Design Engineering in the Age of Industry 4.0

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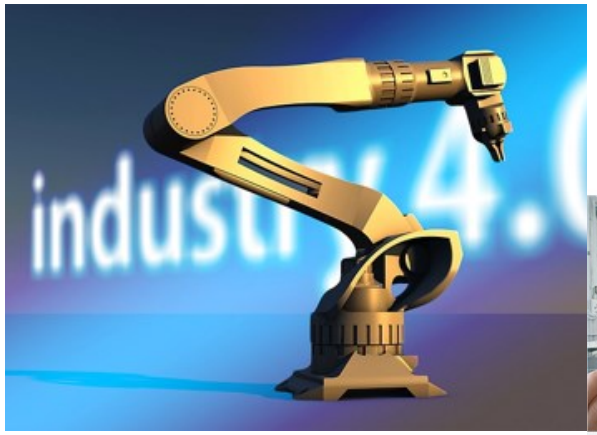

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Design Engineering 4.0

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Design Engineering in the Age of Industry 4.0

Industry 4.0 is based on the digitization of manufacturing industries and has raised the prospect for substantial improvements in productivity, quality, and customer satisfaction. This digital transformation not only affects the way products are manufactured but also creates new opportunities for the design of products, processes, services, and systems. Unlike traditional design practices based on system-centric concepts, design for these new opportunities requires a holistic view of the human (stakeholder), artefact (product), and process (realization) dimensions of the design problem. In this paper we envision a "human-cyber-physical view of the systems realization ecosystem," termed "Design Engineering 4.0 (DE4.0)," to reconceptualize how cyber and physical technologies can be seamlessly integrated to identify and fulfil customer needs and garner the benefits of Industry 4.0. In this paper, we review the evolution of Engineering Design in response to advances in several strategic areas including smart and connected products, end-to-end digital integration, customization and personalization, data-driven design, digital twins and intelligent design automation, extended supply chains and agile collaboration networks, open innovation, co-creation and crowdsourcing, product servitization and anything-as-a-service, and platformization for the sharing economy. We postulate that DE 4.0 will account for drivers such as Internet of Things, Internet of People, Internet of Services, and Internet of Commerce to deliver on the promise of Industry 4.0 effectively and efficiently. Further, we identify key issues to be addressed in DE 4.0 and engage the design research community on the challenges that the future holds. [DOI: 10.1115/1.4051041]

Keywords: Industry 4.0, industrial IoT, human-cyber-physical systems, smart manufacturing, operations and services, smart and connected products, design engineering 4.0, design automation, design for manufacturing, design integration, design methodology

1 Frame of Reference[2]

Integration of smart sensors and networked manufacturing systems has given rise to human-cyber-physical manufacturing systems that can address the requirements of individual customers on a global scale [1–8]. The ability to bring together technologies such as Internet of Things (IoT), Big Data Analysis, Machine Intelligence with traditional technologies such as Smart Automation, Supply Chain, Logistics, and Cloud Computing has resulted in a new wave of advances in manufacturing technologies for product realization [9], which are collectively envisioned as Industry 4.0 [10]. Factories conforming to Industry 4.0 will integrate services across the entire manufacturing and operations processes and will be able to adapt to disruptions in real-time, thereby improving the quality of products and services [11]. The vertical integration of IoT and data analytics will enable these factories to optimize supply and logistic networks, implement policies based on predictive instead of reactive behaviors, improve end-to-end throughputs, and provide services and products at a lower cost [12].

