Open Science Index, Economics and Management Engineering Vol:11, No:7, 2017 publications.waset.org/10007379.pdf

Digital Manufacturing: Evolution and a Process Oriented Approach to Align with Business Strategy

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Abstract**—**The paper intends to highlight the significance of Digital Manufacturing (DM) strategy in support and achievement of business strategy and goals of any manufacturing organization. Towards this end, DM initiatives have been given a process perspective, while not undermining its technological significance, with a view to link its benefits directly with fulfilment of customer needs and expectations in a responsive and cost-effective manner. A digital process model has been proposed to categorize digitally enabled organizational processes with a view to create synergistic groups, which adopt and use digital tools having similar characteristics and functionalities. This will throw future opportunities for researchers and developers to create a unified technology environment for integration and orchestration of processes. Secondly, an effort has been made to apply "what" and "how" features of Quality Function Deployment (QFD) framework to establish the relationship between customers' needs – both for external and internal customers, and the features of various digital processes, which support for the achievement of these customer expectations. The paper finally concludes that in the present highly competitive environment, business organizations cannot thrive to sustain unless they understand the significance of digital strategy and integrate it with their business strategy with a clearly defined implementation roadmap. A process-oriented approach to DM strategy will help business executives and leaders to appreciate its value propositions and its direct link to organization's competitiveness.

Keywords**—**Digital manufacturing, digital process model, quality function deployment, business strategy.

I. Introduction

THERE is a growing need for reduced product development time coupled with demands for more customer-oriented product variants in the automotive market all over the world. In addition to these, there are continued expectations from customers for advanced product features at affordable and competitive prices with access to the best after-sales services. To meet these objectives, manufacturers continuously strive to adopt state-of-the-art Information Technology (IT) systems to integrate all functions and business processes in the value chain in order to create a unified enterprise view. These systems are based on digital factory/manufacturing concepts, according to which product data management systems and simulation technologies are concurrently used to optimize the manufacturing processes, plant layout and material flow before the starting of production and supporting ramp-up phase [1].

This paper provides a historical perspective of systematic adoption of digitization in manufacturing (DM) value chain in specific reference to automotive industry. The approach taken will be to identify business processes with early adoption of IT to improve the efficiency and productivity at the functional level. Subsequently, these discrete IT landscapes have been integrated with various other digital technology platforms like SMAC (Social, Mobility, Analytics and Cloud technologies), Machine-to-Machine communication using Industrial Internet of Things (IIoT) and various other technology platforms with a view to have a unified enterprise view.

While the paper will discuss the evolution of digital technology in a time phased manner, it will also try to highlight the strategic needs of manufacturing enterprises to adopt the digital strategy in their value chain and the expected business benefits.

II. Literature Review

A. Definition and Purpose of DM

DM comprises use of various computer assisted applications, analytics, simulation, three-dimensional (3D) visualization, and various collaboration tools, which are integrated with a common communication infrastructure to create simultaneous definitions of product and manufacturing process definitions [3]. DM provides distinct advantages in terms of shortening of product development time and cost; integration of data and information generated by manufacturing processes and functional departments; effective coordination and collaboration among distributed production sites involved in manufacturing of varieties of parts and products; and finally, establishing effective and efficient collaboration with external partners and agencies like suppliers and service providers [1].

B. Computer Aided Processes (CAx): A Historical Perspective

The following section will deal with the historical perspective and evolution of DM in manufacturing.

In the late 1980's, the concept of computer-integrated manufacturing (CIM) was introduced. The purpose of CIM was to improve operational and functional efficiency, seamless integration of information across functions, product quality, operational flexibility, labour productivity and time to market. However, the full strategic advantage of CIM was poorly understood at that time and could not be exploited to its full extent [1].

Computer-aided design (CAD) tools have helped product

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designers to achieve higher efficiency levels in modelling, analysing and finalizing the product features, dimensions and functionalities, which has cut down the product development time drastically, enhancing faster time to market. CAD systems have inbuilt features to integrate with finite element analysis (FEA), kinematics analysis, and other tools to simulate geometrical properties. These systems can be easily integrated with advanced manufacturing processes through generation of codes for driving machines and producing parts. Rapid prototyping is achievable through this process, which results in reducing product development time [1].

