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Transition from Industry 4.0 to Industry 5.0: A Focus on Key Concepts Applied in the Manufacturing Industry

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***Résumé* – L'industrie 4.0 a apporté de l'intelligence aux systèmes de fabrication grâce à des jumeaux numériques, des systèmes cyber-physiques (CPS) et l'Internet de tout. L'industrie 5.0 vise d'aller plus loin dans la réalisation des objectifs de l'industrie manufacturière moderne en alliant la précision des robots / cobots à la créativité humaine. Des robots et des cobots peuvent être intégrés dans les lignes de production et coopérer avec des machines-outils à commande numérique (CNCMT) pour automatiser les tâches chronophages et améliorer la qualité des pièces. L'objectif principal de cet article est de présenter un état de l'art des principaux concepts moteur de cette nouvelle transition industriel vers l'I 5.0. Les auteurs proposent également un nouveau concept pour faire le pont entre ces deux évolutions industrielles en contrôlant une cellule de travail CNCMTs-Cobot via une interaction Homme – jumeaux numériques. Prédire le comportement de la cellule de fabrication et optimiser son efficacité opérationnelle par l'analyse de données infonuagiques apportera des solutions à de nombreux problèmes rencontrés dans l'industrie de l'usinage. Les opportunités sont discutées selon trois facteurs clés de la pyramide des besoins humains de l'industrie du futur. Le concept proposé peut offrir des solutions à l'industrie de l'usinage mais qui peuvent être appliquées à d'autres secteurs de l'industries manufacturières.**

***Abstract* – Industry 4.0 brings smartness to manufacturing systems through digital twins, cyber physical systems (CPS), and Internet of Everything. Industry 5.0 seeks to go a step further towards achieving modern manufacturing industry goals by incorporating the precision of robots / Cobots along with human creativity. Robots and Cobots can be integrated into the production lines along with CNCMTs (Computer Numerical Controller-Machine Tools) to automate time-consuming tasks and to enhance parts' quality. This article presents a state-of-the-art of the main driving concepts of this new industrial transition to I 5.0. The authors also introduce a new concept to bridge these two industrial evolutions by controlling a CNCMTs-Cobot work cell via a Human - Digital Twin (DT) interaction. Predicting the CNCMTs-Cobot work-cell behavior and optimizing its operational efficiency by big data analysis gathered through physical twins, sensors, and DTs, will bring solutions for many concerns encountered in the machining industry. Opportunities for adopting the proposed concept are discussed along three key drivers and the industrial human needs pyramid. The proposed concept can provide relevant solutions to the machining industry which can be adopted by other manufacturing industries.**

***Mots clés* - Industrie 4.0, Industrie 5.0, systèmes cyber-physiques, Jumeaux numériques, Cellules d'usinage.**
***Keywords* – Industry 4.0, Industry 5.0, Cyber-Physical Systems, Digital Twins, Machining Work Cells.**

1 INTRODUCTION

Ever changing manufacturing industry is pushing its boundaries day by day. With this fast-moving nature, companies struggle to keep their head high above the volatility, uncertainty, complexity, and ambiguity (VUCA) environment by utilizing strategies to reduce manufacturing time and costs. The labour shortage that most countries are experiencing has also become a burning cost pressure on the manufacturing industry.

To tackle these challenges, Industry 4.0 (I 4.0) has been introduced into the manufacturing industry since 2011. This has allowed the companies to achieve mass personalization, consistency in quality, lowered labour and material costs, increased productivity, and improved profits (Dafflon et al., 2021; Maddikunta et al., 2022; Zhu, 2022).

Real-time data acquisition and storage, data analysis using machine learning, and intelligent monitoring and control are the essential areas of I 4.0 (Dafflon et al., 2021). Cyber Physical Systems (CPS) and Digital Twins (DT) are the prominent concepts that are being used to achieve these I 4.0 essential areas (Aslam et al., 2020; Maddikunta et al., 2022).

CPS integrates the machine in physical space with its digital model in cyberspace, to monitor real-time machine-generated data and to predict the operation accordingly. As (Lee et al., 2015) describe, CPS is a 5C-level architecture (connection, conversion, configuration, cognition, and cyber). Digital Twin is positioned at the third C level of this architecture as a tool for real-time control of the machine.

I 4.0 proposes solutions for mass personalization through the digitalization of the production systems and this view limited the creativity in the industry due to less human involvement. However, with evolving consumer habits, customization is being embraced. This encourages the use of critical and creative cognitive thinking of humans to be included along with the I 4.0 prominent concepts such as CPS and DT (Maddikunta et al., 2022).

