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Design of networked manufacturing systems for Industry 4.0

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Abstract

Advances in internet technologies have spurred global growth in manufacturing on an unprecedented scale. Distributed global manufacturing requires these industries to support flexible, large scale automation to meet dynamically changing user requirements and to allow interconnection for data exchange between various components of the manufacturing enterprise. The proceeding needs are addressed with design of Networked Manufacturing Systems (NMS) anchored in Industry 4.0. In this paper, we address the requirements for and the salient features of the design of NMS illustrated using an automotive panel stamping process.

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Keywords: Networked manufacturing systems; adaptability; operability analysis; cyber-physical design and manufacturing (CBDM)

1. Frame of reference

Networked manufacturing systems (NMS) are complex facilitating one or more operations required to assemble or manufacture a product. Typical examples of networked manufacturing systems (NMS) are automotive machining, packaging processes, semiconductor lithography processes, etc. NMS have characteristics of both mechanical systems and control systems. One of the problems to be addressed is dimensional variations in the finished product due to imprecise fixturing of parts, deterioration of tools, or sensors over time. Dimensional variations can occur in one or more stages of manufacturing. These errors accumulate and propagate through the process and affect the final product quality. The degradation of quality impacts process productivity, efficiency, and result in increased process cost [1 - 3].

Why are networked manufacturing systems needed? Modern manufacturing is characterized by global, distributed assembly and manufacturing systems that are greatly impacted by wide variations in customer needs/preferences. Further, we are at the threshold of the 4th industrial revolution where mass customization, globalization, interconnectivity between devices and smart (digitized) manufacturing are the trends. Global competition requires enterprises to be able to respond to these changing requirements in a cost-effective and timely manner while maintaining product quality [3].

What are the requirements? To respond to these changes in the market, in the context of Industry 4.0, it is required for an NMS to facilitate flexible production in the system.

What is the challenge? The challenge is to design an NMS that can accommodate dynamic changes, and respond to unexpected disturbances while managing complexity and uncertainty.

Why it is important to address this challenge? Integrating flexibility in selection/determination of design parameters affects not only the dimensional quality of the product but also the cost of the process. Resolving this issue provides a design engineer with better design alternatives and the opportunity to select an NMS configuration that is robust to variation. Integrating flexibility in an NMS is necessary to accommodate unexpected modifications in the manufacturing process. The mechanical and control systems are interrelated and cannot be selected in isolation. Simultaneously addressing both mechanical and control systems at design-time can support

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flexible production and improve the design of the NMS [3, 4]. Further, such a design can help maintain functionality and performance of an NMS in the face of disturbances or when requirements change [3]. Lastly, the ability to switch configurations and adapt to changes / disturbances is important to maintain and (re)establish connectivity between elements of NMS [5].

Making it happen? A critical review of over 250 publications is included in [3]. In Table 1, in the context of adaptability, operability and reconfigurability, we include a summary that differentiates our work from that of others, namely, current approaches for designing manufacturing systems are primarily for large-scale manufacturing of a product in the most efficient manner. These processes cannot easily handle the design of robust NMSs when the requirements are partially known, product requirements change/vary in a dynamic manner, or when a system failure occurs because of a breakdown of interconnectivity between elements of the NMS. As an answer to these challenges, in this paper, we propose a computational framework, Design for Dynamic Management (DFDM), to support flexible, operable, and rapidly configurable NMSs. This framework is foundational for further digitization of an NMS, Fig. 1. The use of DFDM is illustrated using an automotive panel stamping process.

Table 1. Rationale for development of computational framework for dynamic management.