Industry 4.0 represents the Fourth Industrial Revolution and provides a framework to address the challenges arising in the integration of cyber systems and physical resources and covers all aspects of manufacturing systems [13], including robust and flexible automation; data collection, analysis, learning and decision-making; distributed production systems; industrial IoT; and supply chain integration. Industry 4.0 is characterized by a digital model of end-to-end supply chain enabled by smart manufacturing processes, and thus provides a mechanism to transfer autonomy from the physical realm to the cyber-physical realm. Cyber representation of physical processes is much more involved than just networking the associated components of the manufacturing system and involves human interaction with the automation, leading to a human-cyber-physical system [14]. Systems realization in the age of Industry 4.0 requires a new paradigm that considers the distributed and networked aspect of the manufacturing processes [15]. The design process must be able to satisfy the structural

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[2]Definitions of the terms used are in the Appendix–Glossary.
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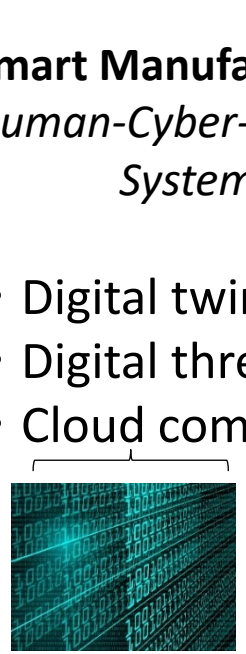
Industry 4.0

Industry 4.0:
The comprehensive transformation of the whole sphere of industrial production through the merging of digital technology and the Internet with conventional industry.*

Smart Manufacturing:
Human-Cyber-Physical System

- Digital twin
- Digital thread
- Cloud computing



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Key Principles:

- Connectivity, Virtualization and Interoperability
- Big Data and Information Transparency
- Decentralization, Modularity and Interactivity
- Service Orientation and Networked Resources

*https://www.bundesregierung.de/Content/EN/Reden/2014/2014-02-19-oecd-merkel-paris_en

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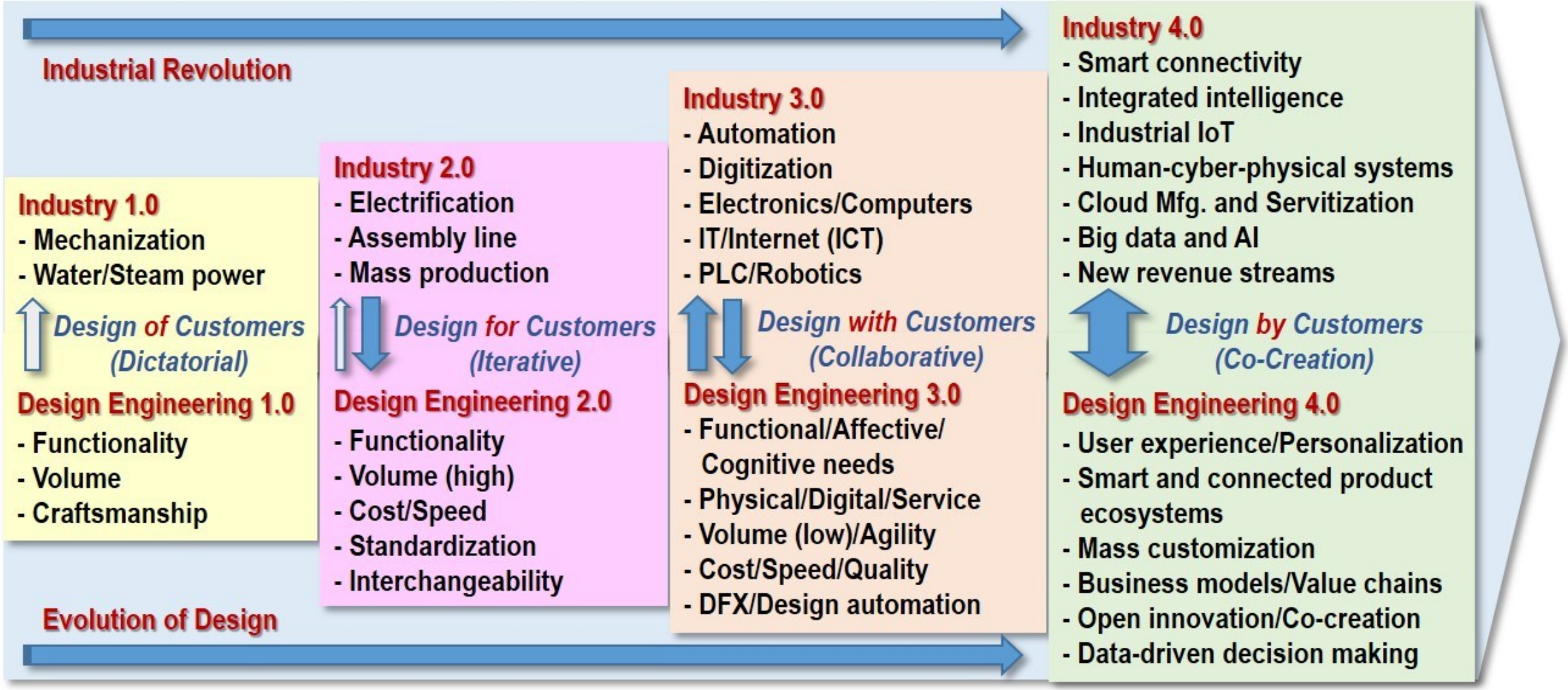
The Co-Evolution of Industry and Design Engineering



