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ORIGINAL PAPER

HYPOTHESES CONCERNING COMPLEXITY SURGES IN MODERN AND FUTURE INDUSTRIAL INFORMATION SYSTEMS

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ABSTRACT. **Background:** This paper has the central aim to provide an analysis of increases of system complexity in the context of modern industrial information systems. An investigation and exploration of relevant theoretical frameworks is conducted and accumulates in the proposition of a set of hypotheses as an explanatory approach for a possible definition of system complexity based on information growth in industrial information systems. Several interconnected sources of technological information are investigated and explored in the given context in their functionality as information transferring agents, and their practical relevance is underlined by the application of the concepts of Big Data and cyber-physical, cyber-human and cyber-physical-cyber-human systems.
Methods: A systematic review of relevant literature was conducted for this paper and in total 85 sources matching the scope of this article, in the form of academic journals and academic books of the mentioned academic fields, published between 2012 and 2019, were selected, individually read and reviewed by the authors and reduced by careful author selection to 17 key sources which served as the basis for theory synthesis.
Results: Four hypotheses (H1-H4) concerning exponential surges of system complexity in industrial information systems are introduced. Furthermore, first foundational ideas for a possible approach to potentially describe, model and simulate complex industrial information systems based on network, agent-based approaches and the concept of Shannon entropy are introduced.
Conclusion: Based on the introduced hypotheses it can be theoretically indicated that the amount information aggregated and transferred in a system can serve as an indicator for the development of system complexity and as a possible explanatory concept for the exponential surges of system complexity in industrial information systems.

Key words: complexity, complex systems, industrial systems, information, cyber-physical systems, Big Data.

INTRODUCTION

Today, it is possible to identify the increasingly strong impact of accelerating technological developments and its changes. The rising potency of technology in areas like general computer processing power, sensors, Artificial Intelligence AI, machine learning, robotics and automation technology often breaks through the limits of the anticipated growth rates and manifests in modern interconnected approaches for value creation, for example smart manufacturing, the internet of things or cyber-physical systems [McAfee, Brynjolfsson, 2014; Törngren, Sellgren, 2018].

Underlying drivers for the possible exponential development of technology are the often mentioned "Moore´s Law" which shows that the number of transistors per microchip increased by the power of 10 in the last 40 years , "Metcalf´s Law" can also be mentioned which states that computing hardware becomes more powerful, small and more embedded over time and the vastly increased and ever increasing speed of technology adoption by users, as well as "Butter´s Law of photonics", which says the amount of data one can transmit using optical fiber is doubling every nine months, "Rose´s Law", which states that the number of qubits in quantum computers is growing exponentially and the concept of "Big

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Data" referring to the exponential growth of information generated by modern systems [Gimpel, Röglinger, 2015]. The potentially exponential nature of technological and informational growth is often primarily ascribed but not limited only to information technologies and it is possible to identify a wide variety of converging technological fields where exponential growth can be observed [Nagy et.al, 2012]. These developments underline the potential of exponential technological and informational growth as an autocatalytic process to cause significant technological paradigm shifts which often lead to severe changes in systems impacted and supposedly governed by human behaviour, often by making systems more interconnected, non-linear and as a result more complex for the linearly thinking human mind to comprehend and to predict and therefore at the same time cause and effect for its central characteristic of increasing system complexity [McAfee, Brynjolfsson, 2014, Gimpel, Röglinger, 2015, Törngren, Sellgren, 2018, Spencer, 2017]. The increasing complexity of human socio-technical systems in relation to exponential digital technologies can be regarded as a crucial impact factor for human society. It is defined by many researchers as the most essential characteristic of modern society since technological and economic advances ultimately lead to an increasingly interconnected and complex system of systems. [Mourtzis et.al, 2019, Duan et. al, 2019, Freund, Al-Majeed, 2020]. The idea of the central importance of increasingly technologized and complex systems is supported by the thoughts of many researchers who regard obtaining an understanding of complex systems as essential for handling the design and transformation process of modern complex engineered systems of organizational value creation [Törngren, Sellgren, 2018]. Consequently, obtaining an in-depth understanding of the nature of possible surges in system complexity and their possible connection to an exponentially progressing development of technology and information can therefore be regarded as an important aspect to understand the transformative impact of these developments on the value added for human society in general and for individual systems in the sphere of engineering and system design in particular. [Horvath, Geritsen, 2012, Freund, Al-Majeed, 2020]. This paper has the central aim to provide a first theoretical considerations through the introduction of a set of hypotheses concerning the interconnected nature of information growth and complexity as the origin of increases of system complexity. This is achieved through reviewing and analysing current relevant literature in relevant research fields in a first step. In a second step the findings are applied to networks of sources of technological information in the context of modern systems of industrial information technologies, like cyber-physical, cyber-human and cyber-physical-cyber-human systems. This is achieved by establishing a set of assumptions and definitory notations concerning the nature of technology and the influence of technological growth on the complexity of a given system in the sections to follow. This allows the construction of a logically consistent and coherent argument that proposes that technology and information can be regarded as indicator for system complexity as a conclusion to this article.

