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► To cite this version:

Hind Bril El-Haouzi, Etienne Valette. Human system integration as a key approach to design manufacturing control system for Industry 4.0: Challenges, barriers, and opportunities. 17th IFAC Symposium on Information Control Problems in Manufacturing, INCOM 2021, Jun 2021, Budapest (virtual), Hungary. hal-03269332

HAL Id: hal-03269332

<https://hal.science/hal-03269332>

Submitted on 23 Jun 2021

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Human System Integration as a Key Approach to Design Manufacturing Control System for Industry 4.0: Challenges, Barriers, and Opportunities

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Abstract: This paper is intended to discuss the works and challenges raised by Human-System Integration (HSI) as a key approach to deal with the changes that Industry 4.0 will bring to Smart Manufacturing Control System (SMCS). Industry 4.0 has come with many technological advances allowing significant possibilities to enhance flexibility, efficiency and human well-being but also increasing the complexity and the lack of exhaustive view on the behaviour of autonomous agents. This leads to the questions of acceptability, comprehension, or adaptation between humans and systems. This paper suggests some challenging perspectives from the organization, technology, and social dimensions' triptych. An overview of works related to organisation theory, HSI & SMCS have been done to evaluate the barriers, opportunities, and action levers for the future smart manufacturing control systems' challenges.

Keywords: Human System Integration, Human Factor, Smart Manufacturing Control System, Industry 4.0, Social Inclusion, Organization Theory.

1. INTRODUCTION

Industrial landscape has constantly been evolving over the centuries. In the later ones, four major transformations have been identified as “Industrial Revolutions” by their close relationship to technological breakthroughs and by their deep impact on production, consumption, and business model paradigms. These changes are the result of the convergence between the evolution of societal needs (i.e., the market) and the appearance of technological enablers (such as steam machine, electricity domestication, microprocessors, or networked agents).

Achieving this convergence necessarily came with a certain number of challenges attached to each change of paradigm. Since the 80's and the emergence of flexible production and mass customization & personalisation paradigms, the main challenge was relying in the search for systems' adaptability to face the variability issued from markets changes and demand volatility. To answer this need for adaptability in industrial systems, a series of joint initiatives between research centres, universities and companies have been led since the 90's with the common objective to develop present and future's production systems. In this context, one of the most important initiatives has been the Intelligent Manufacturing Systems (IMS) Project, started in 1989, which has brought together works in Automation, Computer Science and Mechanics (Yoshikawa, 1995). The main concerns of the IMS project are attached to the design and implementation of agile systems in order to bring quick responses to disruptions into production systems. There are defined as complex systems composed of numerous autonomous units. They are endowed with a certain adaptation capability and can be the scene of important emerging phenomena, that cannot be simply understood,

explained, or modelled based on the knowledge of their components.

To reach this adaptability, the IMS community was strongly relying on the enhanced automatization and robotization of manufacturing systems, enabled by the appearance of new Information and Communication Technologies (ICT). For the last 10 years, several of these technologies and concepts, such as Cyber-Physical Systems, Internet of Things, Big Data analytics, cloud computing, virtual reality, or advanced robotics, have experienced notable advances and have significantly grown in popularity. Along with the emergence of these technologies, new societal considerations have risen. Consumers are now focusing on environmental and ethical issues. From the convergence of new technologies and new societal concerns have emerged a new sustainable, durable production paradigm. Focusing on the situation in Germany, the report from (Acatech, 2013) have established a strategic plan for future industrial developments known as “Industry 4.0”. By its pertinence, the Industry 4.0 was rapidly extracted from the German context by scientific and manufacturing communities – becoming Industry 4.0 – and is now commonly used to refer to a 4th industrial revolution.