Process planning activities determine the necessary manufacturing processes and their sequence in order to produce a given part economically and competitively. Computer-aided process planning (CAPP) systems are used to generate process plans with operation sequence; machines needed, cycle time, tools and fixtures required to produce the product quality consistently. These systems are essential components of CIM environments [1].

Computer-aided engineering (CAE) systems provide advanced engineering research features like engineering mechanics and strength of materials (FEA); computational fluid dynamics (CFD); simulation of machines and mechanisms; thermodynamics and robotics [1].

The great step towards the implementation of computer-aided manufacturing (CAM) systems was the introduction of computer numerical control (CNC) machines. CAM systems have capabilities to link with CAD models and import data and program codes to run the machines, sequence the production, achieve the product quality and provide operational flexibility to change over the parts within shortest possible time [1],

Other systems, such as computer-aided quality (CAQ) systems, have also started to emerge and to become part of the engineering workflow. Product data management (PDM) and product life-cycle management (PLM) systems provide various product data management tasks like product structure, and change management during the life cycle of the product. These systems also provide various workflows, which are used to manage changes at different stages of value chain and to integrate applications, information, and processes, involved in defining the product from design to end-user support. The purpose of PDM systems are generally to maintain and control product related information, files, documents, and work processes, which are essential to design, manufacture, distribute, support and maintain products. Some of the product related information are geometrical dimensions, fits and tolerances, parts and assembly drawings, bill of material, process plans, quality plans, numerical control machine-tool programs, various simulation and analysis results, correspondences, and engineering change orders [2].

DM has been considered as an IT enabled discipline, within PLM, which provides an integrated view of the product flow through various manufacturing processes and it can act as a primary competitive differentiator for manufacturers in meeting customer needs responsively and efficiently [1].

Radio frequency identification (RFID) provides a digital identity to the objects. This enables accurate identification, traceability, and monitoring of products and components in the supply chain, whether in stores, warehouses, production shop floor or in the field. RFID tags can be both active and passive and information is retrieved by a reader through wireless communication. Use of global system for mobile communications (GSM) and 802.11 as communication media for IT applications and digitally identifiable objects in the shop floor has become a reality. However, at the shop-floor level, use of such systems is still constrained due to frequency interference, security, and availability [1].

Computer simulation tools are in extensive use in manufacturing systems design. These tools help decision makers to iteratively evolve an optimal design configuration for plant layout, material handling systems, facilities planning, capacity planning, operations sequencing, automation etc. It provides opportunities to examine all feasible alternatives and workout a scenario which optimizes the performance and efficiency.

SCADA (Supervisory Control and Data Acquisition) systems collect and store operations data o real-time basis for legal, health and safety reasons. In the absence of these systems, there is the risk of process interruptions, quality and safety issues, and lost data. These issues create operational, regulatory and compliance challenges, which can result in additional costs and disciplinary penalties, apart from issues like loss of revenue, reputation and long-term business relationships [4].

Digital mock-up (DMU) software provides features to visualize production processes and allow for viewing the complete factory operations for a manufacturing job. On the other hand, discrete event simulation (DES) software focuses on individual operations and helps in evaluating and improving operational performances through quantity and location of inventory, handling system design, throughput analysis etc. [1].

Virtual reality (VR) technology is another kind of simulation tool, which provides virtual models to view, analyse and work out the optimal scenario for various manufacturing systems. VR is used for factory layout, process planning, material handling systems design, operation training, testing, and process control and validation [1].

Human-related factors, ergonomics, play very crucial roles in deciding productivity levels in assembly processes. The limb motions are simulated and analysed in a 3D mode during an assembly operation with a view to economize motions and establish the optimal sequence for reducing human fatigue and improve productivity [1].

Enterprise resource planning (ERP) systems integrate various business processes and provide horizontal seamless information architecture with a central data repository. With a three layered architecture of data, application and user interface, it provides a unified enterprise view of a business organization. Apart from transaction processing features and capabilities, ERP systems, nowadays, are equipped with planning, scheduling, forecasting, and optimization functionalities [5].