METHOD

The definitions and concepts presented in this study are largely based on secondary sources and research, meaning a systematic foundational review of relevant literature. Information on the core research complexes "information", "complexity" and "systems" is mostly available in (academic) books, professional journals, academic journals, reports or internet sources, mainly published in the research fields of philosophy, information technology, physics, engineering and business studies, as demonstrated by the following sections of this chapter. This paper quotes a wide range of sources in the form of basic theoretical considerations, expressed though the introduction and discussion of relevant definitions to allow a coherent pursuit of the previously mentioned aim of research through summarizing and synthesizing previous sources to develop a set of hypotheses out which directions for new future research may be derived. In total 85 sources matching the scope of this article, in the form of academic journals and academic books of the mentioned academic fields, published between 2012 and

2020, were selected, individually read and reviewed by the authors and reduced by careful author selection to 17 key sources which are contributing to the theoretical foundation to this article.

A DEFINITION OF INFORMATION

To avoid potential misunderstanding it is now necessary to provide the definitions for the terms of "information", "data" , "agent", "environment of an agent" and the "relationship of data and information".

It is necessary to state that the term "Information" is itself to be regarded as a polymorphic phenomenon and a poly-semantic concept with many possible meanings. The term "information" is now defined for this paper according to the notions established by Meijer under the assumption that information is generated through the interactions of a set of communicating agents. The term information shall therefore be defined as "(…) *anything that an agent can sense, detect, observe, perceive, infer or anticipate*" [Meijer, 2013]. An agent shall be defined according to Meijer as:

"(…) *a description of an entity that acts on its environment. Note that agents and their environments are also information, as the can be perceived by other agents. An agent can be an electron, an atom, a molecule, a cell, a human, a computer program, a market, an institution, a society, a city, a country or a planet. Each of these can be described as acting on their environment, simply because they interact with it*" [Meijer, 2013].

The idea of the environment of an agent is again defined according to Meijer as the following statement. "*The environment of an agent consists of all the information interacting with it*" [Meijer, 2013]. The environment of an agent shall from this point onwards be regarded as a synonym of the term "system". The term "data" is now described as the basic individual items of information, obtained and conserved through observation and data storage but devoid of an attributed context. There are many kinds of data existing, like sensory data, geographical data or network data [Duan et.al, 2019]. As a logical consequence of the presented definitions of the term data and information the relationship of data and information can be described as the following concept: Data + *storing / recovering by an agent / set of agents in a given environment→ Information.* Consequently, any form of stored and recoverable data through the means of an agent in a system shall be regarded as information. This results in the core assumption that if data is stored and recoverable in any given form it shall be regarded as information. It can now be concluded that data and information represent the building blocks for any technology. The relationship of data, information and technology can be defined on the basis for Hypothesis 1 (H1).

Agent based information and data hypothesis

(H1) The amount of information in a system is represented by the amount of data stored and recoverable by agents contained in the system.

The next chapter now provides further information on how information could be generated via the introduction of different sources of information.

TECHNOLOGICAL SOURCES OF INFORMATION

To further expand on the notions of H1, it is possible to classify the following agents and agent combinations as major sources of information under the assumptions of a modern, interconnected technological environment or system [Based on: Duan et.al, 2019, Gimpel, Röglinger, 2015]. The following sources of information in the form of agents are hypothesized for this paper:

- Machine generator (M): Autonomously generated by machine activity through sensors and instruments, for example the amount of information generated and stored by a smart factory or an artificial intelligence.
- Machine-machine generator constellation (MC): The combination of autonomously

generated by machine activity through sensors and instruments that processed by another machine, for example the amount of information generated and stored by a smart factory that is again processed by an artificial intelligence.

