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A System Dynamic Model for Implementation of Industry 4.0

Marzieh Khakifirooz*, Dimitri Cayard, Chen Fu Chien, Mahdi Fathi

Abstract— **With advances in information and telecommunication technologies and data-enabled decision making, smart manufacturing can be an essential component of sustainable development. In this era, the promising relevant opportunities to reduce costs to boost productivity and improve quality is based on the integration or combination of simulated replicas of actual equipment, Cyber-Physical Systems (CPS) and regionalized or decentralized decision making into a smart factory. However, this integration also presents the industry with different unique challenges. The stream of the data from sensors, robots, and CPS can aid to make the manufacturing smart. Therefore, it would be an increased need for modeling, optimization, and simulation to the value delivery of manufacturing data. This paper aims to outline the approach that was used to develop a system dynamics model to evaluate a superior design of "Industry 4.0" implementation for smart manufacturing.**

Index terms: Casual-Loop Diagram; Cyber-Physical System; Industry 4.0; Open Connectivity Unified Architecture; Smart Manufacturing; System Dynamic; V-Model Diagram.

I. Introduction

A. Industrial Revolutions

The manufacturing process has undergone subsequent revolutions throughout the time since the first Industrial Revolution. Until now the world has witnessed three industrial revolutions and is facing the fourth one. The first industrial revolution was defined by the transition to new manufacturing processes and developed heavy mechanical manufacturing equipment and steam engine [1]. The second one made mass production possible, fostered the advent of electricity in the assembly line [2]. Tremendous application of information combined with communication technologies was the core of the automation of production processes that defined the third industrial revolution. Lastly, the development of Cyber technologies integrated into ecosystems of digitalized industry contributed to the development of the fourth industrial revolution, mostly named "Industry 4.0".

B. An Overview of "Industry 4.0"

Communication and information technology have registered a significant evolution during the last decades, that could not go unnoticed within the industry due to its impact on efficiency and competitivity [3]. Those revolutions have led to changes in the mean of production going from massive use of steam to sophisticated manufacturing processes. Through smart manufacturing, manufacturing processes are becoming more flexible with the utilization of sophisticated manufacturing technologies and information [4]. With these new trends and technologies, the German government fathered the term and concept of "Industry 4.0" which represents the core of the fourth industrial revolution.

"Industry 4.0" serves a strategy where the combination of CPS, "Internet of Things" (IoT), and cloud computing lead to upgrade the manufacturing technologies in the process of creating smart factories [5]. Under the framework of "Industry 4.0", physical and digital processes work as one system to form the "Cyber-Physical System" (CSP). Those technological breakthrough are meant to affect product and processes [6] [7]. Within the "Industry 4.0", manufacturing systems can create a replicate of the physical world that is called the "cyber twin" while making sure that humans and machines and sensors are continually connected [8].

C. Objective of This Paper

This study intends to focus the discussion on the principal requirements to switch to the "Industry 4.0" and uses a System Dynamics (SD) framework to analyze how the different components of "Industry 4.0" are linked together. The literature about "Industry 4.0" comprised several studies aiming different scopes. Some authors like Hercko et *al.* [9] identifies four essential elements of "Industry 4.0". However, the literature is divided into whether "Industry 4.0" can be identified through four components or even more. Schmidt et *al.* [10] highlight the potential uses of "Industry 4.0". Wang et *al.* [8] bring together the cloud, the supervisory control terminal, the industrial network and other smart shop-floor objects to design a framework of a smart factory for "Industry 4.0". More recently, Tjahjono et *al.* [11] discussed how "Industry 4.0" impacts the whole supply chains. Yang [12] conducts research which aims to review the contents, scope, and finding of "Industry 4.0". However, little attention has been given to the link between the components of "Industry 4.0" and how they influence each other and therefore the "Industry 4.0" as a system.

The structure of this paper is as follows: Section 2, introduces the fundamental structure of "Industry 4.0". Section 3, describes the design principal and technology requirements for "Industry 4.0". Section 4, presents the SD modularization and the Causal-Loop Diagram (CLD) and bring forward the case of telematics device for car insurance premium. Lastly, Section 5 comprises the conclusions and future research directions.

