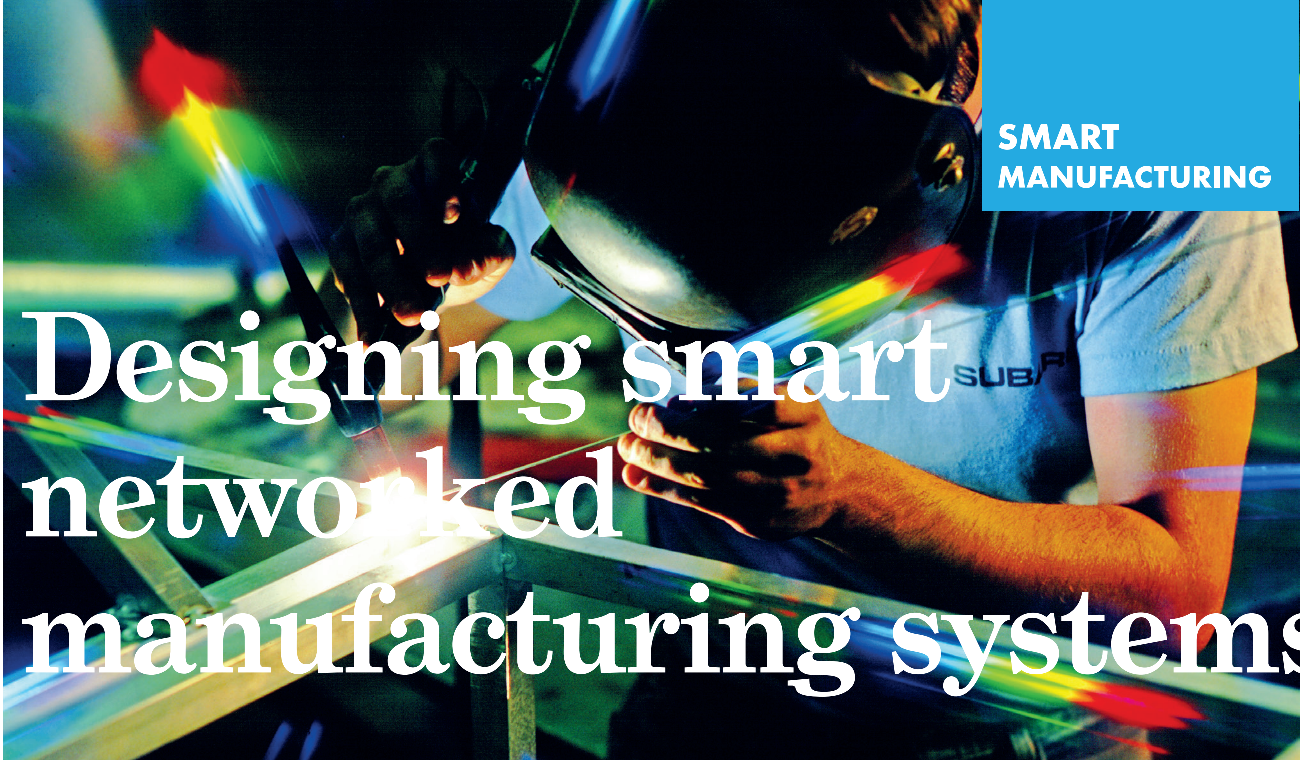


Designing smart networked manufacturing systems

With a view to fostering discussion on designing smart networked manufacturing systems, this article examines the following: the latest trends in manufacturing, bridging physical and cyber worlds, the benefits of Industry 4.0, an architecture for the realisation of the Fourth Industrial Revolution as a digital thread and a digital twin, addressing the real industrial problem via the DFDM Framework, and ways forward and plans for the digital transition of industry. By **Jelena Milisavljevic-Syed[1] , Janet K. Allen[2] , Sesh Commuri[3] , and Farrokh Mistree[4]**

In global markets characterised by dynamic changes and necessitated by changes in customer preferences, timely adjustments are required in manufacturing to meet fluctuating demands. Conventional manufacturing processes are designed for mass manufacturing and are not suited for agile, flexible and highly reconfigurable smart manufacturing. Foundational to the Industry 4.0 construct is digitisation that should be harnessed for smart manufacturing. Hence, we propose designing smart Networked Manufacturing Systems that embody Design for Dynamic Management (DFDM). The DFDM framework is a service-oriented product/system development computational framework that facilitates the harmonisation of conflicting needs associated with the design and manufacture of engineered systems.