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Design Engineering 4.0

Design Engineering 4.0 represents the **human-cyber-physical view of the systems realization ecosystem** that is necessary to accommodate the drivers of Industry 4.0 (IoX).

- *Design considering user preferences, and how users interact with products and among themselves (Internet of People)*
- *How businesses can monetize services (Internet of Commerce)*
- *How to customize products and services to user requirements while producing products of "zero lot size" and "mass production costs" (Internet of Services)*
- *How to design systems that can collaborate and adapt to improve product quality, process reliability, system agility, and sustainability of the systems realization ecosystem (Internet of things).*

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Strategic Areas/Themes of Design Engineering 4.0

Connectivity, Virtualization and Interoperability

1. Smart and Connected Products
2. End-to-End Digital Integration
3. Customization and Personalization

Big Data and Information Transparency

4. Data-Driven Design

Decentralization, Modularity and Interactivity

5. Digital Twins and Intelligent Design Automation
6. Extended Supply Chains and Agile Collaboration Networks
7. Open Innovation, Co-Creation and Crowdsourcing

Service Orientation & Networked Resources

8. Product Servitization and Anything as a Service (XaaS)
9. Platformization for the Sharing Economy

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1. Smart and Connected Products – Research Questions

- How can the design process of smart products be directly influenced and improved through near-real-time analysis of vast amounts of user data automatically collated from prototypes and/released products being used in diverse ecosystems of other interconnected smart systems?

- To what extent will computers be able to autonomously shape design aspects of smart and interconnected products or conceive new innovative features based on user data analytics (autonomous or semi-autonomous data-driven design and innovation)?

- How can customer privacy and the ethical usage of data from interconnected smart devices be designed into smart products and the corresponding legal framework, including the GDPR and new policies governing the usage of smart and interconnected products across countries?

- …

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6. Extended Supply Chains and Agile Collaboration Networks – Research Questions

- What are DE4.0 principles and methods to be applied to ensure fail-safe performance of the entire virtual value chain for product realization, which includes product design, production planning, and the supply chain?
- How can the rapidly changing demand forecasts be used to dynamically adapt the value chain?
- How can the effects of disruptions in any part of the supply network be rapidly mitigated through rapid and holistic redesign of the product, the manufacturing process, and/or realignment of the supply chain?
- …

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Design Engineering 4.0 – Research Opportunities

- The Human Perspective – Design for Human Experience
  - User Experience Design towards Product Ecosystems
  - Cloud-based Computer Supported Collaborative Work
  - Social Product Development

- The Business Perspective – Design as Strategic Engineering
  - Smart Innovation and Business Value Chain Design
  - Collaborative Crowdsourcing of Product Fulfillment
  - Open Architecture Product and Service Platform Design