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II. The Basic Components and Concepts of "Industry 4.0"

The details about the main components of the "Industry 4.0" are based on the research of Hermann et *al.* [13]. After a thorough search in the literature based on keywords such as IoT and most frequently searched concepts related to the subject, they come up with four main components of "Industry 4.0". The most cited terms in academic research publications such as the CPS, IoT, the Smart Factory, and the "Internet of Services" (IoS) represent the essential components of the "Industry 4.0".

A. Cyber-Physical System

In 2008, Edward A. Lee [7], defined CPS as follows:

> *"CPS are the integration of computational and physical processes. Entrenched computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice verse."*

That combination of the virtual and physical world consists an essential component of "Industry 4.0" [14]. The CPS focuses primarily on measuring information about physical devices. It relies on the internet as a means of communication to ensure that physical devices are running securely, smartly with high-efficiency [15].

Three phases characterize the development of CPS.

- Identification: In manufacturing, identification plays an essential role as the basic language used by the machine to communicate. "Radio-Frequency Identification" (RFID) tags as the first generation of the identification technologies are used for unique identification and tracking by mean of an electromagnetic field.
- Integration of sensor and actuator: The second generation of the CPS, sensors are equipped with a limited range of functions. They allow the machine to control its movement and sense changes in the environment. However, their use was restrained and communication between them, impossible.
- Development of sensors and actuators (agent-based system): CPS third generation, equipped with sensors are connected to the network. That allows them to store and analyze data, and exchange information.

B. Internet of Things

Kagermann [14], suggests that the introduction of the IoT and IoS in the manufacturing process marks the starting point of the fourth industrial revolution.

IoT is built upon on the cloud computing and networks of sensors. It consists of objects with embedded technologies that enable them to sense and send data for a specific purpose. It offers a mobile, virtual, and instant connection. Trough the IoT, "things" and "object" as RFID, sensors, mobile phones are integrated into individual links, which can work with other objects/things to reach a common objective. IoT's vision is to connect the physical world with the virtual one and facilitate communication between all entities. As mentioned by Atzori et *al.* [16], IoT's implementation should be "internet-oriented" (middleware), "semantic-oriented" (knowledge), and "things oriented" (sensors).

C. Internet of Service

The IoS makes services as tradable goods by creating an internet infrastructure to offer and sell services. Brought together, service consumers and providers can trade services while involved in some business interaction which represents a supporting technology for the IoS vision [17]. It is the customers gateway to the manufacturer.

This business network assures that customers are served by a system where organizations work together. Values are created along the supply chain between a company, its suppliers, its customers and aggregators. For example, in a service network, including research, development, conception, marketing, and sales, all sections are working interchangeably to add value to the overall service.

On the IoS, value-added services are offered by various suppliers. Suppliers and customers use different channels to communicate between themselves given that the standard, tools, and applications to support the business are well defined in a developed IT perspective [18]. The activities in the value chains are positively impacted by the value-added service which introduces a new dynamic variation. It is likely that in the future, this concept will be applied to entire values added network instead of single factories.

D. Smart Factory

Smart Factory represents the essence of "Industry 4.0". In a smart factory, humans and machines are assisted by context-aware machines that support them in the execution of their tasks. Everything revolves around it to make the business model. The smart factory is also referred as key advantages to "Industry 4.0" [4]. Real-time information about the status of the service is necessary to reach this objective. Context-aware systems which use context-related information such as location and status or a product as much as the so-called calm- systems need information produced by the physical and the virtual world to accomplish their tasks [13].

III. Design principles of "Industry 4.0"

In "Industry 4.0", the sensors, machines, and technologies applied to communication creates the CPS whose objective is to monitor the physical process and make decentralized decisions [19]. Assuring the communication between humans and machines can be achieved with centralized controllers. Baur and Wee [20], are identified eight value drivers and 24 dependent industry levers involved in "Industry 4.0" (Fig. 1). Communication between units are seamless, virtualized and decision making, decentralized; Customers benefit self-service from the practical guidance and service orientation with real-time capability for fast response [21].