This future evolution is referred to as Industry 5.0 (I 5.0) and it encourages the close working relationship between the human and robots / Cobots (collaborative robots) for workload distribution. Humans' inherent creativity will be utilized more by assigning routine operational tasks to the obedient smart assistant. I 5.0 also look into the much neglected environmental sustainability aspect, which can create a more harmonized manufacturing industry (Maddikunta et al., 2022). Therefore, human - machine/robot interactions, and CPS / DT usage will be dominant in I 5.0 for creative, sustainable, smart manufacturing. When humans work closely with robots / Cobots, there are specific guidelines to be introduced to the work cell to ensure the safety of humans, hence human safety is key in these future industrial evolutions (Demir et al., 2019). With digitalization, cyber and data security have become crucial aspects as well. Cyber security guidelines for CPS and DT are still being investigated and enhanced, and it is recommended that these systems should be inherently secured at the design stage itself for the cyber-physical layer (Autiosalo et al., 2020).

This paper analyzes the frontiers of knowledge in a broad spectrum to summarize how the manufacturing industry is handling this industrial transition. This analysis was needed to be done to identify the opportunities for the essence of this paper, which is, a proposal of a human-DT interaction concept that can be applied for a human-CNC-Cobot work-cell to bear the transition from the I 4.0 to I 5.0. This proposed concept can be used as a reference model for similar work cells in industrial applications when the I 5.0 transition starts to become a reality.

The paper is organized as follows. In Section 2, the opportunities of I 4.0, key drivers and new features of I 5.0 are discussed, followed by Section 3 which gives the proposed concept for human-DT controlled CNCMTs-Cobot work-cell and its opportunities, and finally, Section 4 provides the conclusion of the analysis and elaboration of future work.

2 STATE OF THE ART

This section analyzes the frontiers of knowledge in I 4.0 and I 5.0, leading to the concept that is described in this paper.

2.1 Challenges in the manufacturing industry and I 4.0 opportunities

Interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity are the six design principles of I 4.0 as argued by Hermann et.al, 2015 (Rosenberg, 2015). This section mentions the opportunities of integrating these design principles via CPS (or DT as a sub-layer of CPS) to overcome the existing challenges in the manufacturing industry.

2.1.1 Overcoming the challenge of productivity improvement

Traditional production environments use centralized production planning, which increases safety stock levels and slows down the planning-to-production process. Therefore, to overcome the related issues and improve productivity, it is important to adopt decentralized production and planning. CPS is considered to be the tool to achieve that in the manufacturing industry (Al-Jaroodi, 2018; Spath et al., 2013).

For productivity improvements through smart machining, Computer-controlled Numerical Controllers (CNC) are widely being used since the third industrial revolution.

When a CPS is developed for a CNC - Machine Tool (CNCMT), the g-code programs can be utilized to extract information related to the work-piece features, quality, and machining process, which can then be analyzed for quality and process optimizations. Similarly, collected machine tool data can be used for CNCMT and cutting tool conditions predictions and optimizations (Chen et al., 2015) as well. This analysis using CPS allows the prediction of resources and failures. Which assists to streamline production schedules, inventory, and maintenance activities (Dafflon et al., 2021), to overcome the challenge of productivity improvement.

While researchers globally are working to identify potential CPS frameworks for planning, controlling, and predicting manufacturing operations with different service-oriented architectures (Al-Jaroodi, 2018; Lu, 2017; Vyatkin et al., 2015), industries are already using CPS frameworks to overcome their challenges in overall equipment efficiency (OEE) and productivity improvements. COMAU® has used a Digital Twin for their product development process. This Twin-control has been used to simulate their prototypes virtually via which they could achieve a 10% reduction in time and cost. RENAULT® has been able to reduce 11% of the design time when using a Twin-Control for machine tool and process selection (Armendia et al., 2019). These applications justify the theory that CPS usage can result in productivity enhancements.

With real-time data monitoring and decentralized decision-making, almost all the waste types in the manufacturing industry can be addressed (Hadorn et al., 2015), resulting in a productivity improvement. Therefore, when a factory is aligned with I 4.0, it can be considered that it is aligned with Lean manufacturing as well.