Industry 4.0 (or I4.0) can be presented through many prisms. It can be seen as a depth thought upon the triptych “**Technology, Organization & Human**”, relying smart machines, smart products, and enhanced human's paradigms in order to handle societal issues such as ageing population, immigration, human inclusion, etc. It could equally be envisioned as a response to needs for adaptability to changing environments, real-time problem solving, inter-agents' connectivity, ability to couple physical assets to their virtual image and achieving convergence between methods of artificial intelligence, automation, and human know-hows & expertise. The big

challenge for the years to come will consist in designing and controlling these new adaptable socio-technical ecosystems, evolving through a changing environment.

Few tangible and achievable research results on mastering the complexity of general system theory have been proposed. Consequently, implementations of intelligent manufacturing control architectures remain limited to date, and acceptance in the industrial field varies according to their applications (Lanz et al., 2012). Moreover, the majority of proposed complex-adaptable models are techno-centered (Bril El-Haouzi, 2017). Human is placed in the control loop, *a posteriori*, when the situation deteriorates or when faced with an unforeseen element (Le Moigne, 1977). Hence, this paper proposes a discussion about HSI in manufacturing control through the theory of organizations' perspectives within the framework of I4.0.

The next section aims to recall some of the theory of organizations' key concepts, in particular those resulting from Mintzberg's work. We will propose our retrospective analysis regarding coordination mechanisms and work organizations across the last decades and introduce our vision of future I4.0-related developments. Section 3 aims to reaffirm the primary role that human agents are playing into control architectures and to take a look upon the current efforts made to bring him "back in the control loop". The last section aims to discuss the challenges, barriers, opportunities, and action levers raised by HSI into manufacturing control systems' design, regarding from the triptych "**Technology, Organization & Human**" in the search for more human mechatronic systems (Valette et al., 2020).

2. A RETROSPECTIVE ANALYSIS REGARDING WORK ORGANIZATIONS

2.1 The theory of organizations' key concepts

According to (Mintzberg, 1979), "Every organized human activity – from the making of pots to the placing of a man on the moon – gives rise to two fundamental and opposing requirements: the division of labor into various tasks to be performed and the coordination of these tasks to accomplish the activity". Hence, any system (including manufacturing control ones) can be perceived as structured by 1) its mission or activity, decomposed in several sub-missions or sub-activities; and 2) by the coordination mechanisms operating to complete the system's mission / activity. Five fundamental coordination mechanisms are to be considered:

- **Mutual adjustment:** achieves work coordination by informal communication (fast communication that is not supported by predetermined channels, without paper trail, or official documentation). It is used in both simplest and most complicated organizations.
- **Direct supervision:** achieves work coordination by having one agent responsible for the work of others, giving instructions, and monitoring them.

Work coordination can also be achieved through 3 main types of standardization:

- **Work processes:** standardized when the contents of the work are defined. Work coordination is directly achieved by the designer of the work contents.
- **Outputs:** standardized when the expected results of the work are defined. Work coordination is directly achieved by the designer of the finished work characteristics.
- **Inputs:** standardized when the skills and knowledge required to perform the work are defined. Work coordination is indirectly achieved by the designer of the working agent's training.

Within any organization, all these five coordination mechanisms are more or less presents, at the same time. However, according to (Mintzberg, 1979), the difficulty and the nature of organizational work give way to one or the other of these mechanisms to a preponderant position. Since the difficulty of organizational work is not always constant, the predominant coordination mechanism of a system may change over time (Fig. 1: Based on (Mintzberg, 1979))

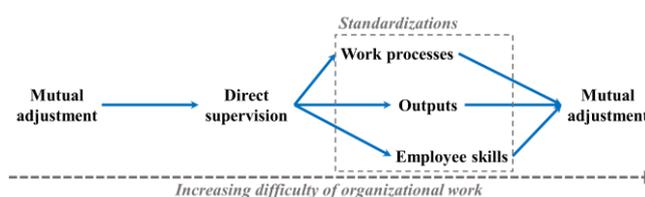


Fig. 1. The continuum of coordination mechanisms.