Business Analytics (BA) are a set of data mining applications, which are capable of analysing the business data captured through ERP systems and provide real-time decision support to management. They use various algorithms, mathematical models and optimization tools to predict the nature of reality.

Various middleware technology platforms have been developed to interface and integrate disparate and distributed business applications in any organization. These systems provide a common communication medium for applications to share the data and computing resources. A new concept of service oriented architecture (SOA) has been proposed by various software vendors for easy synchronization and orchestration among various applications [1].

III. Digital Process Model: An Enterprise View

Considering various organizational processes like engineering, operational, business intelligence and customer interfacing activities, which have adopted various digital technology tools and platforms to improve their functional performance and efficiency, a DM process model is designed, which is given in Fig. 1. While this model has partially adopted few elements from a webinar presentation of PwC [6], it has organized the functionally related digital processes in four cohesive groups or categories like engineering, operations, customer interfacing, and decision supports. These groups of processes are interfaced and connected with each other through various digital technology platforms.

Each of these digital processes is explained below to have a better understanding of the nature and cohesiveness of the processes inside a group category.

a) Engineering processes: In manufacturing organizations, engineering processes constitute activities pertaining to product, manufacturing processes, plant layout and material handling, and, finally quality. These activities need to be carried out prior to actual execution in a virtual mode using 3D models, and simulation tools. Organizations have adopted discrete digital tools like CAD, CAE, CAPP, CAQ, Simulation software, and Plant Layout software etc., to virtually model the plant and material flow and optimize the performance characteristics of processes before implementation. These processes are the early adopters of various digital tools in manufacturing organizations.