2.1.2 Overcoming the challenge of dynamic reconfiguration

If a system can change its configurations according to the gathered real-time data while in its operation, then those systems are called dynamically reconfigurable (Fornari & Santiago Júnior, 2019). Such systems are agile as it is flexible enough to adapt to any scenario without affecting their initial set-up. This can be achieved via both the physical space and cyberspace of a CPS (Dafflon et al., 2021).

Industrial floor designing, human workforce training, Robot programming (to achieve easy calibrations, changeovers, and intuitive operations), and continuous improvement make the physical space reconfigurable (Hess, 2015; Vanichchinchai, 2022). Cyberspace reconfiguration can be achieved through two aspects; by using suitable algorithms to design the CPS function, and/or by using a suitable network layer to integrate the cyber and physical counterparts. For example; task prioritization using scheduling algorithms and self-optimizations (Anacker, 2014; Riedl et al., 2014), provides cyberspace reconfiguration through CPS designing, while an appropriate selection of software applications, communication protocols, and IoT (Internet of Things) networking (Dafflon et al., 2021; Riedl et al., 2014), provides cyberspace reconfiguration through networking.

These changes can provide a 'plug and produce' function for manufacturing systems. This is becoming a useful function for mass personalization and flexibility as demanded by the I 4.0 (Hess, 2015; Rosenberg, 2015).

2.1.3 Overcoming the challenge of standardization

As with any emerging field, with the manufacturing industry also, standardization is required to keep the field evolving in a more organized manner. For this purpose, ISO (International Organization for Standardization), SISO (Simulation Interoperability Standards Organization), and other such global standardization bodies are working towards forming standards and regulations for CPS-based frameworks (Jain et al., 2015). For CPS / DT systems, standards need to be in-placed for the design of each layer.

Physical layer standardization needs to be through the factory floor level and the programming of robots/ industrial automation systems. Usual industrial-level standardizations such as industrial and occupational health and safety guidelines (Occupational Safety and Health Administration – OSHA, Commission des Normes de l'Équité de la Santé et de la Sécurité du Travail – CNESST, etc.) can be used for the standardization of factory floor, while IEC61131 and other IEC standard protocols can be used to standardize the programming of the physical layer (Dafflon et al., 2021).

The cyber layer standardization can be achieved through communication protocols used for interoperability such as OPC UA (Speicher et al., 2015). This standardization has made sure that the methods and semantics used by any application or embedded device are understood by many and are universal, which provides ease of use and data transferability.

With the introduction of the cyber layer to machining monitoring and control, cyber-security also comes in as an important aspect to investigate. Big data in cloud platforms are vulnerable to cyber-attacks but is essential in I 4.0. Therefore, cyber security related guidelines and protocols are also being standardized. These are currently ongoing research and not as standardized as the standards used for designing CPS as described above. Once done, the security will be inherently available in CPS platform designs (Autiosalo et al., 2020; Posada et al., 2015).

2.1.4 Overcoming the challenge of adequate use of Information Technology

Analytical and visualizing software (such as Finite Element Models), 3D models, CAD drawings, and other such visual computing techniques are currently being used in the manufacturing industry as independent tools. CPS/DT frameworks combine and utilize these independent tools to achieve the design principles of I 4.0. (Posada et al., 2015). The Human-Machine Interface (HMI) of CPS platforms acts as this information technology enablement, where the human can use 2D interfaces or augmented reality interfaces to interact with physical machines (Pirvu et al., 2016). It is considered that augmented reality, gamification, mixed reality, wearable technology, etc. based human interaction can be advantageous to build more sophisticated and robust CPS/DT frameworks. Such a framework will facilitate human involvement for better adaptability, interpretability, and controllability (Quint et al., 2015; Speicher et al., 2015).

When it comes to designing CPS, near real-time control of the physical layer through the cyber layer is a complex but required task (Dafflon et al., 2021). OPC UA and other such communication protocols and standards as afore-described can make this a reality once integrated with these information technologies that are used for HMI designing (Speicher et al., 2015).

I 4.0 introduced many advances in digital platforms such as Artificial Intelligence (AI), CPS, Industrial Internet of Things (IIoT), etc. These technological developments ensured mass personalization and shorter lead times in the industry. However, the isolation of the systems from human involvement was the major limitation of I 4.0, as it created job insecurity, resistance to adoption, and a lack of creativity. It is important to be mindful that with industrial evolutions, the human factor does not get subordinated by technology; technology has to be only a tool to support humans (Zizic et al., 2022).

These limitations are amongst the main precursors of the transition towards the 5th industrial revolution (I 5.0).