2.2 A retrospective analysis of coordination mechanisms and future challenges

In our reading the two first coordination mechanisms, namely **Mutual adjustment** and **Direct supervision**, are directly related to Fiske's Communal Sharing and Authority Ranking, which are 2 of the 4 fundamental relational models structuring human societies (Fiske, 1992). Consequently, they are present in most (if not all) human societies, making them a fortiori observable in organizations such as manufacturing systems – where they will be related to respectively **heterarchical** and **hierarchical** organization management. They can always naturally be found, even in strongly standardized systems.

On the contrary, the 3 standardizations are not based on natural relational models but are the result of an upstream standardization work. They do rely on inter-agent relationships to achieve work coordination but are either achieved by the design of the processes to follow, the definition of expected results, or by the training of agents to develop and increase their skills and knowledge. Even though Mintzberg does not openly refer them, our analysis strongly relates these standardizations to 3 great philosophies of work organizations: **Taylorism**, **Fordism** and **Toyotism**.

The first one, also known as the Taylor's Scientific Management (Taylor, 1911) is characterised by the decomposition of work processes into elementary tasks for which, the one best way to perform is searched (i.e. **work processes standardization**). The great manufacturing performances brought by this new work organization led to its improvement several decades later. Around 1910, Ford

developed the Taylorism with the generalization assembly lines and the products standardization (i.e. **work outputs standardization**) (Ford, 1922) Starting as a development of Taylorism, the impact of this new work organization model was such that it was later independently referred as Fordism. In years 1960's, motivated by the post-war socio-economic situation of Japan and relying on its "distinguishing features" (Sugimori et al., 1977), Taiichi Ohno developed a third work organization: the Toyota Production System (TPS, or Toyotism). This last one being based on a series of innovative methods, such as Kanban, and supported by the strong qualification of workers to improve their autonomy and flexibility (i.e., **skills standardization**).

This retrospective analysis led us to 3 interrogations. The first one concerns the organization of work: Will there be a next wave of standardization or we will just update the old ones with new technologies to move from mechanical to cyber-physical Fordism throughout a digital one? The second question concerns the strong interactions enabled by the technological evolution from I4.0 between physical and virtual objects, human and artefactual agents: Will there have to reach a new level as mutual adjustment, to overcome the complexity and instability into manufacturing systems that will follow the rise of I4.0? To conclude, it is well known that what will come to reality in the future never only depends on technical feasibility and economic profitability, but also on how society negotiates and shapes future developments. Thus, the third question will concern societal model-based issues raised by past and future developments of manufacturing systems: What will be the place of human in these new systems? We will try to provide some of the answers in the following paragraphs.

3. SMCS & HUMAN FACTOR

The results from this Research & Development campaign are today expressed through technical developments aiming to bring the desired reactivity, proactivity, flexibility, and resiliency to manufacturing systems. But the integration of these new technologies into manufacturing systems, or into any organization, is not self-evident. In order to answer these issues, a great amount of research have been conducted for the past decades in the field of control architectures, notably Holonic ones (HCA). In (Cardin et al., 2018), these HCA are presented as the main implementation and coordination supports through which I4.0's enabling technologies will be able to fully emerge and express their potential. The authors have established a typology of HCA, by listing some of the most recognized ones, from 1998 to 2017. They have organized those according to both their contribution to the I4.0 and a set of criteria (such as ability to improve flexibility or connectivity into a system). Still, these architectures are strongly attached to either the technologies they are supporting or their enabling ones and can be characterized as "techno-centred".

And if HCA research is aiming to support the I4.0 deployment into manufacturing systems, this "techno-centred" aspect brings a complex issue (Schirner et al., 2013). Because of the focus set on technical elements, the human factor is often under-considered. In such systems, human agents are often either considered as quasi-robotic, performing repetitive tasks

when the system is ideally functioning, or as quasi-divine as soon as an unexpected event occurs. In these situations, human agents are in charge of the problems solving while ensuring the system's performances. This phenomenon, known as "*Magic Human*" (Trentesaux and Millot, 2016), is particularly undesirable from I4.0's perspective for it leads to human agents' physical or cognitive overloads, lack of Situation Awareness, errors, etc., perturbing the global functioning of the system and lowering its performances.

