Design for Manufacturing & Assembly Across Three Industrial Revolutions

by
Bradford L. Goldense
President
Goldense Group, Inc.

SUMMARY

DFM and DFA practices started in the 2nd Industrial Revolution [IR] when people wanted improved household products and equipment that had remained plain and simple to make for centuries. People's desire for more aesthetically pleasing and functional designs spawned Industrial Design which then led to the DFM and DFA we know today. Frederick Taylor and Henry Ford laid down early markers.

The USA's late entry into WWII, and that immediate need for production velocity, exposed many shortcomings of initial methods. Post-WWII industrial competition then increased the emphasis on also minimizing the costs. Several pioneers will be showcased, and what each sought to achieve.

By the 60s and 70s, acquired knowledge started to become systematized. It was first implemented in reference tables and tools with "slide ruler thinking" - like the Westinghouse Calculator. In the 80s and 90s, computers and software enabled widespread corporate and then global use of DFM and DFA.

As the 3rd IR unfolded, the digital revolution, enablement moved from tools wielded by experts to tools of teams across geographies; and practices became integral to the design management process. Plus, the digital revolution added a whole new "category" to the body of knowledge as 3D printing and multi-material products have their own nuances.

With much still to be done, the 4th IR is already upon us. Sustainable designs, global designs, micro designs, 2D designs, biomaterials, bioplastics, and the integration of computer and internet technology into the fabric of products will certainly keep DFA and DFM healthy and moving forward.

PREFACE

Research reported in this paper is still ongoing. Findings indicate conflicting dates as to when certain research, works, and software were first published vs. republished; and who the authors and publishers of record were. Additionally, research contributions from Brazil, Japan, South Korea, China, and other geographies are incomplete and are not adequately represented in this paper. Research on contributions from the United States, United Kingdom, and Europe are relatively more complete.

ISBN13 978-1-937115-42-5
BOOTHROYD-DEWHURST, INC. 35nd International Forum on DFMA
Providence, Rhode Island
June 18, 2024

Artisanship

Until the dawn of the Italian Renaissance (1400-1600), the creation of goods was done from the memories of the artisan as the product was being made. Replication and consistency over time occurred as master craftsmen taught apprentices who, in turn, then became masters who taught their own apprentices[1]. As centers with significant populations began to develop across Europe and the known world, it quickly became timelier and more economical to produce locally than ship to all geographies from a single production location. Like the old Silk Road though, every country extracted their taxes as goods crossed borders.

16th Century

Fairly quickly, within a few years of becoming geographically separated, consistency of replication began to degrade. The first manifestation of "drawings" to assure the consistency of products began in the early 15th Century. First documented were the logos and brands of the day. "Pattern Books" were collections of engravings illustrating decorative forms and motifs which could be applied to a wide range of products.[2] *This was precedent-changing, creation took place in advance of making the product.* All manufacturing locations could exactly replicate the patterns. One can make the argument that Pattern Books were the beginning of the separation of product design from manufacturing. For the next four centuries, until the mid 1900s, design would become increasingly separated from manufacturing.

17th Century

By the mid-1600s, in what was now a competitive cross-border environment, centers of excellence in certain product categories had developed. The artisans in these centers produced higher quality products than their competing locations. Across geographies, consumers only wanted the goods that came from "that" center. This artistic patronage resulted in the growth of those centers. Louis XIV, for example, opened the Gobelins Manufactory in Paris in 1667. Teams of hundreds of craftsmen, specialist artists, decorators, and engravers, produced products ranging from tapestries and furniture to metalwork and coaches. The idea of a highly profitable mega-manufactory of consistently designed products triggered a next-level of competition. This approach spread around the civilized world. One such operation remains today, the infamous Meissen porcelain workshop established in 1709.

As long as reproduction remained artisan-based, however, the form and artistic quality of the product remained in the hands of the individual craftsman; and tended to decline as the scale of production increased.