- Human generator (H): Generated by human activities, for example a poem memorized by the human brain that generated the poem.
- Human-human generator constellation (HC): Generated by human activities, for example a poem memorized by the human brain that generated the poem and that is also memorized by the other human brains.
- Human-machine generator (HM): The combination of human activity and autonomous machine activity, for example uploading a photo of the poem to the internet with an app on a smartphone device.
- Human-machine generator constellation (HMC): The alternating process of generating and processing information by humans and machines in a tandem, for example uploading a photo of the mentioned poem to the internet with a smartphone device which gets processed by an algorithm to generate advertisements for an app on the smartphone of the user who uploaded the photo, which stimulates the user to buy and download the app.

The described sources of information are indicating that different types of agents represent collections of basic functions which can be placed in an interconnected relation in the form of a heterogenous network system where their position and inherent internal functioning leads to different flows information being created and stored in the system. Any of such systems shall be named industrial information system. Based on (1)-(6) and H1, Hypothesis 2 (H2) results.

Agent based information flow hypothesis

(H2) Any type of information flow in a given industrial information system can be explained by a given combination of sources of information positioned in a network constellation in the form of agents.

A system is now defined as the concept of portioning an operating entity into a set of interacting units with specific relationship among them. A system therefore represents not only physical objects but also immaterial concepts like information and can maintain both system external and system internal interactions [Jalil & Perc, 2017, Mourtzis et.al, 2019]. Consequently, for this paper a system is regarded as an open system. Based on this statement a system is defined as a network of a given number of agents which are characterized by the ability to interact with each other and the system external world by transferring, storing and circulating information in the network topology and which are assumed to be representable by the mentioned sources of information (1)-(6) as expressed in H1 and H2. A network therefore comprises a system of at least two elements that are connected and that exchange information between them and the system external world. One example for such a network could be any kind of machine-machine generator feedback loop. Figure 1 illustrates the core assumptions made in H1 and H2 through the establishment of a hypothetical network system in which three machine-generator agents circulate information in a MC constellation.

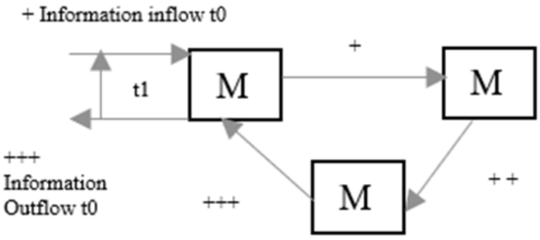

Fig. 1. MC constellation network

Figure 1 shows, that any type of network consisting of technology sensitive agents is expected to lead to a cascadic growth of circulated information if a non-distorted feedback loop is in place. H1 is now accumulating in the practical context in the concepts of cyber-physical systems (CPS), cyber-human systems (CHS) and cyber-physical-cyber-human systems (CPCHS). These concepts are briefly described in the next section to underline the practical relevance of the systemic combination of the sources (1) to (6).

SOURCES OF INFORMATION IN THE CONTEXT OF INDUSTRIAL INFORMATION SYSTEMS

The concept of cyber-physical systems (CPS), cyber-human systems (CHS) are representative concepts of the many upcoming and innovative practical manifestations of different networks topologies with different agent combinations in the context of industrial information systems. A CPS can be described as a new generation of systems that blend the knowledge of physical artifacts and engineered systems due to integrated computational and physical capabilities. CPS are established in order to produce a global intelligent behavior featuring autonomy, self-control and self-optimization and are expected to be a decisive driving force for advances in different applicative domains including manufacturing control and for opening up new areas of innovation [Horvarth, Gerritsen, 2012, Gaham et. al, 2013, Törngren, Sellgren, 2018, Mourtzis et.al, 2019]. A CHS can be defined as the concept that humans have an increasingly interconnected relationship with computer systems and represents an integral factor to establish a functioning CPS. This development is exemplified in the increasing human-machine interaction through new computer systems, the internet, mobile devices, improved sensor technology and possible future applications like brain-machine interfaces and leads to human lives and decision-making increasingly merging with technology [Gimpel, Röglinger, 2015, Freund, Al-Majeed, 2020]. CPS and CHS are expected to continuously co-evolve and converge to human-in-the-loop cyber-physical systems or cyber-physical-cyber-human systems (CPCHS) as they are directly linked to each other [Garcia et.al, 2019]. The provided definitions also make it evident, that a CPS/ CHS/ CPCHS represents a specific network topology with an agent combination of the mentioned sources (1)-(6) that manifests in a practical context of complex economic value creation, for example intelligent manufacturing infrastructure, and therefore shows that the merging of the physical and virtual is already a reality that comes to life. Figure 2 now illustrates the basic layout of a completely integrated cyber-physical-cyber-human system.