Few works exist about human factor integration in manufacturing control (Flemisch et al., 2019). Since these factors will be different for every human being and depending on parameters that might either be internal or external to the system (scholarship, familial environment, etc.), permanent or conjunctural (weariness, awareness, mood, affinities, etc.), they are hardly manageable. These parameters are the basis of the variability phenomenon associated to the human. Facing this variability, two approaches can be observed. The first one aiming to inhibit the human factor variability by means of automation and robotization, and the second one aiming to develop *human-friendly* systems that would be able to withstand it (Vanderhaegen and Jimenez, 2018). The whole challenge is to find the best trade-off between failure risk and improvement opportunity, with regard to the human factor . This will require to find the right balance between: **Human variability** and **Human flexibility**.

This search for this balance is at the heart of the HSI discipline. Several institutions such as the Systems Engineering Body of Knowledge (SEBoK) or the International Organization for Standardization (ISO) have already proposed their definition for HSI and Human-centred design. Among these, we could notably cite the NASA's HSI Practitioner's Guide that defines HSI as "[...] *an interdisciplinary science, craft and art to integrate humans, technical systems and organisations into efficient, safe and user-friendly systems*" (Zumbado, 2015).

In this framework, some work and studies have already been conducted to find ways and methods to overcome this human variability in manufacturing control system. We can notably evoke the development of simulation models that consider worker's fatigue, learning and reliability for job scheduling (El Mouayni et al., 2020), or the search for dynamic balance for authority, responsibility, and control sharing between human and automated agents into manufacturing systems (Flemisch et al., 2019). On the other side, in order to exploit this human flexibility to the manufacturing systems' advantage, human-assisting or enhancing systems have been developed. We can cite as an example the ("Poka: Performance support software for manufacturers," n.d.) system, which is designed as a user-friendly integrative interface between manufacturing system software and operators, providing them with all the knowledges and data they might require. Another example would be (Romero et al., 2016)'s *Social Operator 4.0*, aiming for human-system symbiosis by mean of advanced cyber-physical interfacing technologies.

Despite those works, questions of acceptability, comprehension, or adaptation between humans and systems are often leftover. Following this critical perspective, the main purpose of the next section is to identify some critical

challenges on “human-system integration in smart manufacturing control systems” from the perspective of the organization, technology, and social dimensions’ triptych.

4. HSI AS A KEY APPROACH FOR SMCS DESIGN

Today’s new technological advances, associated with CPS and IoT, allow us to imagine control systems with the objectives of efficiency, agility, and adaptation to user needs. Nevertheless, there is still a lot of work to be done before reaching a better acceptability (technological prism) of these systems by people, to reduce their complexity while guaranteeing their agility when facing changes of environment (work organization prism) and to allow a better integration of the human being either as an individual with its variabilities and as a part of a collective society through the concept of social inclusion (social prism). Figure 2 presents the articulation of these challenges, some few obstacles (in italics) as well as 3 perspectives to respond to these challenges. The following sections details these challenges and perspectives, along with some their obstacles and requirements, for the design of a manufacturing control system with an HSI approach.

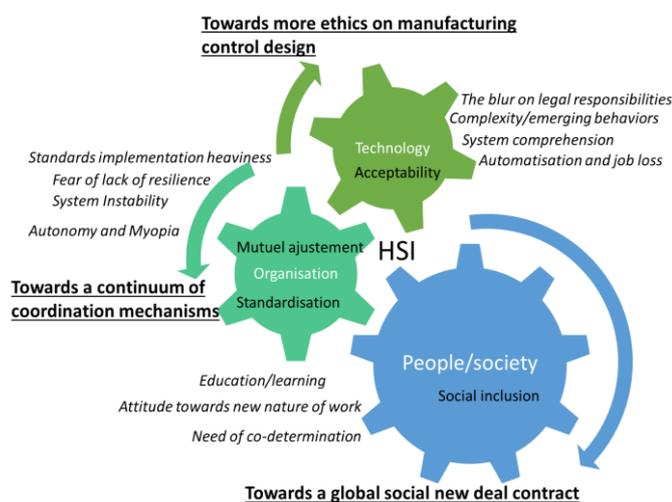


Fig. 2. human-system integration in smart manufacturing control systems main stakes, barriers, and opportunities

