Title
Manufacturing — Its Evolution and Future

Authors
Merchant, M. Eugene
Dornfeld, David
Wright, Paul K

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MANUFACTURING — ITS EVOLUTION AND FUTURE

M. Eugene Merchant
Senior Consultant
TechSolve
Cincinnati, Ohio

David A. Dornfeld and Paul K. Wright
Department of Mechanical Engineering
University of California
Berkeley, California

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ABSTRACT

The paper highlights events of manufacturing's evolution and metamorphosis over a period of 60 years (as noted by the first author) and offers some observations on key developments and activities. It includes the reflections of professional activities of the first author and discussions of how manufacturing is evolving to accommodate the current and expected trends in manufacturing technology. Three specific software environments relative to developments in the design-to-manufacturing cycle are described. These lead into a perspective of what may now lie ahead, relative to enterprise issues, human system interactions, and the fully integrated "digital factory."

THE BEGINNINGS

The Industrial Revolution spawned small companies, a feature of which was good face-to-face communication and collaboration — a situation ideal for excellence in manufacturing. But as companies grew, departmentalization occurred. Departments gradually became isolated from each other and this led to a "bits and pieces" approach to manufacturing. In the 1950's, the advent of the digital computer and associated technology and its initial application to manufacturing was seen as a watershed event. With this technology, the possibility of realizing automated and programmable control over manufacturing operations and processes was introduced. Following that, in the 1960's, the computer was recognized as extremely powerful systems tool and spawned a new understanding of the nature of manufacturing -- manufacturing is a system! This was certainly realized by workers such as F. W. Taylor in their attempts to introduce scientific management concepts to an apparently disorganized work environment. But it was the computer that allowed the automation of such management.

Skilled craftspeople and experienced manufacturing engineers alike recognize the importance of process "intelligence" (originally in the mind of the craftsperson) and databases of information on process, tooling, materials and workpiece requirements (often in handbooks or personal notebooks reflecting accumulated experience). What the advent and introduction of the computer has added is shown in Figure 1. Here process data and models drive design and manufacturing decisions to achieve goals with increasing levels of complexity. This means that, models of the process incorporating subtle details of the process capability, combined with sophisticated simulation tools and information display can extend the ability of the engineer, at the design stage, to “look down the manufacturing pipeline” and observe how well his or her design will fare in the process. Ideally, this occurs before the first chip is cut.

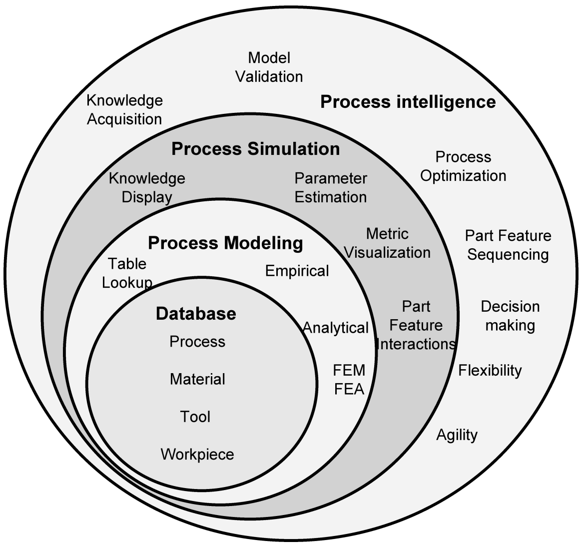

FIGURE 1 PROCESS DATA AND MODELS DRIVE DESIGN AND MANUFACTURING DECISIONS WITH INCREASING LEVELS OF COMPLEXITY [1].

A host of new concepts were introduced that enabled the practical implementation of the systems approach to manufacturing. We reproduce here an early image derived from Merchant [2] showing the basic structure of a computer integrated manufacturing system circa 1969, Figure 2. This shows a first view of that pipeline of the process incorporating most of the elements considered important today. In fact, this view has changed little in the four decades since its introduction. This is discussed in more detail in Section 2 below.