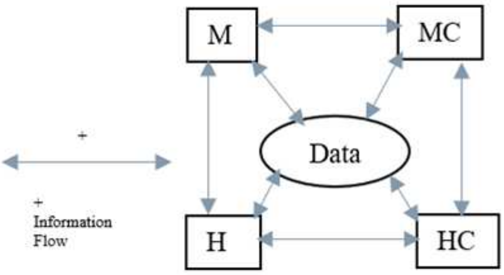

Fig. 2. Basic Layout CPCHS

Figure 2 shows that a CPCHS can be described as a network of human, machine / physical object (M, MC, H, HC) and data interaction enabled through a rich multi-directional information flow in a network topoplogy [Garcia et.al, 2019]. As a result, the illustrated structure of a CPCHS is characterized by the characteristics of complexity, volatility, uncertainty and ambiguity as it is characterized by highly interconnected constellation of agent types [Gimpel & Röglinger, 2015, Mourtzis et. al., 2019]. This concept can now be applied to the basic structure of Figure 1 and the proposed information sources (1)-(6). Figure 3 now provides an example CPCHS model.

Figure 3 shows, that any type of CPCHS can be expected to lead to a cascadic growth of circulated information if an undistorted feedback loop is in place [Jalil & Perc, 2017]. This now allows the introduction of hypothesis 3(H3).

Cascadic growth of information in industrial information systems hypothesis

(H3) Any type of information flow in a given industrial information system in the form of CPS, CHS or CPCHS can be expected to generate cascadic growth of circulated information if an undistorted feedback loop is in place.

After presenting hypothesis H3 it appears now necessary to provide further information on the concept of exponential increases in generated information through introducing and applying the concept of "Big Data" to the notions of H1-H3.

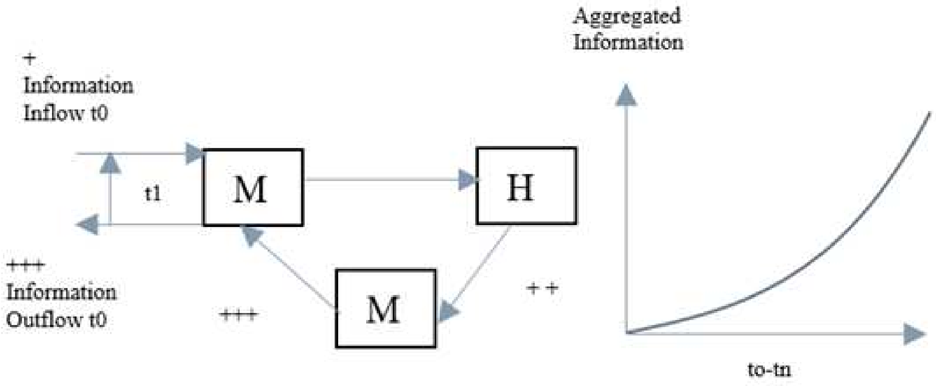

Fig. 3. CPCHS Example

THE CONCEPT OF "BIG DATA" APPLIED TO COMPLEXITY THROUGH SHANNON ENTROPY

Due to the already in the context of CPCHS introduced characteristics of velocity, volume and variety, big data is also defined as a "complex polymorphic object" in the ranges of exabytes and beyond which represent accumulations of extensive datasets which are highly complex and hard to process [Riahi, 2018]. Since CPCHS share these characteristics with the concept of "Big Data" H2 and H3 are supported by the notion of a CPCHS also an entity characterised by the concept of a "complex polymorphic object". The concept of "Big Data" is underlined by the amount of data of 175 zetabytes that is projected to be generated world-wide in the next years up until 2025, which represents a rapid increase to the amount of 2 zetabytes generated in 2010 and the amount of 26 zetabytes generated in 2017, which represents an assumed 87.5 fold increase in 15 years (2010-2025) [Statista, 2018]. These numbers also underline the steady increases in mass data storage capacities of modern information systems (for example the increases in hard disk storage capacity from a few megabyte to several terabyte in the last two decades through the convergence of continuously improving physical and mass storage systems into cloud data systems [Gimpel, Röglinger, 2015]. Based on this it is now possible to explore how these developments concerning the capability of modern systems to aggregate information can be linked to the notion of complexity.