The trend

Bringing together technologies such as Internet of Things (IoTs), Big Data Analysis, Machine Intelligence with conventional technologies such as Smart Automation, Supply Chain, Logistics, and Cloud Computing has resulted in a new wave of advances in Manufacturing Technology collectively called Industry 4.0[1]. Industry 4.0 represents the Fourth Industrial Revolution and provides a framework for digitization of manufacturing.

Connecting physical and cyber worlds

Industry 4.0 is characterised by a digital model of an end-to-end supply network and all the manufacturing processes. It provides a mechanism to transfer autonomy from the physical realm to the cyber-physical realm [2]. Central to the adoption of Industry 4.0 is the concept of the 'Digital Twin'. The Digital Twin is a virtual replica of every entity in the manufacturing process and allows the bridging of the physical and cyber worlds. Such a bridge allows for seamless data exchange in real-time between the physical world and the virtual representations. Since the digital twin represents a high-fidelity model of the physical processes, it can be used to analyse the overall performance of the physical system, diagnose performance, and invoke data analytics and learning strategies to improve system performance.

The benefits

To appreciate the benefits of Industry 4.0 it is essential to realise the full value chain that includes the supply networks, customer and markets. Digitisation of processes across the value chain enable new capabilities such as personalisation, real-time alerts and interventions, innovative service models, dynamic product improvement, increased productivity, higher up-time and, ultimately, new business models.

Architecture for realisation of digitised manufacturing in Industry 4.0.

Digitisation of manufacturing systems that conforms to the Industry 4.0 construct is not a trivial task and can only be realised through the adoption of an appropriate computational architecture; see **Fig. 1**. The architecture must facilitate the integration of digital threads in two ways. The vertical integration of a digital thread facilitates the flow of information between the enterprise and resource planning entities to manufacturing services and planning and control entities within a manufacturing facility, see **Fig. 1**. In the vertical integration low-level components such as IoT sensors, machine controllers and their digital twins across the manufacturing enterprise are networked with big data analytics to monitor the manufacturing process and improve system performance and product quality. Vertical integration also allows for the creation of interoperable 'systems of systems' that can integrate a seemingly diverse set of machines, sensors and controllers to produce a resilient manufacturing process that is capable of withstanding disruptions in the supply network, environment and in the market. Horizontal integration deals with data and material flows across the end-to-end value chain, see **Fig. 1**. The horizontal integration is represented by several digital twins from the supply chain and the manufacturing processes, data flows and IT systems in the product development, to logistics, distribution and ultimately the customer. Elements of the architecture are expanded on in the context of digitised manufacturing processes in the steel industry and are discussed next.

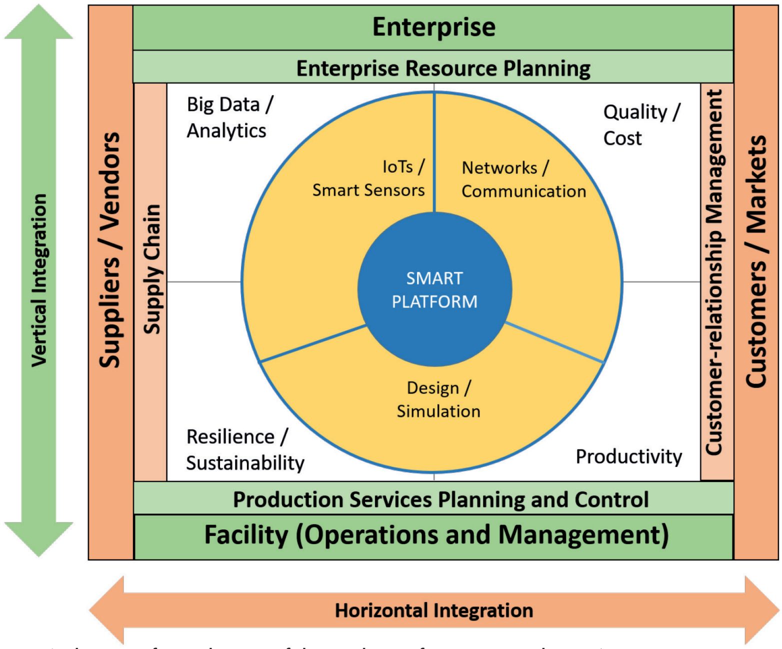


Fig 1. Architecture for realisation of digitised manufacturing in Industry 4.0

Digitised manufacturing

A steel manufacturing process consists of number of unit operations, such as ladle refining, tundish processing, continuous casting, rolling, heat treatment, etc., where each requires proper attention and control [3]. A representation of the different operations involved in the production of sheets (product) from slabs (semi-product after casting) is shown in **Fig. 2**. Each of the operations in the process is performed within specified tolerances, outlined in five scenarios in **Fig. 2**.