The design process that is captured by Figure 2 is made up of several distinct levels depending on what stage of the process is being discussed and what can be effected at that stage, Figure 3. Here we can see, at level I, the ideal design to manufacturing environment envisioned in Figure 2. There are practically no constraints on the design and, as the manufacturing process details have yet to be determined, no constraints on manufacturing either. Level II represents the environment in which the design is substantially fixed and the basic manufacturing process details are being determined — at the macro and micro levels. There is little design flexibility and, although this is not meant to represent over-the-wall manufacturing so often decried, it comes close. Level III is the shop floor environment for which literally no design changes are allowed, the machinery for manufacturing is well set up and operating and the only flexibility one might have to change or improve something would be to adjust machine parameters within the ranges allowable by the machinery. Finally, at Level IV, we find ourselves at the level of secondary operations to finish aspects of the previous processes and/or inspection of the finished part. Although Merchant outlined a plan for Level I manufacturing over 4 decades ago it is more typical to see Level II on down in practice today in many facilities.

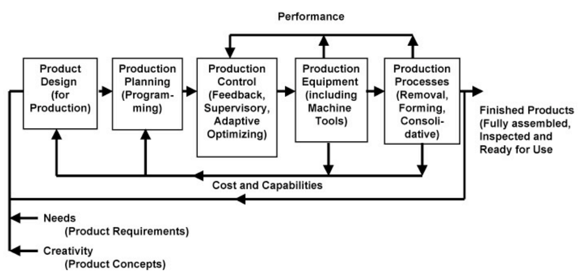

FIGURE 2 INITIAL CONCEPT OF THE COMPUTER-INTEGRATED MANUFACTURING SYSTEM, 1969, AFTER [2].

NEW TECHNOLOGY EVOLVES

Foremost among the new concepts that were introduced enabling the practical implementation of the systems approach to manufacturing was the concept of the Computer Integrated Manufacturing (CIM) System. CIM’s potential capability to integrate former “bits and pieces”, and allow flexible automation and introduce the concept of on-line optimization of the system is shown conceptually in Figure 2. This figure introduced the concept of the manufacturing system linked by a central (and distributed) computer network to insure that design to manufacturing specifications were met along several axes of interest — performance/quality, cost, productivity. It also raised the concern that the needs for the production and the creativity driving the product concepts must be considered in the first place.

The 70’s and 80’s exploited the application of technology but perhaps at the expense of human resource factors - a serious mistake. A long, frustrating struggle to develop and implement CIM system technology and reap its inherent potential benefits ensued. A number of realizable benefits resulted including, substantially:

- decreased costs - increased product quality
- increased productivity - decreased lead times
- increased flexibility (agility) - increased worker satisfaction
- increased product producibility - increased customer satisfaction

But only a few pioneering companies worldwide were initially able to be realize these benefits fully!

The reason for this is interesting. In the '80's and '90's it was found (by benchmarking many of these pioneering companies) that excellent engineering of the application of the technology of a system of manufacturing is a necessary, but not sufficient, condition for enabling it to fully realize the potential benefits of that technology. The technology will only perform at its full potential if the utilization of the system's human resources is also engineered. That is, so engineered as to enable all personnel to communicate and cooperate fully with each other. And failure to meet this condition cripples the technology.

Level I	Feature prediction, control, and optimization in an iterative design and process planning environment	Design: High Manufacturing: High Finishing: High
Level II	Feature prediction, control, and optimization through the selection of a manufacturing plan in an "over-the-wall" design-to-manufacturing environment	Design: Low Manufacturing: High Finishing: High -> low
Level III	Feature prediction and control through limited adjustments to a pre-established manufacturing process	Design: Low Manufacturing: Limited Finishing: High -> low
Level IV	Feature prediction for finishing process planning, finishing tool trajectories and sensor-feedback strategies	Design: Low Manufacturing: Low Finishing: High

FIGURE 3 LEVELS OF DESIGN AND MANUFACTURING FLEXIBILITY, FROM [1].

Non-productive time issues and lean manufacturing

An early study by Merchant showed that the actual time a part spent on a machine tool was only 5% of the available time [3]. Most of the other 95% was "waiting and moving." Then, if you looked at this 5% on the machine, only 30% of that was used in machining, the remainder was in positioning, loading/unloading, gaging, etc. Studies like these motivated the development of numerically controlled machine tools for enhanced productivity and concepts such as "internal" and "external" tasks, e. g. setup, that form part of the Toyota Production System methodology. In fact, this is the fore-runner of what is referred to now as "lean manufacturing." By carefully removing non-essential tasks from the machine, to be performed in parallel off the machine, tremendous improvement in machine utilization was seen. An excellent example of this is the so-called "single minute exchange of dies" or SMED that allowed die changes in large automotive presses to occur in one minute or less compared to traditional die change times of 8 hours. The flexibility that this introduces into the manufacturing system is impressive.