COMPLEXITY AS INFORMATION

It is possible to introduce the idea of a common dominator of complexity by linking the notion of complexity with notion of system entropy. The entropy of a system is in this context regarded as a measure of disorder in the system. Additionally, the concept of energy entropy can directly be linked to the concept of Shannon Entropy, which measures the information content of a message [Li, 2016, Mourtzis et. al, 2019]. This shows that complexity, when brought into the context of industrial information systems, appears to have a common metric for complexity in the form of energy translated to information under the conception of Shannon Entropy. The notion of complexity as information contained in a system is also supported by variety of researchers in the field [Terrazas et.al, 2015, Törngren, Sellgren, 2018]. The entropy of a system of messages is defined by Shannon as described in equation (1).

$$(1) \qquad H(P) = -\sum_{i \in A} pi \; log2 \; pi$$

In this formula pi is the probability of message i in A, which can be identified exactly as the formula for Gibb's entropy in physics. The use of base-2 logarithms ensures that the code length is measured in bits (binary digits).

It can now be seen that the communication entropy of a system is maximal, and the predictability is minimal when all the messages have equal probability and thus are typical [Li, 2016]. Consequently, Shannon Entropy can be regarded a measure of the information content of data, where information content refers to what the underlying data could contain, as opposed to the more intuitive notion of what it does contain. Therefore, Shannon Entropy is essentially about quantifying predictability or conversely randomness in information [Mourtzis et. al, 2019].

INFORMATION AS A METRIC FOR COMPLEXITY

The degree of complexity of system shall now be determined through Shannon Entropy and therefore by the aggregated amount of information contained in the system with an increase of system complexity resulting from any increase in the amount of information transferred and aggregated in the system and vice versa [Terrazas et.al, 2015]. The already introduced concept of Shannon Entropy can serve as an explanatory approach to why the amount information contained in a system can serve as a metric for complexity. The concept of Shannon Entropy can additionally be linked to the context of complex systems through principle of maximum entropy which states that that complex systems tend to maximize entropy production under their present constraints while evolving over time [Hanel et. al, 2014, Jalil & Perc, 2017].

Hypothesis 4 (H4) now results.

Complexity of industrial information systems hypothesis.

(H4) The complexity of an industrial information system is defined by the amount of information contained and produced in the system with more information leading to more complexity and vice versa.

Figure 4 now summarizes the assumptions made in H1-H4. Figure 4 now summarizes the assumptions made in H1-H4.

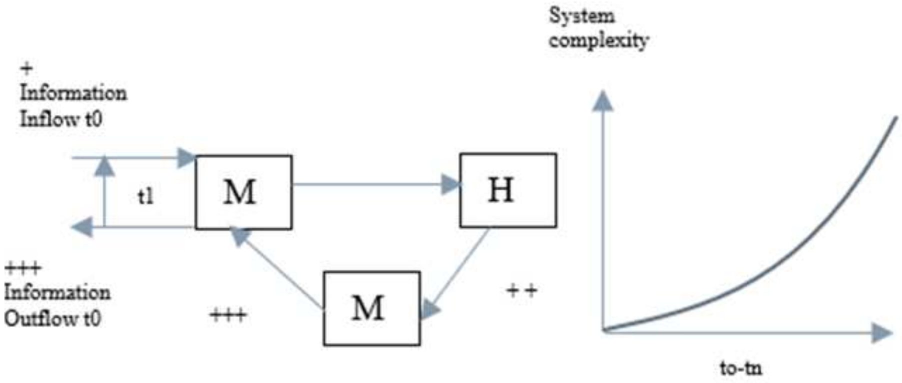

Fig. 4. Development of Complexity in a CPCHS

CONCLUSIONS

The results of this paper show that it is possible to construct a theoretical connection between informational growth and the growth of system complexity. Based on H1 – H4 it can be theoretically indicated that the amount information aggregated and transferred in a system can serve as an indicator for the development of system complexity and as a possible explanatory concept for the exponential surges of system complexity in industrial information systems, like CPCHS, CPS or CHS. This paper provides furthermore first foundational ideas for a possible approach to potentially describe, model and simulate complex industrial information systems based on network, agent-based approaches and the concept of Shannon entropy and thus underlines the potential and the possible applicability of the proposed argumentation in both theoretical and practical contexts. Consequently, it appears necessary to further explore the validity of the hypotheses proposed by conducting further research for example through more specified literature review, system simulations or case study research, especially in the area of the notion of complexity and the practical applications of complex industrial information systems in the form of CPS, CHS and CPCHS.