Aspect	Method	Analysis	Gap	Question	Answer
Adaptability	Material planning (MRP), Kanban control systems, Hybrid strategies [9] Stochastic modeling of manufacturing systems [10]	• Material planning and push, pull, and hybrid control strategies • Stochastic modeling of manufacturing systems where the production function and inventory control • Effect of variability in process times and the size of buffers between stages on the overall performance in terms of production rate and average in-process inventory	While these methods are well known in the literature and have found extensive use in the analysis of manufacturing systems, they are not suited for use in the design of NMS to achieve a specified quality of the manufactured product.	What is the method that facilitates adaptable and concurrent design in the realization of networked manufacturing systems in the context of Industry 4.0?	Computational Framework, Design for Dynamic Management (DFDM)
Operability	• Inherent operability of a process without specific control structure • Safe operating regions and tolerable disturbances with the available inputs • Minimum-time control problem formulation [11]	• Set-point controlled - outputs to be controlled at a desired value • Set-interval controlled - outputs to be controlled within a desired range • Operable regions and tolerable disturbances with the available inputs • Minimum-time formulation evaluates the operability of the process without considering a preassigned feedback controller • Time-optimal control problem formulated as a nonlinear programming problem	While these methods are well known in the literature and have found extensive use in the plant design, they are not suited for use in the design of NMS. Applicable if design engineer has domain knowledge.	What is the method that facilitates dynamic change over time/change in the realization of networked manufacturing systems in the context of Industry 4.0?	
Reconfigurability	• Reconfigurable manufacturing system (RMS) [12] • Reconfigurable manufacturing tool (RMT) [6]	The core characteristics and design principles of RMS The structure recommended for practical RMS Module selection and the assembly relationships among modules in RMT	Verified with simple reacting system. For complex systems such applications would require the solution of larger optimization problems and multivariable controllers.	What is the method that facilitates rapidly changing market requirements in the realization of networked manufacturing systems and remains it competitive in the context of Industry 4.0?	

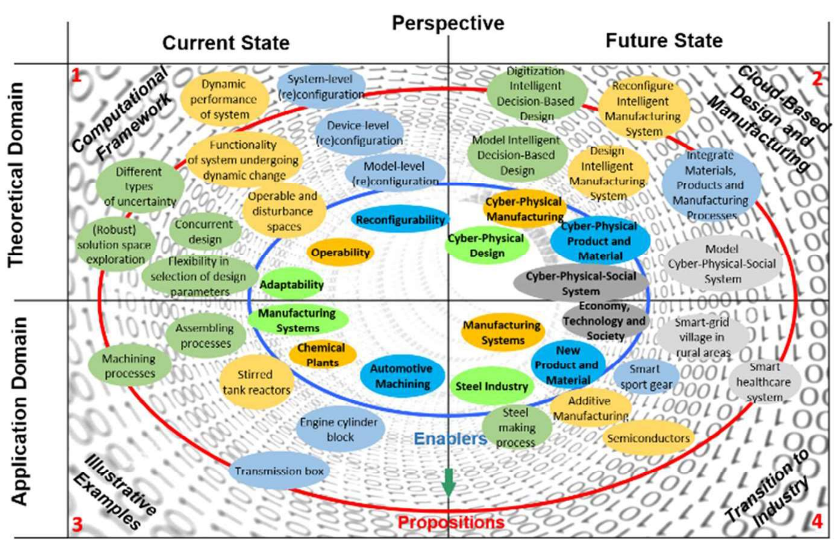

Fig.1. Mental model for DFDM.

Possible way forward? DFDM Framework that is proposed is flexible and can be adapted for the design of dynamic systems other than NMSs.

Some possible theoretical analyses that can be addressed using DFDM are identified in Quadrant 1 in Fig. 1, and possible applications are identified in Quadrant 3 in Fig. 1. In the future, DFDM can be extended to Cloud-based Design and Manufacturing, Quadrant 2 in Fig. 1, and to applications in smart networked systems, Quadrant 4 in Fig. 1. Some possible extension of DFDM in various industries are the following:

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

The remainder of this paper is organized as follows. In Section 2, we present a brief description of DFDM. In Section 3, we present a panel stamping process as an illustrative example. In Section 4, we present the mathematical model of the cDSP formulation. In Section 5, we discuss the flexible and functional design of a panel stamping process in cyber-physical design and manufacturing. The closing remarks are presented in Section 6

2. Computational framework for design of networked manufacturing systems

With the computational framework of Design for Dynamic Management (DFDM) some of the thorny problems in the design and analysis of NMS can be addressed. With this framework the needs of Industry 4.0 can be addressed in the future. The computational framework of DFDM is presented in Fig. 2 and the steps in implementing this framework are presented in Sections 2.1 – 2.3.