Significant shifts are required within the organizational structures, practices, and systems to make "Industry 4.0"

Fig. 1. "Industry 4.0" value drivers and levers [20]

work correctly. Those shifts include new forms of data management, IT architecture and data management and so forth. All those requirements in "Industry 4.0" must follow a design principle, aiming to confirm the computerization of all manufacturing process and to support companies by determining pilots of "Industry 4.0" suitable to be implemented. The literature about the exact number of fundamental principles is not uniform. Hermann et *al.* [13] identify four major vital principles of "Industry 4.0", while six fundamental principles remain the results of Vogel-Heuser et *al.* [22]. Gilchrist [23] supports the same idea of 6 keys principles to be the design of "Industry 4.0". In the context of this study, we adopt the six key principles as shown in Table 1.

TABLE I
DESIGN PRINCIPLES OF EACH "INDUSTRY 4.0" COMPONENT

"Industry 4.0" component	CPS	IoT	IoS	Smart factory
Interoperability	X	X	X	X
Virtualization	X	-	-	X
Decentralization	X	-	-	X
Real-time capability	-	-	-	X
Service Orientation	-	-	X	-
Modularity	-	-	X	-

A. *Interoperability*

Interoperability is a primary key that makes "Industry 4.0" possible. It implies that all components are capable of connecting, to communicate and operate together via the IoT, including humans, smart factories, and the relevant technologies [23]. Specific principles need to be met for fulfilling the requirements of accuracy and efficiency of the process. In this perspective, eight principles that sustain the interoperability of "Industry 4.0" are highlighted as follow: privacy, accessibility, multilingualism, security, subsidiarity, open standard, open source software, and multilateral solutions [12].

B. *Virtualization*

Virtualization implies that a virtual copy of everything is necessary. Therefore, the capacity of CPS makes possible to create a virtual version of the real world through simulation to monitor physical processes. With the existence of a virtual world, and all necessary information, like next working steps or safety arrangements, it is easy for process engineers to work in complete isolation to change, customize their work without altering the physical world [24].

C. *Decentralization*

Decentralization is defined by the capacity of CPS to make a decision on its own and accomplish its assigned functions without deviating from the ultimate organizational goal. Decentralization also creates a more flexible environment for production. In fact, the concept implies more significant customization of products in a flexible manufacturing environment to meet the standard of quality assurance.

D. *Real Time capability*

"Industry 4.0" relies on doing things in real time. Real-time data collection, storage, and analysis are required for a smart factory, to enable the online decision making. The production process, the data collection, and the feedback system should follow the online monitoring requirements. While the status of the plant is continuously tracking and analyzing, it can respond to the machine failure by redirecting products to another machine.

E. *Service Orientation*

Production must be oriented for customers. Customers must be able to customize their products while connected efficiently through the IoS. That testifies why the IoS is essential to "Industry 4.0". Besides, thanks to the IoT, others can consume all the created services.

F. *Modularity*

Individual modules when replaced or expanded, allow smart factories to be flexible. Therefore, they can adapt to changing environments, fulfill updated requirements with great facility and, adjust modular systems to changes in products characteristics with great facility. For example, a whole production system, or even a simple component like conveyor belts that are modular and agile, allow a change in production. Producers can, therefore, ensure that individual products lines can be changed, modified, expanded, while products and production processes remain uninterrupted.

IV. SYSTEM DYNAMICS MODULARIZATION

Forrester in 1997 [25] defines SD as:

> *"the study of the information feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decision and actions) interact to influence the success ox the enterprise".*

Based on Forrester's perspective, systems dynamics also studies the interactions between the flows whether it is of information, money, orders, materials and so forth.