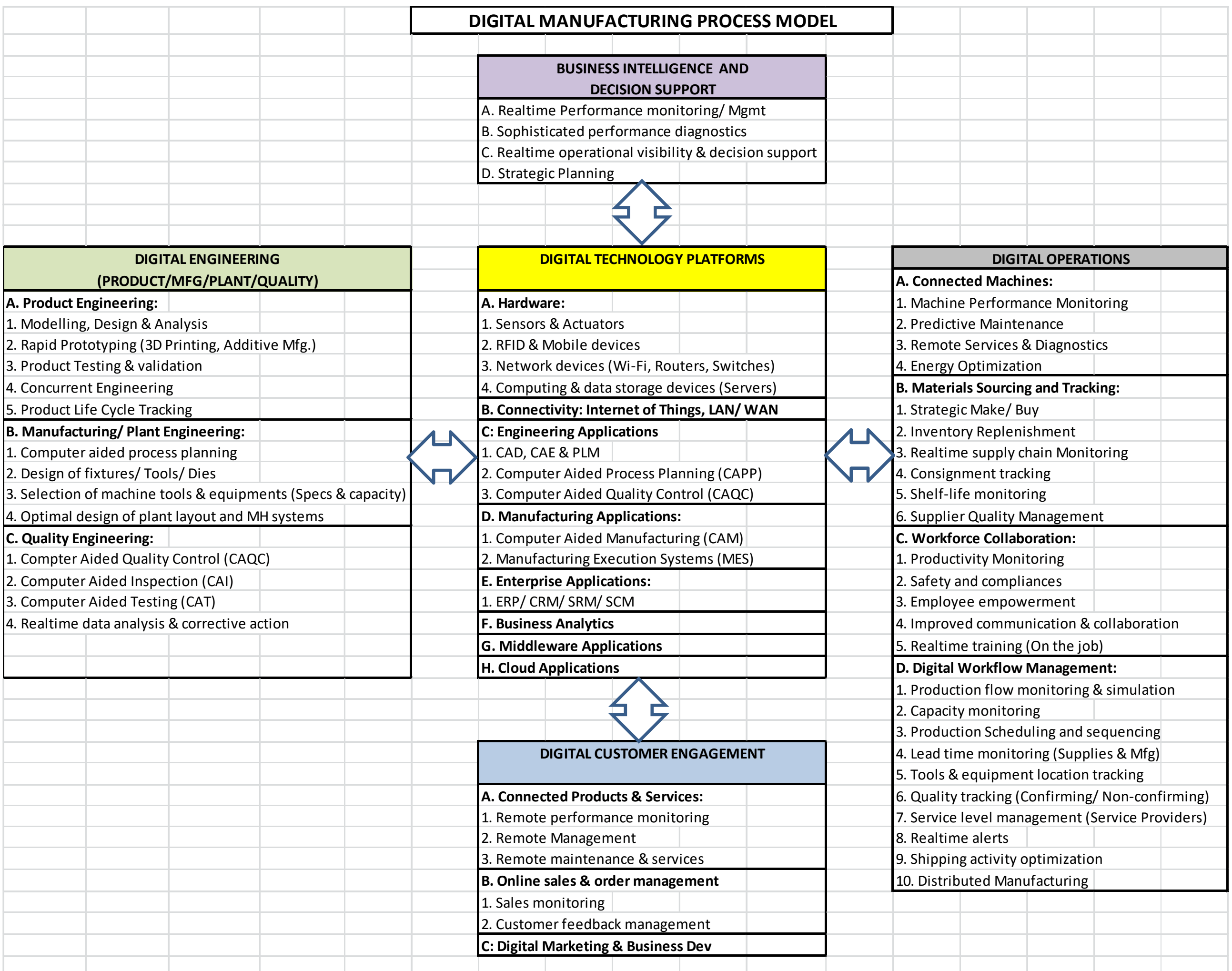

Fig. 1 Digital Process Model – An enterprise view

b) Manufacturing Operations: Operations consist of actual execution of production activities, which covers management of machines, material, manpower and workflow. These processes are very critical as they decide the product quality, the cost and the delivery time, which have severe implications towards business profitability and customer satisfaction.

Asset utilization is very critical in a capital intensive manufacturing environment like automotive. This calls for low machine downtime whether due to unavailability of material, manpower or power apart from machine breakdown. Predictive health monitoring becomes essential for costly equipment with a view to attend the problems before any failure. Organizations have been using sensors to monitor the equipment health and use preventive maintenance for better machine up-keep. Recent development of the IoT can improve machine to man communication to facilitate early maintenance through early alerts.

Use of ERP applications in planning, procuring, storing and tracking materials for production activities has been quite extensive in manufacturing organizations. Use of MRP tools for Just-in-Time procurement, RFID for tracking material location, Advance Shipment Notification (ASN) for managing shipments in transit are some of the common features provided by all Tier-1 ERP's.

Engagement and utilization of manpower in the shop floor have been a very challenging task in earlier days. However, actual productive time monitoring for each operator is now a reality with the availability of CNC controllers in almost all manufacturing equipment. Any quality issue due to operator's negligence is identifiable and traceable, which can help supervisors to take early necessary skill development initiatives.

Apart from the monitoring of quality related issues, other parameters like cycle time, cutting parameters, tool condition, machine health parameters etc. are also captured and stored on a real-time basis. Manufacturing Execution Systems (MES) are integrated with the CNC controllers and configured to pull out relevant data for various shop floor planning and scheduling activities like production scheduling, setup changeovers, progress monitoring, failure alerts etc.

c) Customer Interfacing Processes: Manufacturing organizations are already using various enterprise applications like CRM to integrate with distribution channel partners and end customers. The actual sales data and expected orders are being captured through these systems. However, connecting the products already operating in the field to monitor their performance has been the recent development which uses latest sensor and communication technologies like GPS and Internet. Any failure in the field can be quickly reported to the nearest service centre. This process also facilitates new design and product innovation, which gives a competitive edge to the manufacturer.

Customer involvement in designing and developing products or services and managing the product life cycle has become a reality through use of ICT.

d) Digital Technology Platforms: The preceding sections dealt with various organizational processes, which are currently using discrete digital applications or have potential to use latest technology platforms to improve the business competitiveness of the organization. Now, we talk about some of the latest digital technology platforms, which can support the manufacturing organization in their digital journey.