While water wheels could leverage the flow of a running river or water flowing over a dam, the power generated could only run small operations. There were only a few locations with a significant head of water that could scale, Lowell, Masaachusetts and Horicon, Wisconsin are good examples. It was clear that new power sources were needed.

The beginning and ends of Industrial Revolutions overlap each other. The advent of the steam engine had begun in 1605. Its first application was in Spain in 1606, used to pump the water out of mines in

ISBN13 978-1-937115-42-5
BOOTHROYD-DEWHURST, INC. 35nd International Forum on DFMA
Providence, Rhode Island
June 18, 2024

Spain - a steam-powered water pump. By 1679, there was a commercial pressure cooker that would remove the fat from bones to speed the creation of bone meal. It wasn't until 1698 though that the first steam engine was created that could be used for industrial purposes. Its drawback was that it did not have a piston[3].

18th Century

In 1712, Thomas Newcomen brought together the essential elements to develop the first steam engine for which there could be commercial demand.[4]

- The concept of a vacuum (i.e. a reduction in pressure below ambient)
- The concept of pressure
- Techniques for creating a vacuum
- A means of generating steam
- The piston and cylinder

It would take another fifty years for this initial steam engine to mature to different sizes, configurations, and levels of power, before the 1st Industrial Revolution actually began.

1st Industrial Revolution [1760-1850]

There wouldn't have been an Industrial Revolution if it wasn't for the Agricultural Revolution that preceded it. Now that a sufficient food supply could be assured for any level of population growth (in that era), population and centers of population began growing rapidly. In 1700, there were 600 million people. In 1800, there were 990 million people. In 1900, there were 1.65 billion people.[5]

Back then, it was just called "The Industrial Revolution." With hindsight, we can now see subsequent progressions and classify it as the first. It began in Great Britain circa 1760, and spread to continental Europe and the United States.

Wooden sailing ships were regularly navigating the world by this time. There were established trade routes and demand for certain goods from every corner of the civilized world. New chemical manufacturing and iron production processes had led to the development of the first machine tools. The efficiency of water power had improved, and new steam power was coming of age. The idea of a mechanized factory system was budding, and artisans increasingly began to operate new machines. Daily output was greatly increased and could now meet the demands of a growing population and civilized world.

The textile industry was the first to use modern production methods. Textiles became the dominant industry in terms of employment, value of output, and capital invested.

Before machine tools, the use of metal had to be kept to a minimum. It was simply too laborious and costly to design and produce with metal parts. Inventions of new machine tools occurred rapidly: boring

ISBN13 978-1-937115-42-5

machine (1774) and planing machine (1750-1810)[6], milling machine, (1780-1810)[7], shaping machine (1791-1836)[8], and precision lathes and screw machines (1770s)[9], paper machine (1798) and sheet glass (1832)[10], and more. The ability to make and produce chemicals in volume also played a big role. Sulfuric acid, hydrochloric acid, chlorine, sodium sulfate, calcium sulfide, and potash were all productionized in this same period. Portland cement was invented and patented (1823 -1824).[11]

GDP per capita was broadly stable before the Industrial Revolution and the emergence of the modern capitalist economy. The Industrial Revolution began an era of per-capita economic growth in capitalist economies. Economic historians agree that the onset of the Industrial Revolution is the most important event in human history since the domestication of animals and plants.[12]

The 1st Industrial Revolution was mostly about increasing the output of manufacturing. Refinements in the approach to design had not begun yet. The artisans of old were now running equipment. Design was still mostly utilitarian, as it had been for centuries. Consumers had just started to express their preferences for goods that were designed in certain ways to meet their particular needs.

2nd Industrial Revolution [1830-1920]

The rise of *engineering* as a profession had began in the 1700s. It was narrowly applied to the fields of mathematics and science. By the turn of the century, military engineering, civil engineering, and the mechanic arts were areas where one could find training.[13]

19th Century

The earliest indication of *design* as a profession didn't occur until 1839. The term "*industrial design*" was used to retroactively describe the School of St. Peter, founded in 1750, which had hundreds of draftsmen employed creating patterns for silk manufacture.