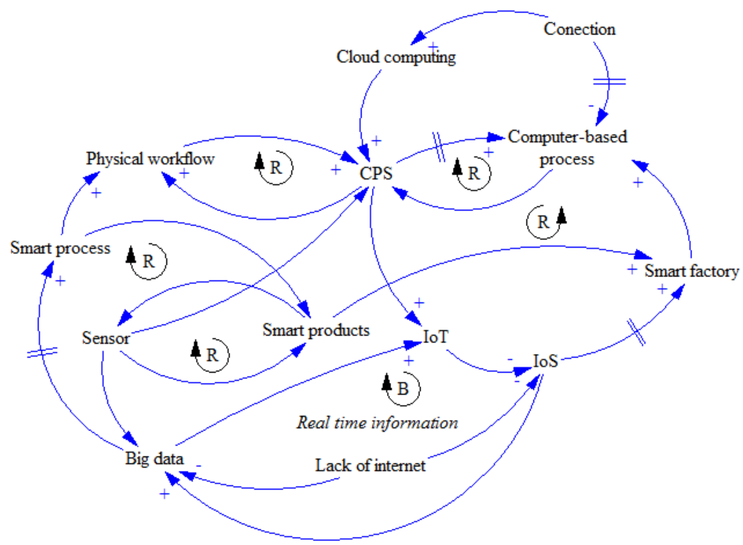

Fig. 2. Causal-loop diagram for principal design of "Industry 4.0"

The primary function of an SD is to solve problems based on the feedback from the system information. It holds that characteristics and pattern that define a system depend on its internal dynamic feedback structure and interactions of its parts [26]. The models developed through an SD approach aims to present, defines and analyze how complex systems work. Therefore, the primary goal is to understand how specific behaviors affect the system and how to predict consequences over time.

A. Implementation the "Industry 4.0" with SD model

In this section, we develop a framework that summarizes the characteristics and requirement of "Industry 4.0" regarding systems dynamics principles. This framework intended to create a platform that showcases another view of "Industry 4.0" and give priority to the components with high influence on reaching the full potential of "Industry 4.0".

1) Casual-Loop Diagram: The CLD is an essential tool in SD developed by Forrester [25]. It is used, to develop an understanding of complex systems. Every arc in CLD is marked by $(-)$ or $(+)$. The mark $(+)$ indicates that when one variable has an impact on the other variable if the first variable is changed, then the second variable will be changed in the same way. The mark $(-)$ indicates the similar relationship but when the change occurs in the opposite direction [27].

In this paper, the CLD of "Industry 4.0" consists of six major loops divided into five reinforcing loops and one balancing loops. The diagram is shown in Fig. 2.

The five reinforcing loops including smart process, smart products, physical workflow, computer-based process, and smart factory and one balancing loop is the real-time information loop.

CPS consists of two components which are the physical workflow and the computer-based process system. Between the CPS and its physical side, there is a reinforcing loop. The physical workflow positively influenced on the CPS. And any malfunction of it has indigence on the functioning of the CPS. Therefore, a reinforcing loop exists between the CPS and its computerized side, which represents its second part (computer-based process system) because it can influence positively and negatively the status of the CPS.

The sensorsmart products loops has a reinforcing loop that can be explained by the fact that smart products rely on sensor real-time data to figure out if they fit the requirements of the customers. The sensor needs information of the smart products to be updated continuously. Consequently, any wrong message from the sensor has a bad incidence on the smart products. Connected to the loop of sensors and smart factory, two other elements are influencing on this loop. The smart process which is the fundamental of smart manufacturing and Big data which is generating the communication among sensors.

Between the smart factory and CPS, there is a reinforcing loop. The smart factory is a big component of the industry as much as the CPS. As all the components are linked through the IoT, the smart factory performance influence positively or negatively on the CPS depending on if it is performing adequately or not. Therefore, there is a reinforcing loop between them.

One important loop is the IoS-Big data loop. IoS rely on a full-time internet connection to work. One of its key support is the IoT which allows all objects to be connected in real time. The lack of internet influences negatively the creation of Big data. With no Big data, IoT will affect adversely on the IoS. On the contrary, with a more stable internet connection, the IoS will be more attractive, and Big data will be generated, and IoS are positively influenced to create more Big data. There it exists a balancing loop between Big data-IoS and IoT.

2) V-Model Diagram: The V-model represents a variation of the waterfall model is basically a software development

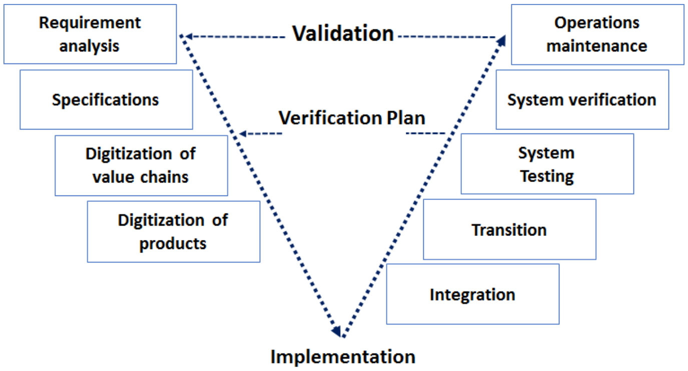

Fig. 3. V-model diagram for the principal design of "Industry 4.0"

process proposed in the late 1980s by Paul Rook [28] and is still in use today. The process is presented with two sides that form a V. The first side presents the project definition while the right side of gives an overview of the project test and integration. The Fig. 3, represents the V-model associated with the implementation of "Industry 4.0" as a project.