Now-a-days, these concerns are lumped under the heading of "non-productive time" issues. And, they include in addition to setup, tool path planning, high speed spindles for increased removal rates, linear, motor technology for higher acceleration speeds in machine tool axis drives, etc. A recent CIRP Keynote detailed many of the advances seen in this area [4]. An example, from that paper, is given below and describes combining processes to reduce non-productive time.

Combined processes to reduce non-productive time

Much time is spent, as pointed out in the early Merchant survey, moving parts from machine to machine. A novel concept recently introduced by machine tool builders is to combine operations on one machine tool. These are often operations that are not traditionally thought of as combinable. The following process strategies have innovated the classical process chains with sequential and dedicated machine applications in one clamping or at least in one machine, often called complete machining :

- Integration of various machining processes into one machine tool (e.g. turning, milling, drilling, grinding, deburring)
- Six side machining

In addition, process designs have been further optimized regarding productivity by introducing:

- Parallel processing: 2 or more processes are utilized independently on a single machine (e.g. 4 axes turning)
- Hybrid processes: 2 or more processes are coupled to achieve a specific workpiece alteration, also called assisted machining (e.g. laser aided turning)
- Integrated processes: New processes based on 2 or more conventional processes (e.g. grind hardening)

All these approaches have one main goal: reduce non-value adding processing times due to transportation and part handling. Furthermore, inventory can be reduced because the number of unfinished parts within the process chain is widely eliminated. Usually, this goes along with an elimination of re-clamping operations which has positive effects on the part accuracy.

UTILIZATION OF HUMAN RESOURCES

Excellent engineering of the application of the technology of a system of manufacturing is a necessary, but not sufficient, condition for enabling it to fully realize the potential benefits of that technology. Only if the utilization of the system's human resources is also engineered will the optimum benefit of the technology be realized. A critical element of that is enabling all personnel to communicate and cooperate fully with each other. The lines and arrows in Figure 2 represent as well human interaction with the systems as the flow of bits of information in computer communication. Communication is one element of the interaction. Cooperation among the system's users must be facilitated.

The question is, then, how can utilization of human resources be properly engineered? The methodology for enabling this is now being gradually discovered and developed. Some of the more effective methodologies which have already emerged include:

- empower individuals with the full authority and knowledge necessary to carry out their responsibilities
- use empowered multi-disciplinary teams (managerial and operational) to carry out the functions required to realize products
- empower a company's collective human resources to be both willing and able to communicate and cooperate with each other

Some of these ideas were seen in the writings of Deming and the teachings of the Toyota Production System. But can hardware assist in this task? Can the computer and design/manufacturing environment (starting with the CAD system) facilitate this? We will illustrate the potential for this in an example of the digital factory concept below.

NATURE OF FUTURE MANUFACTURING ENTERPRISES

Where are we today? Manufacturing enterprises are rapidly learning how to achieve good integration of equipment, people, and operations via digital computer technology. They are also beginning to discover how to integrate engineering technology and human resource utilization so that both technology and people perform at full potential. In addition, economics plays an increasingly important role. There should be a strong integration of technologies and management using information technologies (IT), for example, integration of the process planning and production planning, simulation of manufacturing systems, agile manufacturing, fast redesign of new products, modeling of manufacturing equipment performance, including the human operator, functional product analysis, virtual machining and inspection algorithms etc. The key change drivers in most cases of manufacturing technology include: diminishing component size, enhanced surface quality, tighter tolerances and manufacturing accuracies, reduced costs, diminished component weight and reduced batch sizes [4].

Computer technology is now developing in at least three new areas vital to future manufacturing: holonic systems, virtual reality and intelligent systems. What is the likely nature of the future manufacturing system and of these three needed technologies? One likely scenario is a human-centered, virtual enterprise, comprising an integrated holonic system of cooperating but autonomous units globally distributed. An example of this is now referred to as the "digital factory" and a detailed example of this, as applied in a major automotive manufacturer, will be given in the paper.