The *Practical Draughtsman's Book of Industrial Design* was printed in 1853. The subtitle of the (translated) work explains, that it wants to offer a "complete course of mechanical, engineering, and architectural drawing." This work paved the way for a big expansion in the field drawing education in France, the UK, and the United States.[14]

Christopher Dresser (1834-1904) is considered the first independent industrial designer. Born in Glasgow, Scotland, he was a pivotal figure in the Aesthetic Movement and a major contributor to the allied Anglo-Japanese or Modern Style (British Art Nouveau style). In 1873 he was requested by the American Government to write a report on the design of household goods. Consumers were demanding products with increased "*Aesthetic Designs*."[15] The completely utilitarian products of prior centuries were on their way out. And, like Boothroyd and Dewhurst's National Medal of Technology and Innovation in 1991 affirmed the fields of DFA and DFM, so too did the recognition of the United States government's action in 1873 affirm the fields of consumer and industrial design.[16]

19th -20th Century

The first use of the term "industrial design," in the context of a profession, is generally attributed though to the industrial designer Joseph Claude Sinel (1889-1975) in 1919 who proclaimed himself in writing to be an "industrial designer."

While colleges like the Rhode Island School of Design originated in 1877[17], the country's first industrial design degree program occurred in 1934 at Carnegie Institute of Technology.[18] Was this the beginning of "*Design for X*?" Henry Ford might have something to say about that as early as 1903 however, "*Design for Assembly Line Production*."

Frederick Winslow Taylor, the father of "*Scientific Management*," was born in 1865. Through a series of work experiences, he realized he could improve both worker output and worker satisfaction. There was a great deal of labor unrest at this time. Factory owners were pushing and pushing workers, now using machine tools and textile production equipment, to get more output out of their machines per day. There were great differences of opinion around a "fair day's work for a fair day's pay." Both sides were using their own biased emotion-based judgement to determine what both "fair" and "day" meant. Strikes began. Some involved armed conflict between the workers and their company owners. Taylor sought to improve the balance, and developed a reputation for doing so.

> Two principles had to be in place at all times. (1) Both sides must take their eyes off the division of the surplus as the all-important matter, and together turn their attention towards increasing the size of the surplus. (2) Both sides must recognize as essential the substitution of exact scientific investigation and knowledge for the old individual judgement in all matters relating to work done in the establishment.[19]

By the late 1800s, he was traveling to different factories around the United States and Europe to help create definitions for companies as a consultant and advisor. His solution was to do exact and detailed measurement of each job or task, and develop a standard time. Taylor won over both sides eventually. His standard times were reasonable. Each worker could always achieve their standard time or better. And, when a standard existed, it could be exactly accounted for which management liked. The essence of Taylor's "Scientific Management" advanced the two principal technical professions of the time, engineering and accountancy.

At the turn of the century, when Taylor was in his mid 40s, the world began to recognize his contribution. He received awards in Paris and from the Franklin Institute of Pennsylvania. He was awarded Honorary Doctor of Science (Sc.D.) from the University of Pennsylvania and Doctor of Laws (LL.D.) from Hobart College; and became President of the American Society of Mechanical Engineers in 1906.

The exactness of Taylor's standards was a great beginning. Taylor's work was perhaps the beginning of "Design for Cost" as we know it today. The advent of a standard, and the ability to account for it, enabled pricing the item with a known profit that could be planned for. His successors would work to enable more flexible approaches around standards that were more suitable for a world that was becoming increasingly nuanced and consumer driven, and to improve planning for these standards, but Taylor laid the foundation.

