as reliability, availability, and readiness of manufacturing equipment. The attributes of dependability appear in the overall discussion of resiliency.

√ Quality

Product quality may be affected by any change in a manufacturing stream, e.g., material, process, or machine operator, thus leading to resiliency concerns.

√ Compatibility

This is a key attribute of dependability that deserves its own study. It relates to the degree to which manufacturing capability can be seamlessly replicated. A higher compatibility degree supports resiliency.

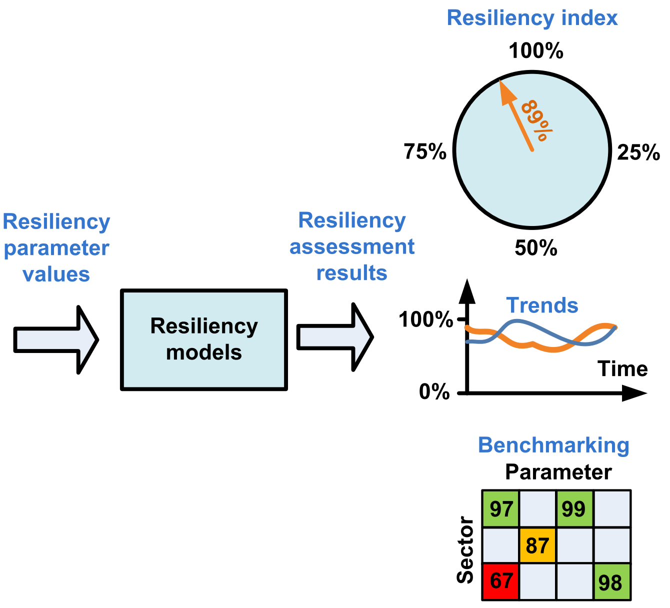

Fig. 5. A system for modeling, analysis, and assessment of manufacturing resiliency.

√ Societal values

Societal values are changing and so do the incentives motivating people to perform, from the shop floor to the executive suite. It is not likely that the incentives that have worked in the past, e.g., increased pay for an extra work, will be as effective in the future.

√ Workforce

The growing number and type of industrial tasks require the workforce to be more knowledgeable, flexible, and having the skills needed. The fact that workforce might be more distributed poses another resiliency challenge.

√ Sustainability

There is a potential of reducing manufacturing output or even shutting down company operations due to unsustainable practices. The decision factors could range from judicial and regulatory to the inability of a company to compete on the cost basis or due to shortage of materials.

Each resiliency attribute can be expressed in different forms, metrics, and variables. The form of expression depends on the nature of the attribute, availably of data (variable values), and the application needs. Research is needed to define the measurements for each attribute. The dependency among variables needs to be considered. This could be accomplished with a system analysis and assessment of manufacturing resiliency illustrated in Fig. 5.

The scope and implications of sustainability is much larger than any other attribute of sustainability and it makes an important characteristic of smart manufacturing.

4. Sustainable manufacturing

The manufacturing of the past has been largely linear involving transformation of raw materials into products to be largely discarded at the end of their useful life. This process of undesirable interaction with the environment has gradually intensified over the last century. Though combatting the green gas (CO_2) and actions surrounding it have been the focus of environmental protection for decades, other contaminates from the combusted fossil fuels such as mercury, sulfur oxides, and nitrogen oxides have rarely been mentioned.

The environment cannot tolerate the accumulation of waste contributed by the industry and commonly used products such as plastic bottles littering the earth and oceans. It is puzzling that in the 21st century a plastic bottle has not been replaced with a net-zero environmental impact material. Most products exhibit the fate of the plastic bottle, however, the fact they are produced in lower quantities does not translate into loud headline news. The reality is that sustainability practices have not been fully deployed across the design and manufacturing chains for most products. A paradigm shift is needed. The fact that the sustainability solutions exist, and new ones are emerging, a unique opportunity to transform the industry is within a reach.