What is the nature of a holonic manufacturing system? A holonic manufacturing system is one in which every entity in the system (people, machines, software elements, etc.) is enabled and empowered to fully communicate and collaborate with every other entity. Very sophisticated technologies are needed to enable enterprises to be holonic. They must enable the capability for global “same room”, “face-to-face” communication and collaboration, the capability to transfer, person-to-person, each person’s information, knowledge, understanding, and intent, and the capability to fully virtually replicate locally the environment of distant sites. To accomplish this, the development of virtual reality technologies is a must. And this is an area well outside of the usual competence of manufacturing researchers. We will need to engage with other expertise, computer scientists and the like, more and more in the future to keep our own progress steady.

EXAMPLE: THE DIGITAL FACTORY

One emerging concept that embodies the future manufacturing enterprise envisioned in [1-3] and Figures 1-3 is the “digital factory.” Digital factories are a new trend that semiconductor, automobile and other manufacturing industries are following to showcase sophisticated Information Technology – IT (Figure 4). The digital factory aims for digital verification of product design, production and assembly before the foundations for the actual factory are laid (that means…the total design to manufacturing pipeline as outlined in Level I of Figure 3). The authors have been developing a suite of computer-based tools that show promise in achieving this desired full-flexibility of Levels I-IV design and manufacturing. These are now briefly reviewed with citations to fuller details:

Manufacturing Advisory Service

The Manufacturing Advisory Service (MAS) provides a product designer with a web-based service that advises on the most appropriate manufacturing process for an emergent early design. The underlying philosophy is to maintain the three levels of “high flexibility” shown in the top right box of Figure 3. The designer is given full creative freedom in terms of product shape, geometrical flexibility, material choice, batch size, desired tolerance, surface finish etc. Then, working in the background, the MAS interprets the design for the most appropriate manufacturing process, encompassing a wide range of casting, forging, machining and polymer processing methods [6]. The system has been constructed with a very rich set of databases on available processes and these can be added to at any time – perhaps educating a designer in new processes that are unknown and unexploited thus far. This “digital interaction” thus leads to accurate predictions of the appropriate “pipeline”, prior to any detailed design on the one hand, and equipment purchase/selection on the other.

Probabilistic Precision Process Planning

A priori Probabilistic Precision Process Planning tools provide more detailed design refinements in the Level II area of Figure 3. These software environments allow a designer to move along the “pipeline” to detailed part design while gaining the benefit of past experiences from prior art. For example, databases on precision finishing [7] allow tool paths to be selected that not only generate basic part geometry but also avoid burrs and other surface finish problems. Similarly, knowledge of appropriate fixturing methods and physical constraints [8], provides for deterministic process planning long before raw stock is procured, and/or machinery is purchased, setup and selected for manufacture. The cost and time savings are clearly evident in such digital factory methods.

A specific example of the digital factory concept applied to automotive manufacturing is shown in Figure 4, from [10]. This pictures an interactive CAD system used for a “feature oriented design optimization” scheme at use in a major European auto manufacturer. The purpose of this specific module illustrated is for providing feedback to the designer on the impact of design features, at the production level, on burr formation for an automobile engine of cast Al-Si material.

In this context, the “digital factory” plays the role of linking the engine development to production through the intermediate step of production planning. The burr minimization information is available to the designer (Level I), optimum process parameters and tooling are introduced as part of the Level II planning, and production has access to simulation tools for accessing the suitability of tool paths for milling, allowing optimization again to minimize burr formation. It is anticipated that, as part of this, constraints on surface finish, form error, etc. would also be considered.