3rd Industrial Revolution - Part I [1900-1950]

Taylor was soon to pass in 1915, but not before he and Henry Ford collaborated. Henry Ford was born in 1863, seven years after Taylor. By his early 20s, he built himself a small tractor to help on his father's farm. He then built a steam engine to power the tractor. In 1893, by day, he was Chief Engineer at Edison Illuminating Company of Detroit and a close colleague of Thomas Edison. By night, he was working to develop a gasoline engine. On Christmas Eve in 1893, the first gasoline engine sputtered for thirty seconds. Three years later in 1906 he built his first horseless carriage called the "Quadricycle."[20]

Design for Producibility

Over the next seven years, 1906-1913, with Taylor and others, Ford developed a mass production method. The method, replete with standard times and tasks at each station on a moving production line, became known as "Assembly Line Manufacturing." Parts were designed to fit the assembly line process. And, increasingly, parts had to be redesigned as assembly lines were sped-up. Taylor's standard times resulted in the need to redesign parts to rebalance the time flow across the work stations on the moving line. *This was the advent of Design for Assembly*. Since the late 1880s, all design initiatives related to the ability to make something had been called *Design for Producibility*.

Ford also gets credit for *the advent of Design for Manufacturability*. Ford Motor was a completely vertically integrated company all the way down to the raw materials. Ford owned mines and smelted ore. Each and every part was optimized from its inception to fit to the flow of the assembly line, and to make it at the least cost so he could sell the Model T to everyday people.

> In 1913, his company was the first to develop a moving assembly line for cars. By 1914, Ford's mass production methods allowed the company to **93 man-minutes, down from 12.5 man-hours**. The moving assembly line allowed for Ford to implement a three-shift day. That in turn increased the productivity tremendously. By 1920, Ford was producing about one million cars a year, up from about 40,000 a decade prior.
>
> Ford deployed moving assembly line technique of production that allows for items to move at a predetermined pace from one workstation to another until the final product is fully assembled. It's been said that **Ford divided the manufacturing process of the Model T into 45 steps**.
>
> Ford made cars affordable. It's been estimated that over 15 million Model T cars were produced. At those figures, the Model T held a 50% market share of the American automobile industry by 1918.[21]

ISBN13 978-1-937115-42-5

Every profession and industry has its own nomenclature and acronyms. DFA and DFM are no exceptions. The bolded words just above first became industry nomenclature with Taylor's clients in the late 1800s, and others he mentored. It wasn't until Henry Ford started publishing phrases like this that the rest of industry awoke, and followed. Taylor and Ford both contributed to paving the road for what we know as DFA and DFM today: minimum parts, ease and speed of assembly, compatible materials, robust design, and low cost.

Henry L. Gantt[22]

In this same time period, Henry Gantt (1861-1919), inventor of the infamous Gantt Chart, made several significant contributions to bring about the DFA and DFM work environment that still exists today. Like Taylor, Gantt really sympathized with the worker. He was one of the earliest members of the Scientific Management community to direct his efforts toward the human being in industry. "In all the problems of management," he wrote, "the human element is the most important one." His first original contribution was the "task and bonus" system of wages which he presented at ASME in 1901.

Gantt's next contribution was to evolve graphic charts for production control. The "Daily Balance Sheet," forerunner of his better-known Gantt Chart, was to give a picture of the prior day's work by noon the following day to facilitate continuous preplanning of production. This is the forerunner of production planning as we know it today.

What is less well known was one of the most radical things that ever happened in business. Up until Gantt, all production in the 1st and 2nd Industrial Revolutions was quantity-based. Gantt's experience in production planning with his Daily Balance Sheet gave him the confidence to push the merits of time-based design and production, which then pervaded all industries.

Frank B. Gilbreth Sr[23]

Scientific Management, as Taylor and Gantt had developed it, was a series of principles for analyzing the routines and procedures of workers on the job.

Gilbreth's first contribution was to develop lines of authority and responsibilities of each worker's job – Job Descriptions.