The recent years have given some voice to the transformation of a linear economy into a circular economy (Geissdoerfer, Savaget, Bocken, & Hultink, 2017; Stahel, 2016) and a performance economy Stahel (2010). This voice has had a positive impact on sustainability, however, the environment damaging trend has not been reversed.

The distinguishing characteristics of the three models of economy (linear, circular, and performance) are shown in Table 1.

The performance economy scores best in the top nine characteristics listed in Table 1. The three bottom characteristics demonstrate a shift of the product ownership from a user to a manufacturer, the primary waste ownership to the manufacturer, and the innovation focus to the design of sustainable materials and components.

4.1. Strategies for attaining sustainability

Energy generation, transport, manufacturing processes, and discarded commercial and consumer products and packaging are the basic sources of environmental contamination (Coulter, 2010). Strategies are needed to reverse this trend.

Energy is a commodity without which today's economy, including manufacturing, could not function. At present, most electricity around the globe is generated from combustion of fossil fuels. Any effort designed to curb emissions, ranging from using more carbon friendly fuels (e.g., natural gas in place of coal) and improvements in combustion efficiency by installing filters capturing harmful particles at power plants and the introduction of carbon capture and storage technology is welcome.

At present, two industrially viable options for generation of clean electricity are available, wind energy and solar (photovoltaic and thermal). Progress has been made in the production of biofuels, with ethanol dominating the energy market.

Transport impacts sustainability through energy source and the material used to manufacture equipment and vehicles and energy to power them. Once these domains attain sustainability, the transport will become environmentally benign.

Manufacturing processes consume energy mostly in the form of electricity. Some processes such as aluminum or steel production are highly energy intensive, while discrete manufacturing (drilling or turning metal parts) have modest electricity needs. Progress has been made in reducing the negative environmental impact of oils and coolants used in manufacturing. Despite progress in energy consumption, processes such as plastic injection molding pollute environment in different ways. Research in production planning and scheduling to save energy by reducing idle processing time and more efficient processing has been published (e.g., Mansouri, Afshin Aktas, & Besikci, 2015, Raileanu et al., 2017, Wang, Wang, Yu, Ma, & Liu, 2018). Faulty or rejected items in manufacturing are also a factor in the environmental equation.

Besides a *simple product*, such a cloth hanger, it is difficult to think of higher complexity products that have been designed for reuse or remanufacturing. The *remanufacturing* market is growing, with companies such as Caterpillar, John Deere, and Fuji deeply

Table 1
Characteristics of three models of economy.

Characteristic	Linear economy	Circular economy	Performance economy
Natural resource consumption	High	Lower	Lowest
Waste generation	High	Lower	Lowest
Greenhouse emissions	High	Lower	Lowest
Energy consumption	High	Lower	Lowest
Research focus	High	Lower	Lowest
Business activity focus	High	Lower	Lowest
Job creation potential	Low	Higher	Highest
Value preserving focus	Low	Higher	Highest
Shared economy potential	Low	Higher	Highest
Product ownership	User	User	Manufacturer
Waste ownership	User	User/manufacturer	Manufacturer/user
Primary innovation driver	Market	Market/product design	Material/component design

engaged in refurbishing components and assemblies for resale. It appears that most remanufacturing is due to the nature of the items being refurbished (e.g., electric motors or metal shafts lasting longer than other components of the same product such as a washing machine), rather than intentional design of products for remanufacturing.

4.2. How to accelerate progress in sustainability?

The developments in sustainability are pursued by academia and industry, however, the information about the success cases is usually scattered and its publicity coverage could be uneven. It is difficult to assess significance, development stage of the new discoveries.

Presenting the information about the environmental efforts in a user-friendly way could have a great impact on the adoption rate and innovation of sustainability solutions. Some aggregation, systemization, and presentation of the information about the new developments is long overdue. Data science tools could be deployed for extraction of meaningful findings and visualization of information. It could be accomplished with labeling materials for environmental content and recognizing environmental recovery activity as value-adding.