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REFERENCES

Duan et. al., 2019. Artificial intelligence for decision making in the era of Big Data – evolution, challenges and research agenda, International Journal for Information Management, 48, http://doi.org/10.1016/j.ijinfomgt.2019.01.021

Freund L., Al-Majeed S., 2020. Cyber-Physical Systems as Sources of Dynamic Complexity in Cyber-Physical-Systems of Systems, 2020 International Conference on Innovation and Intelligence for Informatics, Computing and Technologies (3ICT), Sakheer, Bahrain, 2020, 1-5, http://doi.org/10.1109/3ICT51146.2020.9312015

Gaham M., Bouzouia B., Achour N., 2015. Human-in-the-Loop Cyber-Physical Production Systems Control (HiLCP2sC): A Multi-objective Interactive Framework Proposal. In: Borangiu T., Thomas A., Trentesaux D. (eds) Service Orientation in Holonic and Multi-agent Manufacturing. Studies in Computational Intelligence, 594. Springer, Cham. http://doi.org/10.1007/978-3-319-15159-5_29

Garcia et. al, 2019. A human-in-the-loop cyber-physical system for collaborative assembly in smart manufacturing, Procedia CIRP, 81, 600-605, http://doi.org/10.1016/j.procir.2019.03.162

Gimpel H., Röglinger M., 2015. Digital transformation: changes and chances, Project Group Business and Information Systems Engineering (BISE) of the Fraunhofer Institute for Applied Information Technology FIT, https://eref.uni-bayreuth.de/id/eprint/29908

Hanel et. al., 2014. How multiplicity determines entropy and the derivation of the maximum entropy principle for complex systems, Proc Natl Acad Sci U S A., 111, 19, 6905–6910, http://doi.org/10.1073/pnas.1406071111.

Horvarth I. Gerritsen B., 2012. Cyber physical systems: concepts, technologies and implementations, Proceedings of TMCE 2012, May 7–11, 2012, Karlsruhe, Germany, ISBN 978-90-5155-082-5.

Jalili M., Perc M., 2017. Information cascades in complex networks, Journal of Complex Networks, 5, 665–693, http://doi.org/10.1093/comnet/cnx019

Li H., 2016. Information Efficiency of Communications for Networked Control in Cyber-Physical Systems: When Carnot Meets Shannon, 2016 IEEE 55th Conference on Decision and Control (CDC), 2016, 12-14, http://doi.org/10.1109/CDC.2016.7798536

McAfee A., Brynjolfsson E., 2014. The second machine age, W.W. Norton & Company

Meijer D., 2013. Information: What do you mean?, Syntropy Journal Syntropy 2013 (3): 1-49 ISSN 1825-796

Mourtzis et. al., 2019. Modelling and quantification of industry 4.0 manufacturing complexity based on information theory: a robotics case study, International Journal of Production Research, 57,22, 2019. http://doi.org/10.1080/00207543.2019.1571686

Nagy et. al., 2012. Statistical Basis for Predicting Technological Progress, Statistical Basis for Predicting Technological Progress. PLoS ONE, 8, 2, http://doi.org/10.1371/journal.pone.0052669

Riahi et.al., 2018. Big Data and Big Data Analytics: Concepts, Types and Technologies, International Journal of Research and Engineering, 5, 9, http://doi.org/10.21276/ijre.2018.5.9.5

Spencer D., 2016. Work in and beyond the Second Machine Age: the politics of production and digital technologies, Work, employment and society, 31, http://doi.org/10.1177/0950017016645716

Terrazas et. al., 2015. Complexity measurement based on information theory and Kolmogorov complexity, Artificial Life, 21, 2, 1-20

Törngren M. Sellgren U., 2018. Complexity Challenges in Development of Cyber-Physical, Systems, Springer International Publishing AG, part of Springer Nature 2018, 2018,478-503, http://doi.org/10.1007/978-3-319-95246-8_27

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