His unique contribution was on human efforts and the methods he devised for fleshing-out wasteful and unproductive movements. There was "one best way to do the work." If it could be discovered, it would add significantly to the gains Taylor was making in the overall system of management at a next level of refinement.

He was the first to apply a motion-picture camera for analysis, and the first to classify the elements of human motions. Gilbreth reduced all motions of the hand into some combination of 17 basic motions.

ISBN13 978-1-937115-42-5

The finding of 17 basic motions, is the final piece of the foundation for DFA and DFM. It underlies all worker and machine motions in today's workplace, the design of all parts to these optimal set of motions; and to design for cost.

1920s-1930s

There were many fundamental changes to methods of design and production, and many advances in enabling technologies, between the late 1800s and 1920. The outbreak and conclusion of World War I and the Spanish Flu finished that period. Industry had learned many things learned from Taylor, Ford, Gantt, and Gilbreth that took time to now permeate across companies. Yes, the airplane came of age and the ability to work with metal advanced significantly, but these two decades were mostly spent permeating the discoveries and methods of that great inventive period across industries and geographies.

Within the engineering profession though, specialization of disciplines continued. As previously written, the first industrial degree program was at the Carnegie Institute of Technology in 1934. Many colleges and universities began offering specific degrees in increasingly specific and sub-fields of engineering. Engineering specialization was maturing.

World War II

Putting aside the horrific human tragedies of WWII, there were great advances with respect to design and manufacturing; and Design for Assembly and Design for Manufacturing. The huge quantities needed, increasingly detailed specifications, and the need to have everything done yesterday in the environment of a shortage of raw materials, pushed design and manufacturing ingenuity to new levels. Supply chains, and materials handling logistics, were no less complex. Design for Handling and Shipping were never coined as terms, but it was just as important to get products as quickly to the battlefield as it was to get them quickly out of the factory.

This period saw the advent of Design for Ergonomics. The first methods for determining Design Quality, whose principles underlie much of DFA and DFM logic, came out of WWII. Operations Research, for improving designs, design time, design quality, and production time came from this period. And, in what was a turning point after near a century of increasing task and job specialization, was the need for Systems Engineering.[24] Products were getting much more complicated. As well, specialization had resulted in people being more siloed in their experience and knowledge of the workplace.. Workers no longer knew how to do every job from concept-to-customer as they did in the artisanship days. There were also geographic distances now to overcome as companies had grown big. A specialized engineering discipline was now needed to integrate design and production activities, Systems Engineering.[25]

It was this increasingly specific and siloed worker training and knowledge that opened the door for all the systems engineering, cross-functionally-dedicated organizations, cross-functional team structures, integration organizations, and project management organizations that we know today. The next fifty years would largely be dedicated to reversing the trend of the previous 100 years of specialization[26]. It would be achieved by adding new organizations, layers of management and workers, and new tools such

ISBN13 978-1-937115-42-5 BOOTHROYD-DEWHURST, INC. 35nd International Forum on DFMA
Providence, Rhode Island
June 18, 2024

as DFA and DFM to all companies. Finally gone in the USA and Europe were the days of the artisan who knew all the jobs. As well, much of the empathy for how one's work affected another's work down the line from them had disappeared. Specialization, and compensation methods for that specialization and resultant output, created the over-the-wall mentality that industry has worked to overcome for these next fifty years. Enter Edward F. Deming and the Toyota Production System. Over-the-wall had also decreased final product quality. Or, was it the inevitable outcome of specialization that led to the most prolific innovation periods in human history? Either way, there were holes that needed to be filled to stay at the forefront competitively. DFA and DFM were among the solutions.

3rd Industrial Revolution - Part II [1950-2010]

After WWII, several years were needed to reconcile the fall out of the war; and for populations and countries around the world to attain their new sense of normal. In the United States, much had been invented, changed, or sped up as a result of the war effort. Europe had much more challenging problems to also rebuild cities and homes, restore agricultural lands, and to rebuild factories which had been major targets of the war. Some years went by as human effort and emotions focused on the simpler things in life.