Sensors and IIoT provide machine to machine (MTM) and also, machine to man communications. This will help organizations to monitor machine health, quality issues, and other operational constraints on real-time basis and facilitate supervisors and managers to take early corrective actions both at the shop-floor and at the customers' end. Industry 4.0 architecture provides necessary functionalities to support connectivity between products, machines and man.

Social, Mobility, Analytics and Cloud (SMAC) provide the foundation for the digital strategy of any organization. Use of mobile devices like tablets, laptops, mobile phone etc., gives access to real-time information on all events on the shop floor. Social apps provide the connectivity among people to transmit information in masses. Analytics can throw all relevant data and information about the business operations to appropriate owner at appropriate time. Cloud will support all kinds of relevant applications, and platforms to organizations for their specific business needs and save them from any large capital investments in IT resources. Cloud technology also provides a platform to effectively coordinate and collaborate among various distributed manufacturing partners, which helps in terms of better resource utilization, lower inventory, and enhanced customer services.

3D Printing and Additive Manufacturing are the advanced computer aided manufacturing methods which help organization cut down their product development time through rapid proto-typing. These advanced technologies have made mass customization a reality. Similarly, the advent of advanced materials like Nano-fibres and ceramics has brought about dramatic changes in manufacturing processes.

Manufacturing organizations have no choice but to adopt digital enablement of their operations for their long term survival in a highly competitive market place. They have to redefine their value delivery models with the help of digitization before the customers demand it from them. Therefore, digital strategy must be integrated with the organization business strategy.

Business organizations understand and appreciate the need for an enterprise-wide digital strategy to integrate the information landscape with a view to be responsive towards customers' needs and expectations, and achieve their long term business objectives of profit and growth. Both business processes and supporting technology platforms are crucial for this digital journey. However, there is a necessity to connect these processes and technology platforms, as identified in above model, to customer needs, expectations and ultimately, to the achievement of business goals, so that business leaders can justify the investment (ROI) required for the digital initiative. Keeping this objective mind, the QFD framework has been thought of to map the processes with customer needs and business goals in the following section.

A. QFD: A Process Perspective

While QFD is intended to translate the voice of the customer-internal and external, both implicit and explicit, into engineering characteristics and functionalities of a product, there are a number of service related expectations of the customer to be fulfilled to achieve overall customer delight. In this context, digital processes play a very significant role to fulfil these expectations.

Table I maps the process and service related expectations of customers, and to digital business processes to achieve these business goals through the 'What' and 'How' of QFD framework.

TABLE I
QFD PROCESS MAP ("WHAT" AND "HOW")

Customer Needs (Ext./Int.)	Digital Processes	Measurable Outputs
a) Product quality & functionalities b) Product customization c) Feature innovation d) Rapid development	Digital product engineering processes using CAD, CAE, PLM	a) Customized features, functionalities b) Timely delivery c) Co-creation/ Innovation of products with customer involvement d) Improved service response
a) Manufacturability of the product without process constraints b) Streamlined product flow c) Low wastage & cost during conversion and handling	a) Digital process planning using CAPP b) Digital Layout & Material Handling system planning c) Digital Quality planning & execution	a) Low throughput time b) High productivity c) Low wastages during processing & Material Handling d) High quality level e) Reduced occupational safety hazards
a) High level of labour engagement & empowerment b) Machine health monitoring and quick response to breakdowns c) Predictive maintenance Low inventory levels Effective Coordination & collaboration between functions	Digital operations using IIoT, SCADA systems, Analytics, Collaborative Social media apps & mobile devices in the shop floor	a) Improved labour productivity b) Increased asset utilization c) High inventory turnover d) Better transparency in operations e) Better collaboration & coordination f) Co-creation with suppliers g) Better collaboration with partnering agencies
Prompt servicing in case of field failure Monitoring of product performance Innovations in product features	Digital Customer Engagement processes using connectivity infrastructure and other interfacing applications like CRM, ERP	a) Reduced downtime of products in the field b) New product innovations c) Field performance monitoring of products d) Crowd sourcing of innovative product features
Real-time view of organization's activities Real-time decision supports Strategic Planning	Digital tools like Analytics which use the transactional data created by other enterprise applications	a) Transparency in operations b) Real-time decision support c) Strategic planning support