- The System Perspective – Design of Human-Cyber-Physical Systems
  - Human-centered cyber-physical system design
  - Design of networked manufacturing systems
  - Design of cyber-physical production systems design for smart and connected supply chains

- The Cybernetics Perspective – Design with Smart Sensing and AI Technologies
  - Machine learning and AI for data-informed design
  - Dynamic risk management of a cyber-physical socio-technical system
  - Verification and validation

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Drivers and Challenges of Design Engineering 4.0: *Internet of Services*

Drivers: Rapidly changing technologies, customer requirements and preferences, and unpredictable and hard-to-manage disruptions. Customize products to user requirements while producing products of ‘zero lot size’ and ‘mass production costs.

Challenges:

- ❑ How to design products and systems that are resilient, sustainable, and can adapt to changing conditions, especially when the change cannot be anticipated at design time?
- ❑ How to develop standards for interfacing and using physical entities and their digital twins across the entire ecosystem from design to product realization?
- ❑ Can digital twins of design variants considered during the parameter selection and optimization phase of the design be used to rapidly respond to disruptions that affect the production process?

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Drivers and Challenges of Design Engineering 4.0: *Internet of People*

The distinction between the 'physical' and 'digital' selves of individuals will get blurred as Industry 4.0 technologies become prevalent. Individuals will play a dual role as co-creators *and* consumers of technology. Changing user preferences and how users interact with the products and between themselves will be the main drivers of Design Engineering 4.0. The challenges to be addressed are

- ❑ *How to foster an "Innovation Ecosystem" where consumers and design engineers play a creative role in shaping the systems of the future?*

- ❑ *How to develop and maintain a workforce that stays in tune with changing technological landscape?*

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Drivers and Challenges of Design Engineering 4.0: *Internet of Things*

- Networked systems and the prevalence of IoTs will make data easily accessible throughout the product lifecycle. The need to design systems that can collaborate and adapt to improve product quality, process reliability, system agility, and sustainability of the systems realization ecosystem will be the main drivers of Design Engineering 4.0. The challenges to be addressed are:
- *Information extracted from diverse data streams in real-time will aid decision-making. However, Data mining techniques applied to Big Data are based on the premise that information is encapsulated in the data in some form. Since initial design iterations are based on actual data, is it possible to design systems when partial or no data exists?*
- *Can one always build consensus when data streams do not indicate any reliable information or contain conflicting information?*
- *Can 'Synthetic Data' be created using the digital twins of the processes and used in the early design process?*

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Drivers and Challenges of Design Engineering 4.0: *Internet of Commerce*

System design and productization are driven to a large extent by the necessity to make a profit. The challenges to be addressed are:

- *How can design anticipate the many ways in which the product can be monetized?*

- *As a result of networked systems and ubiquitous design and data sharing, cyber threats are no longer restricted to loss of privacy or the financial domain. One of the most urgent challenges is how designers can inoculate systems against threats when the nature of the interaction between system components is unclear at design time?*