The I 5.0 is a chronological continuation of I 4.0 (Moller et al., 2022) where emerging technologies are better utilized to complement the industry approach through the aspects of people, organization, and technology (Zizic et al., 2022). This continuation has been supported by the Internet of Things (IoT) being extended towards the Internet of Everything (IoE). The IoT is focused only on machine-to-machine networking, while the IoE focuses on networking among people, data, processes, and things, allowing human involvement in the system (Miraz et al., 2015).

2.2 *Key drivers of I 5.0*

The European Union defines three key drivers for the I 5.0 transition namely; the human-centric approach, sustainability, and resilience (Zizic et al., 2022). This section analyzes these drivers with a focus on key concepts applied to the manufacturing industry.

2.2.1 Human-centric approach

With I 5.0, attention to human-machine interaction expands as this evolution focuses on integrating humans. This human-centric approach is similar to lean management principles, where humans from all levels of a factory floor are encouraged to be proactively involved in process improvements (Moller et al., 2022; Zizic et al., 2022).

When the human is being integrated into the system for close collaborations with machines, there are specific aspects that need to be proactively taken care of to enable the physical, cognitive, and organizational ergonomics of the human. Adopting the industrial human needs pyramid (Figure 1) can ensure this necessity (Zizic et al., 2022).

Human-centric manufacturing must satisfy the industrial human needs pyramid (Figure 1) in areas of safety, health, belonging, esteem, and self-actualization. This is a pyramid relationship that is based on safety, emphasizing that safety is a primary need of humans, and if ensured then their health can be improved. That can lead to a feeling of belonging in them, leading to self-esteem. Achieving all these steps is important for humans to achieve the final stage of the pyramid with self-actualization, which can create a harmonious and satisfactory working environment in human-machine, and human-human interactions (Lu et al., 2022).

In terms of safety, many systems today are reactive, but when human-machine collaboration is expanding, proactive safety and ergonomics measures must be taken to predict complex human movement and human – machine/Cobot interactions (Gualtieri et al., 2021; Malik & Brem, 2021).

This will increase the physical and mental well-being of the human on the factory floor and the trust in the machine they interact with. Also, when the human shares the floor with

Cobots the health of humans can be well improved as long-term musculoskeletal injuries related work can be shared with the smart assistant. This creates an ergonomic and happy environment for the human, and it develops more interest in the work he does (Lu et al., 2022).

When a human feels this belonging and feels that they are heard and actively involved, they thrive and become more creative (Lu et al., 2022). This eventually creates esteem in themselves and self-realization, creating more improvements to their personality and ultimately helping to nurture the machine interactions.

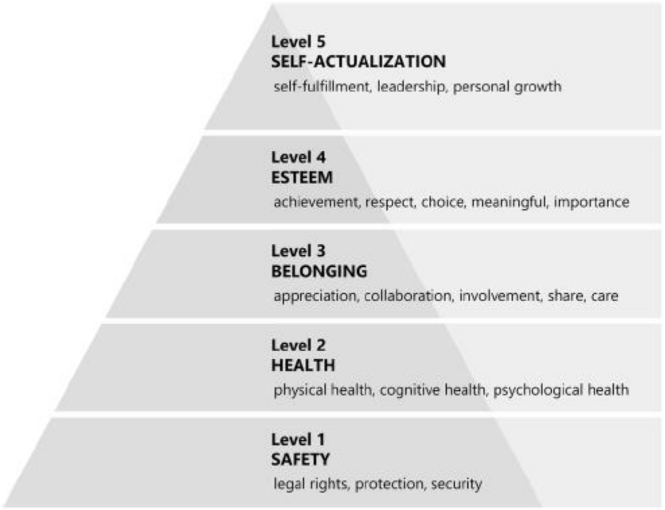

Figure 1: Industrial Human Needs Pyramid (Lu et al., 2022)

2.2.2 Sustainability

I 4.0 focused on profitability through digitalization. This techno-economic model was not sustained as it imbalanced the harmony among humans, technology, and the environment. This major limitation of I 4.0 is being addressed by integrating ‘Sustainability’ into all the aspects of an industry in terms of production, ethics, technology, economy, and workforce retention.

Circular economy at all stages of a product will be addressed by this approach. Initial design phase by advanced materials and nanotechnology usage, the secondary processing phase by intelligent manufacturing and intelligent resource utilization through predictions, and finally the end-of-life phase by sustainable re-integration of materials and resources (Moller et al., 2022; Zizic et al., 2022).