2.1. Step 1 - Adaptable Concurrent Design

Is the system flexible? As a response, we propose Adaptive Concurrent Realization of Engineering Systems (ACRONES) to fit n-stage NMSs with a set of constraints and goals guided by rapidly changing requirements. ACRONES is based on the Stream of Variation (SoV) method to model the NMS and the compromise Decision Support Problem (cDSP). The cDSP is used to manage the structure and information of decision-making within adaptability models with and without uncertainty. For more information about the ACRONES see [3, 4].

2.2. Step 2 - Operability Analysis

What is the functionality and dynamic performance of the system? Based on the output information we obtain from Step 1, Section 2.1, we frame operability and disturbance spaces. Hence, we propose a Steady-State Operability Model (SSOM) to analyze system functionality, and Dynamic Operability Model (DOM) to analyze the dynamic performance of the system. These models are based on Operability Analysis (OA), cDSP, and Minimum Time Control (MTC) to determine a response of a system undergoing dynamic changes. For more information see [3].

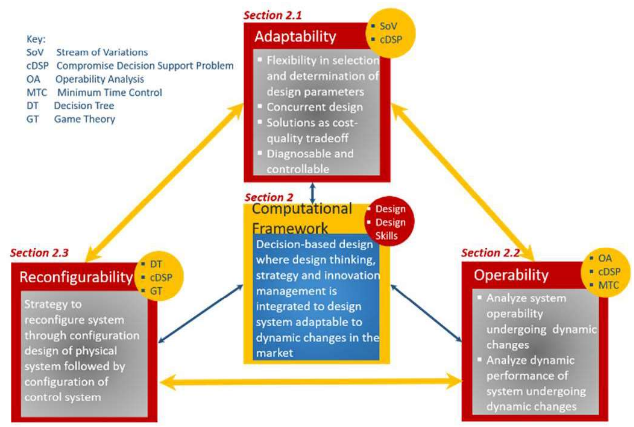

Fig. 2. Computational framework design for dynamic management.

2.3. Step 3 - Reconfiguration Strategy

What is the reconfiguration strategy? Based on the information from Step 2, Section 2.2, we can determine whether the elements in the system are connected and if not how the system should be reconfigured. We hypothesize that different configuration strategies support the repeated systemic reconfiguration among elements in the system, particularly for the Reconfigurable Machine Tools (RMTs), the Reconfigurable Inspection Systems (RISs), and Reconfigurable Manufacturing Systems (RMSs). Reconfiguration strategies are based on Decision Trees (DTs) which are used to transform RMT/RIS configurations from various module libraries into one comprehensive representation, with the cDSP and Game Theory (GT) to explore interactions between RMT and RIS. For more information see [5, 6].

In the proposed computational framework, both consumer and producer preferences are integrated to design a cyber-physical-product-service system of low-cost and high-quality which is adaptable to dynamic market demands. The current status of our work on DFDM is on its uses in cyber-physical design and manufacturing while in future we anticipate accommodating cyber-physical products and materials, and cyber-physical-social systems, Quadrant 2 in Fig. 1.

3. Illustrative example

Design of an NMS has several possible applications, see Quadrant 3 in Fig. 1, (e.g., assembling processes, design of a chemical plant, design of a transmission box, etc.). However, in this paper we illustrate design of an NMS with an automotive panel stamping process.

The challenges in the design of NMS are illustrated through a two-dimensional panel stamping process in which four parts are assembled across three stations, Fig. 3. Each part is restrained by a set of fixtures (Pi), and each position of a part is measured by a coordinate sensor (Mi). At Station 1 Parts 1 and 2 are assembled. In Station 2 Parts 1 and 2 are made into a Subassembly 1 that are assembled with Parts 3 and 4. At Station 3 all parts are assembled in final assembly. Each part at each station has up to 2 sensors that are measurement points. The total number of measuring points is Mi (i=1 – 20). Fixture locators can be active and inactive. There are two types of fixture locators, namely, a 4-way pin, and a 2-way pin.