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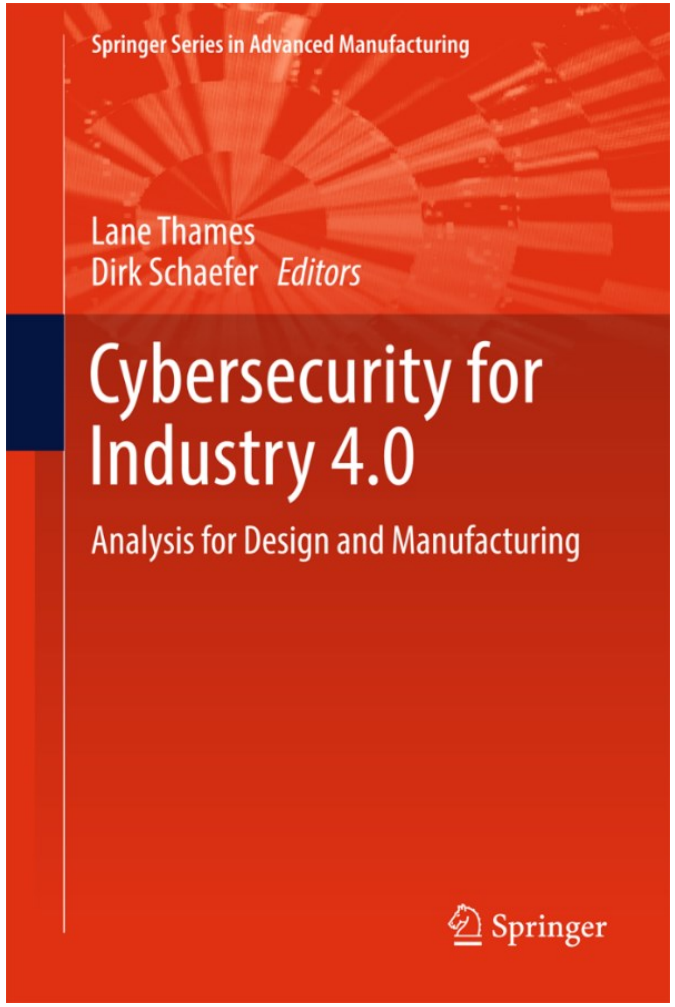
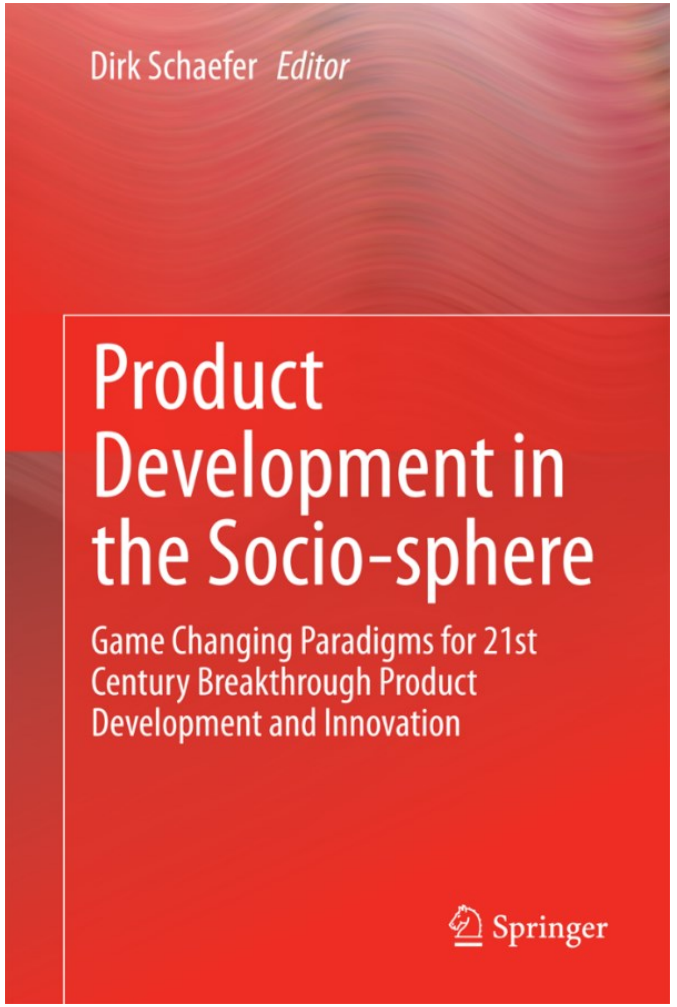
Further Reading





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Thank you!

Research Collaboration

DO YOU HAVE A STRATEGIC KNOWLEDGE GAP?

DO YOU WANT TO DEVELOP A CULTURE AND CAPACITY FOR ON-GOING INNOVATION?

DO YOU WANT YOUR BUSINESS TO GROW?

KNOWLEDGE TRANSFER PARTNERSHIPS (KTP)

IMPACT AND BUSINESS DEVELOPMENT

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