Also, sustainability driver encourages ethical technology aspect (Moller et al., 2022), such as quantum computing which uses optimized resource utilization to reduce costs (Marr, 2021).

Further, it also focuses more on human workforce training and development. This helps humans to find their place in the human-centric industry in a sustaining way (Moller et al., 2022; Momenta, 2023).

Through these, I 5.0 will be positioned at an ecological-economical-societal front (Zizic et al., 2022). This positioning will enable long-term sustaining human-machine interactions in the manufacturing industry.

2.2.3 Resilience

If a system can survive and function well despite the changes in the environment, then that system is resilient.

When the human workforce is better utilized more strategically and creatively by delegating the dull, dirty, dangerous work to the machines/Cobots, that work environment provides a resilient and human-centric work environment creating more jobs such as digital twin engineer, smart factory manager, etc. (Lu et al., 2022). This belonging nature creates self-esteem and self-actualization in the human workforce resulting in a happy ambiance for employees.

This ambiance will bring out more creativity in the human mind to create more advanced AI technologies for resilient systems such as self-configuring, self-healing, and self-optimizing digital platforms. This human creativity and advanced technology will exhibit more innovations, ultimately resulting in enhanced productivity (Lu et al., 2022; Zizic et al., 2022).

This will set the path for a thriving industry where humans take care of machines and vice versa. In other words, it creates human-machine interactions that are bidirectional in empathy, proactive, and collaboratively intelligent (Lu et al., 2022). Despite its importance, the introduction of resilient human-focused aspects in factory operations is an avenue that is not yet exploited (Ivanov, 2022).

Resilience can also be in terms of Resilience Engineering (RE) where it is focused on how a complex system will behave during sudden changes without compromising the safety and ergonomics of the human layer (Costantino et al., 2021). This is mostly studied for Human-Cobot integrations under four risk assessment areas: contact avoidance, contact detection and mitigation, physical ergonomics, and cognitive and organizational ergonomics (Valori et al., 2021).

In many frontiers, the risk assessment at a research level is not aligning with practical applications, when it comes to commercial-level applications the users require user-friendly simulations for risk assessment which can save time and cost (Huck et al., 2021). Also, the available frontiers indicate that only around 30% of research is focused on the ergonomic aspect while the majority is focusing only the safety (Gualtieri et al., 2021).

These research gaps emphasize that RE for safety and ergonomics of the human layer can get more attention with the I 5.0 transition in industrial applications, especially to predict highly vague human behaviour (Gualtieri et al., 2021; Malik & Brem, 2021). The evolution of simulation and modeling techniques, and AI algorithms, will therefore bring a ray of light to this important yet often ignored aspect.

2.3 Added features of I5.0

Hyper customization, cyber-physical cognitive systems, predictive maintenance, and smart additive manufacturing are introduced as added features of the I 5.0 transition, where humans can be integrated to create a hallmark feature to well position the industry at the ecological-economical-societal front (Maddikunta et al., 2022; Moller et al., 2022).

Hyper customization:

In I 4.0 mass personalization was encouraged. In I 5.0 however, customization is encouraged to satisfy every customer. Deep machine learning algorithms, quantum-inspired algorithms, computer vision, etc., can be adopted to analyze real-life data for the customization of products or services. Human creativity integration, results in these flexible and advanced technologies to achieve the manufacturing goals of the industry (Maddikunta et al., 2022; Moller et al., 2022; Zizic et al., 2022).

Cognitive cyber-physical systems (CCPS) :
This feature is a main area where human creativity is well utilized to develop more sophisticated CPS. These CCPS systems can continuously learn the creative and empathetic nature of the human mind for cognitive data analysis to achieve customization in manufacturing (Maddikunta et al., 2022; Oliveira et al., 2019). Human-Cobot harmonized working culture will be significant in these systems (Hadorn et al., 2015; Hummel et al., 2015; Maddikunta et al., 2022), therefore the human centricity through industrial human needs pyramid (Figure 1) will be an important point.
Currently, CCPS are being applicated in industrial safety, healthcare, and power generation sectors (Chen et al., 2020; Oliveira et al., 2019; Wang et al., 2020), manufacturing industry can make use of this feature for customized production through safe working conditions.
With the use of advanced manufacturing technologies such as CCPS, cyber security, and data protection become essential (Topal et al., 2020), emphasizing the need for improvement and standardization of relevant guidelines.