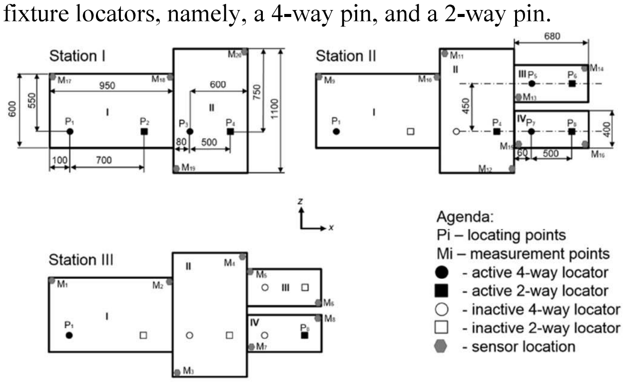

Fig.3. Two-dimensional panel stamping process [7, 8].

4. The mathematical model

In this paper, we address a two-part problem: (1) provide flexibility in the selection and determination of values of design parameters (tool and sensor attributes) that give satisfying (robust) solutions regarding the process cost and quality of product; and (2) provide for the determination of input ranges that give functional system design and satisfying dynamic performance of a system in the presence of changes in requirements. The problem characteristics are the number of work stations, N, the number of parts, n_p, the number of sensors, M_Pi, the number of tools, P_i, and the potential fixture failures in the process, m_r. The requirements for the process are diagnosability, controllability and operability and these must be full. Expected variations, y_k, must lie between -0.8 and 0.8 millimeters. The assumptions are that the expected variations parameters follow Gaussian distribution with zero mean and known covariance. The overall objective is to minimize the process cost and maximize product quality.

The first part of the problem is simulated with the adaptability model, Section 4.1, and the second part of the problem is simulated with the operability model, Section 4.2.

4.1. The adaptability model

The adaptability model is based on the SoV model that we use to model an NMS and identify mechanical and control system drivers and is further partitioned inot smaller process decision and performance measurement cDSP models, the upper part of Fig. 4. The cDSPs models are used to build in flexibility in the selection/determination of design parameters and manage the structure and information of decision-making. For more information about the adaptability model see [3, 4].

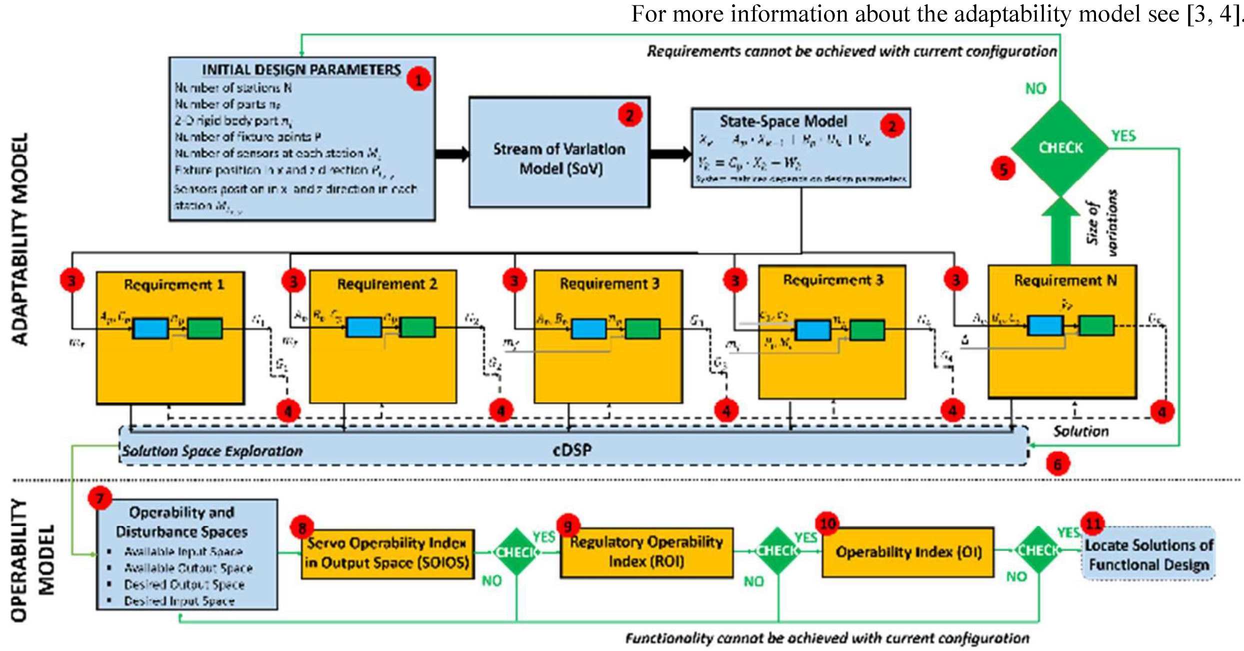

Fig.4. Adaptability and operability model.