It starts with the requirement analysis that is necessary to implement "Industry 4.0" and specifications depending on the types of manufacturing. The next steps are the digitalization of value chains and the digitalization of products which represent two important factors of the "Industry 4.0" framework. The implementation phase of "Industry 4.0" must include the integration of innovated products as shown in the second side of the V-model. The system later has to be tested and verified. Maintenance is always required to keep the system working.

B. Industry 4.0 and Open Connectivity Unified Architecture

OPC (Open Connectivity Unified Architecture) is a widely used standardized data exchange process for automation technology. OPC UA provides a method for secure and reliable exchange of data. With the latest industrial revolution on its way, OPC reveals itself as the fundamental component to support interconnectivity and interoperability at all levels. "Industry 4.0" is characterized by the concept of integrated industry. Therefore OPC UA plays an important role in the IoT through the integration of components in the permanent data exchange of the factory of the future. A presentation of how OPC UA and "Industry 4.0" are related is given in Table 2.

C. Case Study

We illustrate this model with a case of pay-as-you-drive (PAYD) insurance system. In the PAYD system all the transaction of car and driver's behavior, such as speed, frequency use of brake, day/night driving time, and distance, are affecting the premium. The transaction of car and driver's behavior are collecting through a telematics device report to the insurance company by GPS and save in the computer server for further investigation and computing the premium. Some companies also using the mobile application device to give the online reports to drivers about their behavior of driving.

Consider the CLD model in Fig. 2, the components of a PAYD system are described as follows:

- **Sensor**: telematics.
- **Big data**: the transaction of car and driver's behavior.
- **Physical work flow**: GPs, computer server, and vehicle equipped with telematics.
- **Smart process**: the transaction between the telematics, GPS, and the computer server.
- **Smart product**: PAYD insurance.
- **Lack of internet**: disconnection between the sensor of the telematics, GPS, and computer server.
- **Cloud computing**: Analyzing the information from the car and driver for computing the premium insurance .
- **IoT**: Mobile application based for controlling the car and the driver's behavior.
- **IoS**: trust system management between the insurance company and consumers in the content of the sharing economy [29], [30].
- **Computer based-process**: decision support system which computes the premium based on the driving and driver's data.
- **CSP**: the computer server in the insurance company
- **Connection**: between the data center in the insurance company, mobile application, and GPS.
- **Smart factory**: the cooperation of insurance company, telematics provider, the car manufacturer, and telecommunication company which providing the PAYD system to the consumers.

V. Conclusion

As a conclusion and future research direction, firstly we planned to formulate the CLD and upgrade it to the stack-flow diagram. In addition, we attempted to have a broader vision of the requirements for industrial development and intelligence manufacturing. These requirements are barely indicated in literature with analytic context and are known as the new obligations for next step toward smart manufacturing. Following are some of the highlighted topics in this chain.

- Supply Chain Management
- Sustainability and Remanufacturing
- Green Smart Manufacturing

Eventually, the fast-growing smart technology for manufacturing requires a Knowledge Management Systems (KMS) in order to support management decision support system. This KMS will identify and analyze research trend gaps and organize a future research agenda for new product development.

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TABLE II

OPC UA SOLUTIONS FOR INDUSTRY 4.0 REQUIREMENTS

Industry 4.0 requirements	**OPC UA Solutions**
Independence of the communication technology from manufacturer	OPC runs on all operating systems
Scalability for embedded devices	OPC UA is used in embedded filed such as RFID readers, protocol converters
Service oriented architecture	OPC UA independent of the transport system
Integration into semantic extension	OPC is able to collaborate with other organizations (PLCopen, BACnet, FDI)

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