Predictive maintenance (PdM):
Another important feature in this transition of the manufacturing industry will be, foreseeing and optimizing machine downtime and changeover time to reduce production lead time. AI-led self-analyzed, self-healed, and self-optimized predictive maintenance schedules (Compare et al., 2020; Maddikunta et al., 2022; Zonta et al., 2020) will be used over the traditional planned / conditional maintenance schedules that are currently being used in the industry. This method will save unnecessary maintenance downtime and will help to maintain a healthy spare parts inventory level (Maddikunta et al., 2022; Zonta et al., 2020).
As the maintenance procedure can be shared with robots/Cobots, ergonomics of the human will be improved, and this can encourage a human-friendly workplace as the human workforce is proactively utilized than firefighting with machine breakdowns (Lu et al., 2022; Moller et al., 2022; Zizic et al., 2022).

Smart additive manufacturing:
Additive manufacturing (AM) or 3D printing was present in I 4.0 as a rapid prototyping tool for customer satisfaction during the design phase. This new feature of I 5.0 can be considered as an integration of smart manufacturing, sustainable manufacturing,
and additive manufacturing where, the product is personalized by adding layer by layer which reduces resource usage and ultimately helps for sustainability (Maddikunta et al., 2022).
Its current limitations will eventually be addressed (Haleem & Javaid, 2019) to be a value-adding feature of the manufacturing industry. With the adoption of SSAM, human creativity for product innovations and customizations need not be limited, as AI-led emerging technologies can provide flexibility in complex part generations (Maddikunta et al., 2022; Majeed et al., 2021).

I 4.0 to I 5.0 transition is yet another useful application of the decision-making theorem in game theory, where if all in a group do what is best for them and for the team, then there is a better chance of winning for everyone (Chen, 2022; Nash, 1950). Likewise, if this ecological-economical-societal approach was taken then everyone's interests will be satisfied with better outcomes than the techno-economic approach in I 4.0. I 5.0 therefore can be the solution to many current challenges in society (i.e.: aging population, resource scarcity, environmental pollution, and complex international relations), which can be addressed by human-CPS, human-machine interactions, human-Cobots/robot collaborations, and human-digital twins (Mourtzis et al., 2022).

3 DEVELOPMENT OF HUMAN-DT INTERACTION CONCEPT FOR MONITORING AND CONTROLLING CNCMTS / COBOT WORK-CELL

Computer-controlled Numerical Controllers (CNC) are widely being used in the manufacturing industry and are considered the heart of smart machining to date. However, a set of unique challenges come along with the use of CNCs.
During machining processes, heat is generated, and it can directly impact chip formation, tool wear, tool life degradation, and work-piece quality. This results in defective products, and pressures for re-work (Pereira Guimaraes et al., 2022). This creates a waste of resources, limits productivity, limits quality consistency, and ultimately creates a stressful work environment for the human workforce. Apart from that, tool wear and catastrophic failure of the tools can result in unforeseen machine downtime, which can impact production lead times and create stressful firefighting for the human workforce. With all this chaos in the current CNC-focused machining floor, we will be able to see more Cobots in the workspace with the I 5.0 transition, working side-by-side with humans as well as with other machinery.
We can visualize the complexity and sensitivity of this human-machine, human – Cobot, and machine – Cobot interactions, if not properly established and managed.
As discussed in section 2.1, this human-CNC-Cobot work cell will have to overcome its challenges in productivity improvement, by adequate use of information technology. Proper designing of a DT and the use of resilient AI algorithms to control this work cell for ecological-economical-societal well-being is proposed in this paper.

Liu et al., 2018 discuss a generic system architecture for CPMT (Cyber-Physical Machine Tools), explaining different network, data acquisition, and HMI possibilities that can be used when developing DT for CNC machine tools. The architecture has been validated through a prototype CPMT. Inspired by this generic architecture, we propose an original human-DT concept, taking safety aspects into account, which will be applied to a CNC-Cobot work cell. In contrast to the generic architecture which does not focus on human interaction with the CPS (Liu et al., 2018), this proposed human - Digital Twin concept for CNCMT-Cobot work-cell will find its positioning in the RE (Resilience Engineering as elaborated in section 2.2.3) avenue, that has more applicative research potential in the manufacturing industry, especially with human-Cobot interactions. Further, this DT will be a platform to address the PdM feature that is being introduced by I 5.0. In the latter part of this paper, we elaborate on how our proposed concept is aligning with the afore-described industrial human needs pyramid (Figure 1), which is essential to ensure the usability of the concept in human-centric industrial applications.