Table 2. The compromise decision support problem (cDSP) formulation.

Given (Parameters)	
Total number of operational stations	N
Number of stamping parts in the process	n_p
Number and position of fixture points	P_i [-]; (x, z) [mm]
Potential number of sensors and position	M_{Pi} [-]; (x, z) [mm]
Dimensional quality (size of variations) boundary values are set	Y_k [mm]
Find (System Variables)	
Total number of sensors and sensing stations	$M_{Pi,M}$; $M_{S,M\ (M=D,C,E)}$
Use of PT`s control actions	PT
Sensing penalties	P
Sensors distribution schemes that are diagnosable, controllable, and cost-effective	$M_{i,k}$
Satisfy (Constraints)	
Tooling constraints	Use of programmable tooling, Eq. 3.6 in [3]
Sensing constraints	Number, position and distribution of sensors, Eq. 3.6 in [3]
Process diagnosability	100% or partial, see Eq. 3.3 in [3]
Process controllability	100% or partial, see Eq. 3.5 in [3]
Satisfy (Bounds)	
Lower and upper number of sensors	$M_{Pi,M\ (M=D,C,E)}$, Section 4.2 in [3]
Lower and upper number of sensing stations	$M_{S,M\ (M=D,C,E)}$, Section 4.2 in [3]
Use of programmable tooling	PT, Section 4.2 in [3]
Lower and upper limit of sensing penalties	P, Section 4.2 in [3]
Deviation variables	$d_i^-, d_i^+ \geq 0$, Section 4.2 in [3]
Goal 1: Maximize process adaptability	Chapter 4, Section 4.2 in [3]
Goal 2: Maximize process operability	Chapter 5, Sections 5.1 and 5.2 in [3]
Minimize (Deviations)	
Minimize deviation function	
$Z = \min \sum_{i=1}^{3}(W_i d_i^- + W_i d_i^+); \sum_{i=1}^{3} W_i = 1;\ W_i \geq 0;\ d_i^-, d_i^+ \geq 0; d_i^+ \cdot d_i^- = 0\ \ (i = 1-3)$, Section 3.2.1 in [1]	

4.2. The operability model

The operability model is used to analyze the functionality and dynamic performance of the system as the system requirements change. Operability analysis (OA) is accomplished in two stages: steady-state operability analysis and dynamic operability analysis. In this paper, we focus on steady-state operability analysis. Steady-state operability is used to analyze how different requirements, driven by customer preferences, change system functionality. System functionality is analyzed using a Steady-State Operability Model (SSOM) that is based on OA and the cDSP construct, as shown in the lower part of Fig. 4. For further details of the steady-state operability model see [3]. In Section 5, we present the flexible and functional design of the panel stamping process.

5. Flexible and functional design of the panel stamping process

The specification of system variables and their effects on the overall cost and quality of the NMS are difficult to ascertain before implementation. For the sake of illustration, five sensors are assumed to be available for use in the design of the panel stamping process. The results are obtained using a MATLAB simulation.

5.1. Flexible design of panel stamping process

In this section, we answer the question "How does the selection of design parameters (sensors and sensing stations) influence the cost of the process and dimensional quality of the product?"

In Fig. 5 a), it can be seen that when we are using 2 sensing stations the cost of the process is lower than when we are using 3 sensing stations. Further, in Fig. 5 b) and c), the expected size of variations is lower when we are using 2 sensing stations than 3 sensing stations. With the use of 2 sensing stations in the process, we design a low-cost and high-quality system in which all requirements are satisfied.

Our recommendation is that "less is more" with a reduced number of sensing stations we lower the cost of the process and obtain a high quality of the product. Further, the dimensional quality is not improved by an increase in the number of sensing stations but rather with a proper distribution of adequate numbers of sensors.