4.1 Towards more ethics on SMCS design

Under many aspects, I4.0 could be seen as a *Pharm Akon* - both antidote and poison. On the one hand, “Work 4.0” is a realistic opportunity to relieve workers from harassing and dangerous tasks. As a responder to the (*White Paper Work 4.0*, 2017), the Bremen Chamber of Labour even considers Work 4.0 as a real solution for demographic issues, for being “[...]particularly interesting in a phase of demographic change when the average age of workforces is rising and businesses are increasingly required to create appropriate jobs for older workers”. On the other hand, the inherent complexity of I4.0 naturally leads to a lack of exhaustive views about future possibilities concerning the behaviours of autonomous agents in interactions and their environment’s evolutions. This lack of visibility added to the difficulties to explain some behaviours of autonomous entities lead to

acceptability and vagueness issues concerning the moral, legal and societal responsibilities of the stakeholders involved in the lifecycle of systems and products (Trentesaux and Caillaud, 2020).

Moreover, these issues are raising another one: the fear. From an organizational point of view, fear will be related to the questions of the loss of resilience, when facing malfunction into highly automated systems. These issues have been addressed in many works, already evoked in this paper. But fear is multiple, and one of its aspects have poorly been treated into current research: the sociological side, associated to the loss of jobs, of knowledges and know-hows, of control upon the machine, or more generally of what (Morin, 2001) is calling “the ecology of action”, when the consequences of actions, developments, are going beyond the will of their authors.

Facing these fears and uncertainties, relatable to the junction of human, digital and physical worlds, and the new need for humans to interact with complex artificial systems, ethics could be proposed as a regulator. It is the case of (Trentesaux and Caillaud, 2020) reviewing the concept of machine ethics, moral machines, social future robots, moral robots, virtuous robots, etc., aiming to bring ethical concepts into tomorrow’s systems. In philosophy, several approaches are to be found around this notion of “ethics”. Nonetheless, two paradigms are particularly emerging: 1) **Deontology**, when decisions are made using immutable ethical rules, and 2) **Consequentialism**, when decisions are made using rules evaluated in terms of possible ethical consequences. Hence, the definition of ethical rules, and their integration into a design approach such as HSI for manufacturing control, along with the proposal of metrics to assess the performance of control models with regard to these rules, remains important challenges for the future.

4.2 Towards a continuum of coordination mechanisms with a mutual adjustment predominance.

In years 1980’s, the developments of software such as Distributed Control System (DCS), Enterprise Resource Planning (ERP), or Manufacturing Execution System (MES) have greatly contributed to the standardization of cognitive work. And if this tendency keeps progressing, notably by intensive use of Business Process Management (BPM) technologies and intelligent business tools (as power BI), a new wave of standardization focusing on Cyber-Physical System (CPS), build up upon data sciences and their technologies, is emerging.

In fact, many agile production platforms have already been developed to deal with autonomous production characteristics such as self-explanatory qualities, fault tolerance and resilience, resource adaptation and cooperativeness. We can cite as example the cases of (HARTING Technology Group, n.d.) flexible assembly concept or of the AutoPnP research project (Soeldner, 2016). However, the implementation of those platforms are strongly dependent on very specific solution providers. They are therefore not totally compliant with the I4.0 vision, that advocates interoperability and

congruence of multi-vendor solutions. To address this issue, initiatives such as SmartFactory KL are paving the way for the future of intelligent factory by working on standards and solutions aiming to be a basis for high-flexibility automation technology (like Plug-in-Produce) (Popper et al., 2018).