3.1 Proposed concept of human-DT for CNCMT / Cobot work-cell

CNC will be the main machine used in this work cell. A dedicated Cobot will be assigned to this CNC for simple operations such as mounting/demounting of the workpiece. A human will also be involved in this work cell for periodic interventions such as production quality inspection and attending to resolve CNC alarms. This whole work cell will be established as per the industrial Cobot safety, and occupational health and safety guidelines, post a methodical risk assessment.

Data exchanges, human involvement, and machine utilization of this concept are graphically represented below in Figure 2. Safety will be an inherent feature of this framework in both physical and cyber spaces, addressing the industrial human needs pyramid (Figure 1).

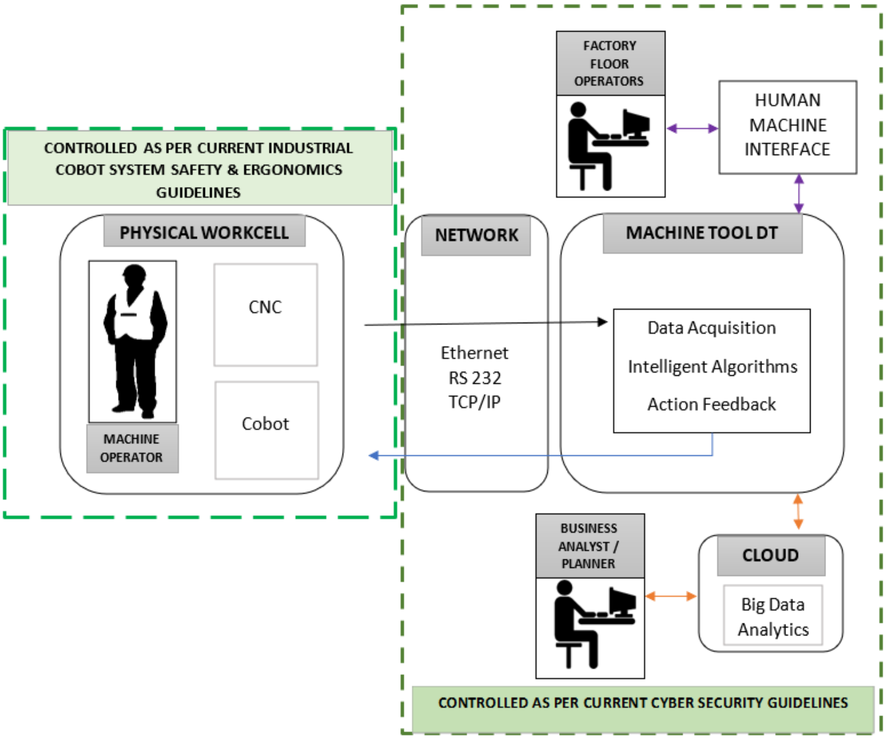

Figure 2: Architecture of Human-DT of CNCMTs-Cobot work-cell (Recreated with permission (Liu et al., 2018))

DT will be made for the CNCMT and Cobot movement. The CNCMT-generated sensor data will be sent to the DT for machine learning-based analysis for predictive maintenance of the tool. Moreover, once a new part geometry needs to be done, the DT will be used to identify the necessary speed and feed of the CNCMT as per the pre-trained path files. Which will allow reductions in changeover time, reduction in quality inconsistency, and ensure the protection of the tool. As human involvement is present in this work cell, the readings of an external light sensor will be passed through the DT to limit the Cobot movement as a contact avoidance measure.

In summary, the DT will be trained on real-time CNCMT data for predictive maintenance analysis. It will be pre-trained on historic CNCMT data for new part changeovers. External light sensor data will be sent in real-time to the DT to control the movement of the Cobot when human presence is detected.

The DT will be connected to the physical layer through Ethernet cabling with TCP/IP network communication protocol (RS232 will also be considered if applicable as per the device type and distance of the device connections). Open-source data acquisition methods such as OPC UA and MTConnect (Liu et al., 2018) will be used for data transfer between the cyber and physical layers.

3.2 Opportunities of the proposed human-DT concept

The opportunities in using this CNCMTs-Cobot Human-DT concept can be summarized in terms of the three key drivers of I 5.0 as described below.