We describe different scenarios, (see **Fig. 2**) that may occur in a steel manufacturing process.

Scenario 1

If we have an ideal situation, a process without errors where models used to represent the process are complete and accurate, and all data are known, then we have an ideal manufacturing process. The outcome is a product of acceptable quality.

Scenario 2

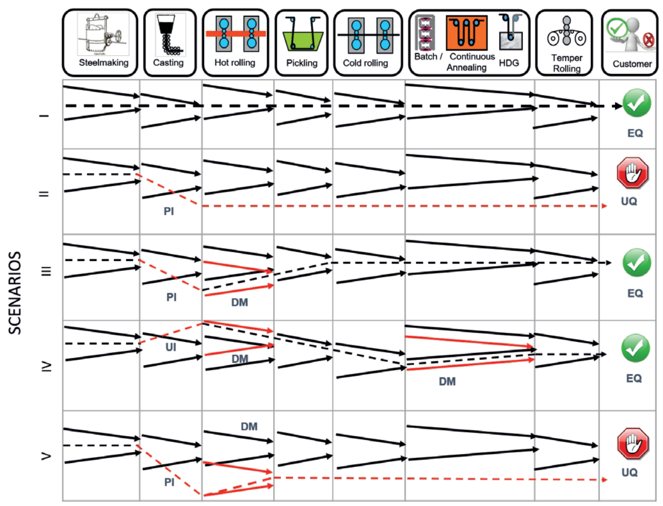
A lack of thermal and chemical homogeneity results in an error associated with the reduced cleanness of the steel [4]. Such an error may appear during continuous casting when the molten metal is in the tundish, the second column in Fig. 2, due to the inability to maintain superheat. Further, due to the characteristics of a networked manufacturing system (NMS) these errors will propagate through the remainder of the process and affect the final product quality[5]. The outcome is a product of unacceptable quality.

Scenario 3

If a processing error that appears in Stage 1 cannot be fixed, then we can make improvements in subsequent stages to ensure a product of acceptable quality. The way to do it is to design a system to make changes by identifying the location and cause of the error, and then take steps to correct the error. As a result, the process rebounds and continues within specified tolerances. The outcome is a product of acceptable quality.

Scenario 4

Since mathematical models that are used to simulate the process are incomplete and inaccurate, we must manage the uncertainties embodied as a result in the



Key:
PI: Processing issue
UI: Uncertainty issue
DM: Dynamic management
EQ: Excellent quality
UQ: Unacceptable quality