What (Goldratt, 2009) stated, is that stability is the limiting factor into TPS implementation and, regarding section 2.2, therefore for standardization. In manufacturing environments, whether it comes from its market, its catalogue, or its production processes, *instability* increases the complexity of work organization. In manufacturing control, this instability will come, notably, from the emergent behaviours or myopia inherent in any complex system. Hence, even if standardization, as a coordination mechanism, is playing a crucial role to decrease system interactions' complexity, two limiting factors are faced: heaviness in establishment & diffusion of standards, and stability of the environment.

In this context, mutual adjustment will be more suitable to deal with instability, and for improving collaboration and dynamic adaptation between humans and machines. In one hand, there are certain tasks in which humans are – and will probably always – be superior to robots (perception, intuitive control, and high-level decision making, etc.). On the other hand, robots can – and probably should – perform tasks such as precise low-level motion planning, solving an optimization problem, and operating in dirty, dull, and dangerous situations.

Therefore, further investigations about new control interfaces and shared control methods are needed. These will enable the effective delegation of tasks the control sharing between human operators and robots, paving the way to the development of field robot systems that will directly support humans. Ultimately, due to these interfaces and methods, inter-agent's communication, including between human and machine, might tomorrow be achieved through informal communication media. To avoid the problems of myopia and nervousness caused by those, interfaces will have to gain in transparency. Tangible objects interactions, electroencephalography or electrocardiography signals, context-aware sensing of human intents by the use of multi-modality will be part of the main keys to reach these more suitable interfaces, but not only. A great deal of work aiming to better implementing a mutual adjustment and its implications into manufacturing control considerations is equally to be conducted.

4.3 Towards a global social new deal contract

Hence, the future big changes induced by I4.0's assets and technologies will not impact the nature of coordination mechanisms within manufacturing systems, except for their balance, but will bring great changes to the nature of work. This has already been stated by the (World Development Report 2019: The Changing Nature of Work., 2019), which forwards the human capital as the key to pass the challenge of this evolution. The report states that the periods of work staying with one company have already been significantly decreasing for the last decades. Future work is then envisioned as axed on short duration missions, requiring both specific and soft skills,

such as technological know-hows, critical thinking, perseverance, or empathy. In this model, workers will not be qualified for a job by their initial formation but will rather be defined by the skills they will have acquired along a life-long formation.

In this context, citizen, companies, and governments along are sharing worries about the emerge of a whole new societal model. Technological breakthroughs raises debates about, notably, social inclusion (improvement of abilities, opportunities, and dignity of disadvantaged peoples), or more broadly their potential economic, social, and life-quality-related applications (ex. Japanese Society 5.0) (Shiroishi et al., 2018) is developing the idea of a human-centered society, highly integrating cyber and physical spaces to solve social issues thanks to economic improvements. In order to successfully transpose this “cyber-society” to the context of work, 5 dimensions have been identified: 1) income and social security; 2) integration into “good work” variety as the new normal; 3) a life-phase approach rather than rigid work models maintaining the quality of work considering co-determination; 4) participation; and 5) corporate culture as a whole. These dimensions must be incorporated as requirements in the design of any manufacturing control system and ensure a more inclusive manufacturing control system.

5. CONCLUSIONS

We have the choice to give in to our fears or to have an exciting vision of I4.0 as an opportunity to open, develop and explore future perspectives for a conscious and human cyber-physical society. In this paper we have established that human factors, and more broadly the HSI approach are not sufficiently considered when designing manufacturing control systems. This lack leads to many barriers for adopting I4.0 assets and taking advantage from its technological advances. From our reading and thinking, the use HSI into design approach for manufacturing control systems will lead to future high challenging perspectives based on the integration of ethical rules and metrics, the adoption of inclusive work approaches and to design control systems as continuum of standardization and mutual adjustment coordination mechanisms. Future work will focus on the specification of requirements for the manufacturing control architecture design this study promotes.

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