IV. DIGITAL TRANSFORMATION DRIVERS AND MATURITY LEVELS

The Internet has significantly impacted connectivity globally. Access to information on products and services, available in all parts of the world has been possible with the Internet, which has created an information highway. The Internet has also impacted the way organizations carry out their businesses, whether it is marketing, sales, product development, supply management, manufacturing etc. All industries have been affected due to these advances and business organizations look for opportunities to use IT and Internet connectivity as a tool for creating business values and business competitiveness. On the other hand, the Internet has given pervasive access to various online information about products and services to customers. This has resulted in increased customer expectations on product functionalities, service features and personal customizations. Due to this, customers have become the primary drivers for digital transformation in organizations [7].

The findings from the 2015 Digital Business global executive study and research project [8] "Strategy, not Technology, drives Digital Transformation" by the joint team from MIT and Deloitte Digital reveals that business organizations remain at three different digital maturity levels i.e. Early, Developing and Maturing stages. These maturity stages depend upon their internal digital strategy, which enables transformation in processes, talent engagement and business models. Organizations, at different points of time, adopt and implement various digital technologies in a discrete and isolated manner with a focus on their functional and operational efficiency. However, in the absence of a long-term vision and roadmap for the digital strategy, they fail to reap the actual benefits of digitization. Most digitally matured organizations develop digital strategies with a focus on transforming the business.

Some of the salient outcomes of their survey [8] findings are given below;

a) Digital strategy drives digital maturity;
b) Scope and objective decide the power of a digital transformation strategy;
c) Maturing digital organizations build skills to realize the strategy;
d) Employees want to work for digital leaders;
e) Taking risks becomes a cultural norm for digitally maturing organizations;
f) Digital agenda is led from the top.

V. BENEFITS THROUGH DM IMPLEMENTATION

Manufacturing enterprises can expect various business benefits through adoption of digital strategy in their value chain. Some of the salient benefits are given below [1]:

a) Reduced product development time;

b) Validation and optimization of manufacturing processes before implementation;
c) Quick production ramp-up;
d) Reduced time to market;
e) Reduced manufacturing costs;
f) Improved product quality;
g) Increase in operational flexibility;
h) Improved customer response.

DM strategy helps enterprises with high capital-intensive manufacturing facilities; complex product structures; highly distributed production facilities; high level of product customizations, and small batch quantity. Enterprises involved in the manufacturing of automobiles, industrial machineries, aeroplanes, high-tech electronics etc. will most benefit from DM strategy. In a complex manufacturing environment, the lack of timely information availability reduces the response ability of people, which results in inefficiencies and lost opportunities. A well designed digital strategy removes these bottlenecks and makes the enterprise more efficient and responsive to customer needs.

The PwC survey, as presented in the Industry week webcast [6] has estimated that the projected investment in percentage of annual revenue will be 4.7% in next five years for US companies across Automotive, Industrial production and Manufacturing Industries as against the actual investment of 2.6% in last two years. This increase in investment would translate to about US$ 350 billion. The expected returns on these investments are aggressive as given below.

- Companies are expecting double-digit downward changes in costs and revenue uplift from digitization with the introduction of smart, connected products.
- These sentiments, in part, are driven by the notion that:
  - Product **variability and labour costs** will decrease as the result of smart machines and software enablement.
  - **Operations and channel costs** will fundamentally shift as companies tap into life-cycle models for engaging customers.
  - New **markets and service models** (e.g. software driven product upgrades, etc.) will represent significant revenue and profit opportunities.

VI. Conclusion

DM should be construed as more of a business strategy than adoption of a bunch of digital technology tools. Generally, it is to be used as a competitive strategy tool to understand and fulfil the customer's needs much before than the competitors. Digital technology has moved a long way to provide the necessary tools and platforms, which can enable organizations to proactively respond to customer's needs and acquire market share. DM strategy provides a comprehensive and collaborative environment in organizations, which can orchestrate in a synchronous manner and fulfil the market requirement at the desired price, time and quality.

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