Fig 2. Problem description - design and analysis of steel manufacturing process

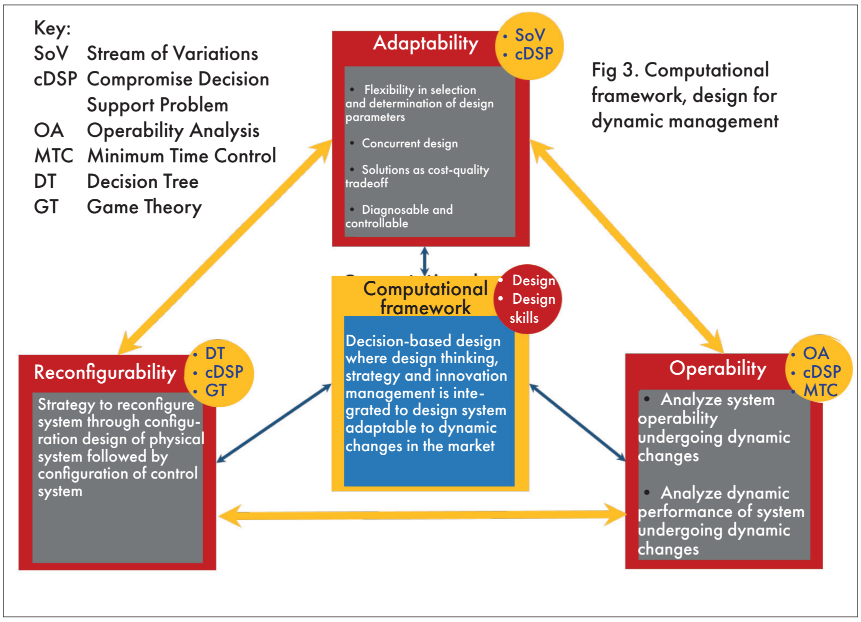


Fig 3. Computational framework, design for dynamic management

mathematical control algorithms. Uncertainties may appear due to inherent randomness or unpredictability of a system, model parameters uncertainty, and model structure uncertainty[6]. Hence, we need to design the system to be operable, to manage uncertainty, transit and stabilise in the presence of change and get back on track within specified tolerances.

Scenario 5

If critical errors appear that cannot be fixed, we can design a system to observe, detect but not to mitigate errors nor manage uncertainty. In this case the decision is to reconfigure the system and not proceed with this process [7, 8].

In the context of the preceding we identify key requirements for a computational framework for a smart networked manufacturing system.

Computational framework

A smart networked manufacturing system (NMS) must be adaptable to dynamic changes and respond to unexpected disturbances, and uncertainty. Additionally, fault-tolerance and robustness to disruptions are critical requirements that must also be addressed in the design. Maintaining connectivity among elements of the process is one of the key characteristics necessary for these systems to be integrated into the architecture. Ultimately, the long-term viability of the system depends on the capability to glean information from the various data streams in the process and learn in real-time to optimise and manage the process. This information is also necessary for the long-term health and resilience of the system. Current manufacturing systems have been designed for large-scale manufacturing of a product in the most efficient manner. Hence, we advocate the design of smart NMS that is able to adapt to rapid changes in product requirements, a system failure occurs because of a breakdown of interconnectivity between elements of the NMS that existing approaches cannot easily handle. Foundational to a smart NMS is a computational framework, Design for Dynamic Management (DFDM), see **Fig. 3**.

DFDM has three critical components: adaptable and concurrent design, operability analysis and reconfiguration strategies [9]. Adaptable and concurrent design methods offer flexibility in selection of design parameters and the concurrent design of the mechanical and control systems [10]. Operability analysis is used to determine the functionality of the system undergoing dynamic change [11]. Reconfiguration strategies allow multiple configurations of elements in the system.

The limitation of the DFDM is that we cannot design processes to mitigate errors when the processing takes place at a station, but the effect of the error in the process is only seen in subsequent stations.

Way forward

We contemplate expanding DFDM to address feed-forward dynamic management, **Fig. 4**, where tools and sensors communicate with each other via the Internet of Things (IoT), and sensors data is used to create enriched digital system models (Digital Twin) to achieve process control, advanced measurements, perfect product, and fast process development.

With feedforward dynamic management we are able to use information picked up by sensors (Step 1 in **Fig. 4**), to explore the solution space (Step 2 in **Fig. 4**), manage the process through smart design through decision-making process (Step 3 in **Fig. 4**), capture and reuse the knowledge with off-line model (Step 4 in **Fig. 4**) for future design or reconfiguration of the process (feed forward control of the process, Step 5