Human-centric approach:

Implementation of Cobots can expose the human workforce mainly to mechanical, electrical, organizational, and psychological hazards, and to ergonomic hazards to a smaller extent as well (Costantino et al., 2021). Moreover, complexity and human behaviour are two main challenges (Huck et al., 2021) that we can anticipate in this CNCMTs-Cobot work cell. Therefore, risk assessment and corrective measures during the design phase are important for this application.

As the focus of this research is not to develop a risk assessment model, we will be using an open-source risk assessment platform such as the COVR toolkit (Valori et al., 2021), as per current ISO 10218-2 standard (Huck et al., 2021) and industrial Cobot system safety and ergonomics guidelines (Gualtieri et al., 2021; Malik & Brem, 2021) when establishing the work-cell.

DT is identified as the ‘next wave’ for the simulation of human-robot collaborations (Malik & Brem, 2021). Our DT will, therefore, be a timely tool to predict the operator’s movement and guide the Cobot accordingly.

This Human – DT is focusing on improved human-machine interactions, where the human does not continuously be involved with the CNC or Cobot to guide the operations. As the repetitive and tedious tasks are assigned to the Cobot, it will also give psychological well-being to the human.

The big data saved in the cloud can be used by any level of employees to make strategic and innovative decisions for the continuous improvement of the industry.

Sustainability:
The DT will be programmed using intelligent algorithms and artificial intelligence to predict the CNCMT health, cutting tools condition, parts' quality, and power consumption. As it optimizes the machine resource utilization and ensures the 'right first time' products, the process becomes optimized and ultimately creates a low carbon footprint in the process.
It also gives a long-term financially feasible solution to keep the quality consistent and reduced lead time to achieve profitability in customized productions.

Resilience:
This CNCMTs-Cobot work cell can address the dull, dirty, and dangerous work in machining as per the directions it receives from the human via the DT. This enables more time for humans to be involved in creativity and complex cognitive thinking that can develop the business proactively.
This DT will be using resilient machine learning algorithms for tool life predictions, workpiece classifications, and operator movement, which can help the operator by better scheduling and delegation of work in a safe and ergonomic work cell.
This also ensures that human is not replaced by technology but be better utilized. When the human layer is taken care of, the business will be taken care of by the humans.

The combination of these opportunities ensures the adoption of the industrial human needs pyramid (Figure 1) that was discussed above. This DT concept can therefore ensure a smooth I 4.0 to I 5.0 transition in the machining industry by appropriate use of human-machine interactions.

4 CONCLUSION

Industrial revolutions and evolutions can be advantageous to industries. Achieving the transitions with fewer hassles is the dream of many business owners. Current I 4.0 provides many assured advantages to the manufacturing industry to overcome its challenges as described. Looking into the future, transitioning from I 4.0 to I 5.0 can provide more advantages to these businesses when the right features are adequately used.

The proposed human - digital twin concept addresses this necessity by looking at the practical transitioning phase of the companies that have already invested in smart machining technologies. This Digital Twin will predict and control the CNC machine tools and will guide the Cobot that is assigned to the CNC work cell.

DT will continuously gather real-time data to analyze the machine tool's health and condition, quality of production, and consumption of power. These data can be utilized for proactive business-specific strategic decisions such as predictive maintenance schedules, tool inventory management, on-time quality inspections, and power consumption optimizations.
Apart from that, it can also be used in this customization era for simulations of rapid prototyping, new product commissioning, and testing. This can provide real-time analytics on the expected outcome without producing a physical product, enabling more innovative product designs and developments.
Most importantly, safety features will be inherent in designing both physical and cyber levels of this human-DT. Therefore, business owners need not be worried about the embrace of technology.
Not only that all these functions will provide profits and brand image for the business, but also will enable a low carbon footprint due to optimized machine and material usage. This feature can create added value to the business as an eco-friendly industry.

With the adoption of this concept, the human workforce will be better utilized in more strategic, ergonomic, and creative ways than continuously observing or intervening in work-cell operation. With that, this concept will address all the tiers of the industrial human needs pyramid through the three key drivers of the I 5.0 transition. It will give a better human-machine interaction to this complex and critical industrial layout to increase productivity while ensuring human-centricity.

This proposed concept is currently an ongoing project which will thoroughly investigate and validate the practical usability through a model work cell. With methodical implementation, this concept of human – DT of CNCMTs-Cobot work-cell can address the I 4.0 to I 5.0 transition of the machining industry. Future research work can be extended to other similar workspaces and industries by referring to this concept.

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