4.2.1. Labels of environmental friendliness

For the existing materials, products, and processes, labels of environmental friendliness (similar to the nutrition labels used for food items in counties like the U.S.) are needed. Some initial efforts have taken place, e.g., the labeling of energy efficient products deployed in the U.S. Such a label should be transparent and thus it would include all details (e.g., equations) behind the displayed values to allow for their adoption to the specific region or application. It is obvious that the information would be structured with different technical details available for the consumers and experts. Energy efficiency of processes such as molding vs 3D printing or machining steel vs an alloy is not easily available. This makes the deployment of energy aware practices in industry difficult.

4.2.2. Environmental manufacturing activity

Recognize the bringing-back clean soil, water, and air as a value-adding activity (Kusiak, 2018a). This would lead to the formation of enterprises functioning the same way as traditional businesses. Such companies would deliver value in a form different from the traditional goods or services, e.g., a surcharge for certified clean environmental conditions. The profile of environmental enterprises could mimic companies in mining (e.g., recovery of materials from the landfills), remanufacturing (recovery of usable components from the products that have become unusable), and manufacturing/processing (e.g., cleaning the environment).

The industrial development activities of the past have focused around the surface of the earth with a negative impact on the soil, water, and air quality (see Fig. 6). The emphasis on bringing back the environment could be a source of future employment (Kusiak, 2018a) as effort is needed.

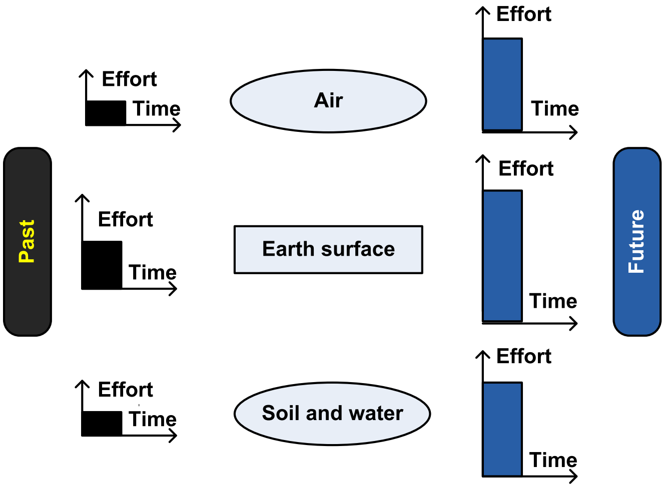

Fig. 6. Focusing on the environmental wellness.

There is a reason for optimism for the environment restoring activities. The developments in artificial intelligence and automation are beginning to profoundly impact manufacturing and services. In fact, the new phase of manufacturing anticipates developments under different banners, such as smart manufacturing or the fourth-industrial revolution (Industry 4.0). Service industry (e.g., banks, hospitals) is bound to undergo a similar transformation. The labor statistics provided by various sources, e.g., the U.S. Department of Commerce, anticipate decreased demand for factory workers.

The benefits of the proposed environmental enterprise model would likely exceed those of the universal payment system that is studied in some countries (e.g., Finland, Norway, and the U.S.).

5. Conclusion

Six characteristics of smart manufacturing have been considered. Two of them, resiliency and sustainability remained the focus. A data-centric view of smart manufacturing was presented. Data sources, storage, usage, and characteristics were provided. Different generations of manufacturing systems were summarized in a two-dimensional graphics with the focus on the evolution in data and communication intensity. Attributes defining manufacturing resiliency were discussed. Application of the proposed business approach to sustainability could offer societal benefits, including employment of the automation-affected workforce. The proposed material labeling scheme of environmental friendliness could become one of the activities on the smart manufacturing development map. Evidence is needed to convince the industry that resiliency and sustainability are worthy business consideration. Streams of data and information, likely intertwined among the six manufacturing characteristics, could be the best sources of generating such evidence and prioritizing developments in the two domains.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.arcontrol.2019.02.001.

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