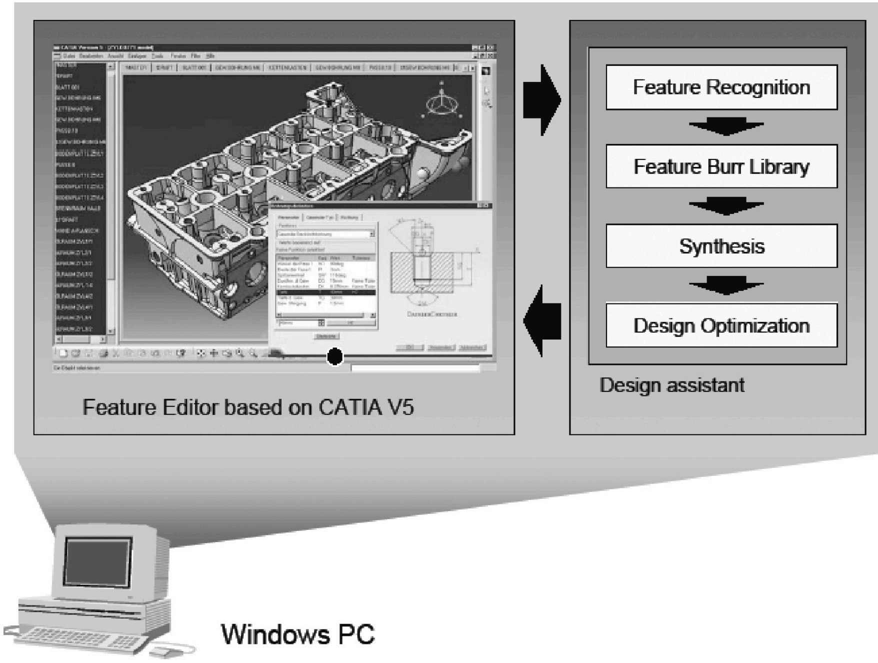

FIGURE 4 EXAMPLE OF “FEATURE ORIENTED DESIGN OPTIMIZATION” [10].

Open architecture machine tool environments

Open architecture machine tool environments provide detailed process monitoring and visualization systems for precision milling and other processes. This address Level III in Figure 3: real time adjustments can be made during manufacturing where the key strategy is to detect, diagnose, and correct machining errors at the earliest possible opportunity. Additionally the data collected can be fed back to Levels I and II as also suggested by the feedback arrows in Figure 2 [and see 2,3]. Hyperpoints are used to relate the sensor data to part geometry. Hyperpoints are Cartesian points in space that augment the 3D-CAD model with additional information such as force, vibration and acoustic emission data [9,10]. In our deployments, visualization routines color-code these sensor data and overlay them onto a 3D-CAD model of the machined part [9]. These become very useful repositories for part designers and process planners.

The expected benefits of these new software and IT environments include, as seen in Figure 5, reduced manufacturing costs, reduction in materials costs and enhanced planning process. The result of the improved planning is expected to reduce the time it takes to design and plan and implement manufacturing for a new automobile. We re-emphasize that the idea behind the digital factory [4] is to insure that, from the beginning, all processing steps and parts of the production processes are “computer supported, planned, developed and optimized before the first physical assembly occurs. Two important goals of this are to integrate the many existing (often excellent) “island solutions” and to extend their capabilities when possible, and to do this through computer software that allows all the players to communicate and collaborate in the process. The plan is to include various aspects of the supply chain as well. This is “manufacturing as a system” taken to its fullest extremes and represents a true view “down the manufacturing pipeline.”

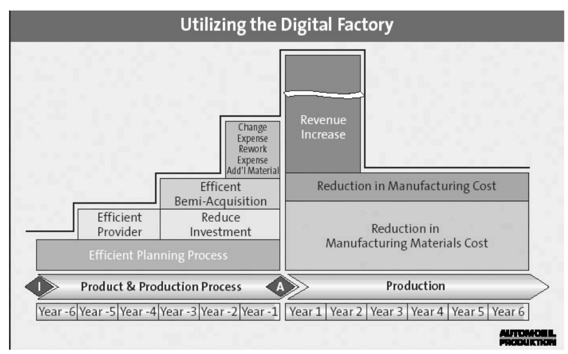

FIGURE 5 AN ILLUSTRATION OF THE TYPICAL PRODUCT AND PRODUCTION DEVELOPMENT CYCLE EXPECTED TO BE DRAMATICALLY IMPROVED BY THE DIGITAL FACTORY AND EXPECTED BENEFITS, [5] (NOTE: “BEMI” IS GERMAN ABBREVIATION FOR BETRIEBSMITTEL - EQUIPMENT, RESOURCES LIKE TOOLS, MACHINES, ETC.).

The guiding principles underlying the development of the digital factory include: standardization, data integration, work flow management and automation of planning. These usually reside on a platform of some commercial CAD software that is already in use in the factory. In this scenario, production optimization tools, virtual reality simulations, and factory layout tools are fast becoming a regular feature in digital factory. On the contrary, process modeling and optimization are widely considered as the toughest steps to integrate into the digital factory.