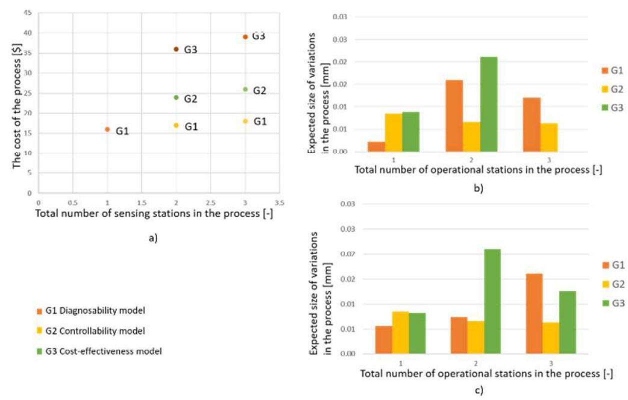

Fig.5. Cost of the process and dimensional quality of the product.

5.2. Functional design of panel stamping process

In this section, we answer the question "Is the system functional in the presence of disturbances?"

In order to analyze system functionality we need to obtain information regarding Available Input Space (AIS), and Desired Input Space (DIS). AIS are inputs of the process which are able to change over a certain range, identified as the feasible design space. AIS is obtained by exercising the adaptability model, shown in Section 4.1 and Fig. 6, a). DIS is the set of input values required to reach the entire Desired Output Space (DOS). DIS is framed according to customer preferences, Section 4.2 and Fig. 6, b).

The Operability of the system is full (a system is functional) where customer preferences (DIS) intersect with ranges of change (AIS) in the presence of disturbances (natural uncertainty) where system can stabilize, Fig. 6, c).

In summary, the solution scheme shown in, Fig. 4, is an elegant and efficient way to explore the solution space and identify both flexible and functional design in cyber-physical design and manufacturing. Exercising the example gives the opportunity of visualizing the dependence of the cost on the number and location of the sensing stations in the process, Fig. 5, a).

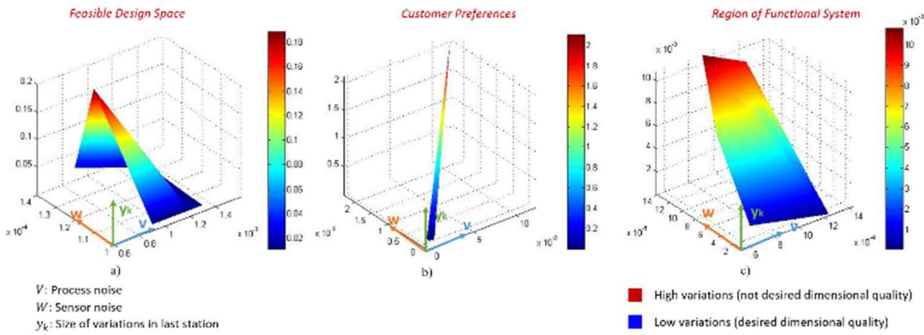

Fig.6. System operability.

However, dimensional quality is improved not by increasing the numbers of sensing stations in the process, Fig. 5 b) and c), but rather by the appropriate selection of the design parameters and sensor distributions. Furthermore, the system is functional where customer preferences intersect with feasible design space even in the presence of disturbances as long system can stabilize, Fig. 6, c), under dynamic change of the requirements.

6. Closure

In this paper, we present a computational framework, DFDM, suited for theoretical analysis of Networked Manufacturing Systems and for addressing the design needs of multi-stage manufacturing processes. In the context of Industry 4.0, DFDM can be used to design NMSs that are adaptable to dynamic market demands, robust to network/connectivity failures, and capable of mass customization. In the future, DFDM can also be used for design of cloud-based cyber-physical and manufacturing systems, based on adaptability, operability, and reconfigurability. In this paper, the use of DFDM in flexible and functional design was illustrated with an automotive panel stamping example.

Within the International System Realization Partnership (ISRP) we are in process of CBDM platformization with possible application of DFDM in cyber-physical design, cyber-physical manufacturing, cyber-physical product and material, and cyber-physical-social system design. Further, we speculate that DFDM will transit to industry and be applied in the steel making processes, additive manufacturing, design of smart healthcare system, etc.

For more information about current projects please visit www.liverpool.ac.uk/engineering/staff/jelena-milisavljevic-syed.

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