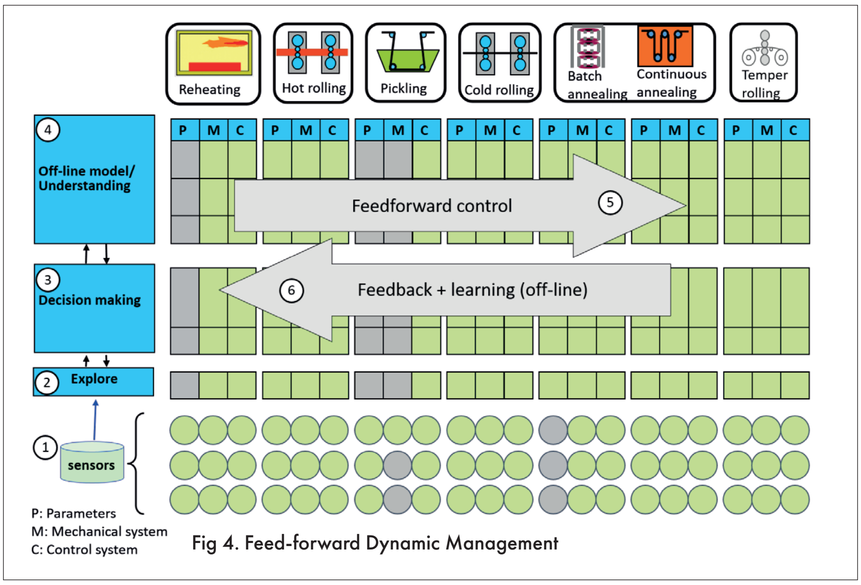


Fig 4. Feed-forward Dynamic Management

in **Fig. 4**). In the next iteration we will obtain new information (feedback learning, Step 6 in **Fig. 4**) that will be further captured and reused. This is an iterative cycle of exponential learning that is foundational to incorporating intelligence in feed-forward dynamic management of NMS.

The resulting outcome is a next generation of smart networked manufacturing systems adaptable to rapidly changing market requirements, resulting in higher quality products and at a lower rework cost. To transition this framework to industry we suggest that DFDM be extended to a Smart Platform, **Fig. 1**. Some possible extension of DFDM in various industries are illustrated in **Fig. 5**:

- Cyber-physical design. Model-based intelligent decision-based design systems. We speculate that there are applications in steel making processes.
- Cyber-physical-social system design. Model cyber-social design decision network in the realisation of intelligent cyber-physical-social systems. We speculate that there are applications in smart healthcare systems and so on.
- Cyber-physical product and material design. Integration of materials, products, and manufacturing processes. We speculate that there are applications in the design of smart sports equipment.
- Cyber-physical manufacturing. Design of reconfigurable intelligent manufacturing systems. We speculate that there are applications in additive manufacturing, and semiconductor lithography processes.

Closure. In furtherance of Industry 4.0 we advocate the realisation of smart Networked Manufacturing Systems. We suggest that Design for Dynamic Manufacturing is foundational to the realisation of smart NMS. In the International System Realisation Partnership (ISRP) we are creating a Cloud-based Design and Manufacturing (CBDM) platform with potential applications in cyber-physical design, cyber-physical manufacturing, cyber-physical product and material, and cyber-physical-social system design. Further, we speculate that CBDM will be transitioned to industry and be applied in the steel making processes, additive manufacturing, design of smart healthcare systems and so on. For more information please visit: www.liverpool.ac.uk/engineering/staff/jelenamilisavljevic-syed.

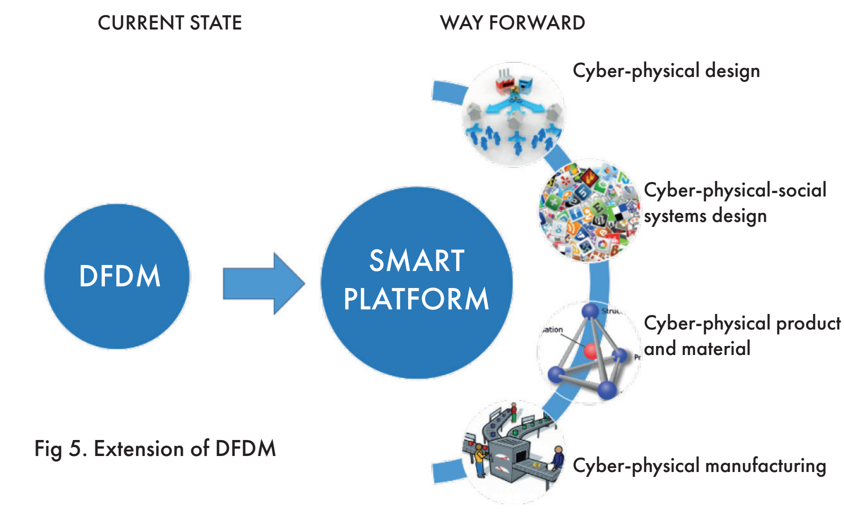


Fig 5. Extension of DFDM

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1. Corresponding author. j.milisavljevic-syed@liverpool.ac.uk Division of Industrial Design, University of Liverpool, Liverpool, L69 3GH, UK.

2. Systems Realisation Laboratory, University of Oklahoma, Norman, Oklahoma 73019, USA.

3. Department of Electrical and Biomedical Engineering, University of Nevada, Nevada 89557, USA.