The real challenge, or opportunity, to be addressed by the digital factory concept discussed here is to extend this to the broadest scale of the enterprise and to include, as well, social scale impacts in the planning. This can be accomplished as part of the digital factory as outlined in the roadmap in Figure 6. It must be emphasized that this roadmap is not to imply that social impacts are considered after all others. Increasingly, the manufacturing enterprise is being called upon to consider in the design and planning process the potential impacts on the environment of its products, technology and processes in parallel with other constraints. Once a cost is associated with a process stream (or Cost of Ownership CoO defining the lifecycle costs of the system or process including all applicable costs) then tradeoffs can be analyzed as part of the planning process. Consider the recent attention given to the reduction or elimination of cutting fluids in machining processes, for example, [4]. And software (or IT) is the connecting element integrating the individuals, models, intelligence, processes, and designs.

CONCLUSIONS

We can see that today's evolving global enterprises will unfold into human-centered holonic systems. This means that all entities (people, machines, software elements, etc.) will be enabled to communicate and cooperate globally as fully as though in same room together. The view "down the manufacturing pipeline" will be available to anyone along the pipeline. The enterprises' product realization process will be based on integration of engineering of the application of product realization technology with engineering of the utilization of human resources. Competent and efficient process models will play an important role in this product realization process to allow the assurance of producing products that meet specifications. Such future promise as has been described here poses to all of us, as manufacturing professionals, an exciting challenge and opportunity!

Clearly an essential element of the roadmap for manufacturing is the integration of manufacturing processes as we have pointed out. In the past, simple process elements have been optimized. Progress will be made by focusing on technology interfaces and on the complete process chain. Our manufacturing systems for cutting technology will be hybrid in nature and will encompass modularity features for ease of reconfigurability and for minimization of non-productive times. Reconfigurable manufacturing systems, when implemented with open architecture control systems for basic machine tool control as well as adaptive control of machining performance can offer substantial improvements in cutting performance by assuring economic flexible systems responsive to changing demands and shorter product cycles. Disparate sensor systems as part of open architecture control will contribute to the development of intelligent machining systems with learning ability. Substantial research work is needed to integrate methods of assessment of part quality with operating machining systems. But, more importantly, we need to insure that our work links into the broader vision of the "digital factory" and that true design to manufacturing integration is realized.

Finally, thought must be given to advancing "beyond cutting" as we conventionally think about it. To keep moving "down the Taniguchi curve" (the metal cutter's version of Moore's Law) we will need to address a scale of material interaction that may go beyond single point cutting. Such processes as "ball-milling" and chemically enhanced polishing are areas we need to be working on. Computational techniques, usually employed in fluid mechanics and elsewhere, must become our "Kistler dynamometer" in the future (that is, our "workhorse investigative tool"). That is not to say that experimental validation is not needed - it certainly is. But, to determine the fundamental process parameters and production system setup, and design rules, in advance, is how we will remain competitive.

We close with a quote from the paper in reference 2 by Merchant in 1961 — a statement that concluded that paper:

‘It appears likely that the new concept of the manufacturing system, developed as a unified, coordinated and automated whole, will produce a revolution in the field of manufacturing as we know it today. As such, this concept and its development provide all of us who are working in the field of production engineering research with a tremendous challenge, an increased impetus, and a changed approach to our research. The era ahead should be a most exciting one for all of us, as well as one of greatly accelerated progress. We can all look forward to it with great enthusiasm.’

This statement is as applicable today as it was 40 years ago! Our research in manufacturing is still being influenced by increasingly capable computer technology and systems methodologies to insure collaborative and cooperative human to human and human-system interaction. Add to that novel materials of impressively small sizes and we have much to look forward to with great enthusiasm!

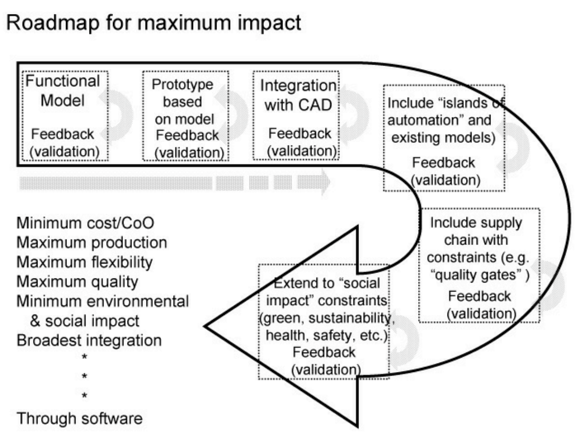

FIGURE 6 ROADMAP FOR IMPLEMENTATION OF DIGITAL FACTORY CONCEPT TO INCLUDE THE ENTIRE MANUFACTURING ENTERPRISE.

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