From an industry stand point, the primary companies contributing to the war effort were now way out in front. They largely had the best of everything, from equipment to processes to people. In this day and age, we would call them the "bleeding edge innovators" and "leading edge" companies - the first quartile of industry. As is our cycle today, the "fast followers" would catch up in the next few years - the second quartile of industry. The third quartile, the "stabilized cost-reduced tech" companies would adopt a few years after the fast followers. And, the "laggards" fourth quartile would then follow in turn. The spreading and adoption of the tremendous advances of WWII would take until the mid 1960s.

Of course, as is to be expected, the bleeding-edge innovators continued to blast away unabated. They had attained a great advantage. They were loaded-up with new technology, assets, and capabilities that were created with government money; that they now owned. Perhaps more importantly though, the speed or velocity of the company culture was at an all time high. For five years, everyone in the company had become highly experienced in inventing and executing at a high rate under pressure. And so it continued, a new normal. The transistor was invented in 1947, the advent of the age of electronics. The first MOSFET integrated circuit was invented in 1959, the advent of Moore's Law. The more capable CMOS IC came in 1963. PCM, for digital voice transmission was in 1962.[27] There were numerous inventions in all the industries that were on the front end of the war investment, momentum is momentum.

Electrical Engineering specificity had been increasing since Edison invented the light bulb. Now there is distinctly Electronic Engineering. It could be foreseen that these bodies of knowledge would grow to equal what was now known in civil and mechanical engineering. Specialization in engineering was continuing unabated for almost a hundred years now. Software would soon add another fifty years. More so, software was transformational as all other engineering disciplines had to incorporate the presence of software into their work - not the least of which was IC design engineering. In hindsight, it could be

ISBN13 978-1-937115-42-5

foreseen that cross-functionally-oriented tools would be needed to combat the ongoing complexity and specialization.

Stuart Pugh[28]

Stuart Pugh graduated from London University with a degree in Mechanical Engineering and became a graduate apprentice for the British Aircraft Corporation. In 1956 he worked in the Warton Aerodrome as a project engineer for the Mach 6 Wind Tunnel. In 1963 he became the Chief Designer of the Mechanical Product Division at the Marconi Company. In the later stages of his industrial career, Pugh worked within the English Electric Company as Chief Designer in the Hydraulic Equipment Division, ultimately progressing to become Divisional Manager.

Pugh left industry in 1970 and began his academic career as a 'Smallpeice' Reader in Design for Production at Loughborough University of Technology. Later, he became the Director of the 'Engineering Design Centre'.

Pugh moved to Scotland and in 1985 became the 'Babcock Professor of Engineering Design' and the head of the 'Design Division' at the University of Strathclyde in Glasgow. The Design Division merged in 1989 with the Department of Production Management and Manufacturing Technology to create the Department of Design, Manufacture and Engineering Management (DMEM), of which Pugh remained head until his death in 1993. It was here that Pugh produced his seminal book, 'Total Design: Integrated Methods for Successful Product Engineering', published in 1990. Pugh Introduced and taught Total Design across the faculty of engineering at Strathclyde University.

Soon after Pugh published his book 'Total Design', Professor Don Clausing (MIT) and Professor Ken Ragsdell (University of Missouri) encouraged Pugh to publish his collection of papers to make his work readily available to design engineers and managers. However, Pugh's untimely death from illness ultimately led Don Clausing and Ronaldo Andrade (Universidade Federal de Rio de Janeiro, Brazil) to complete Pugh's book 'Creating Innovative Products Using Total Design: The Living Legacy of Stuart Pugh'.

Pugh's Corporate Legacy

Pugh started an intellectual revolution of thinking, and associated cross-functional approaches, that needed the input of all stakeholders to get a best outcome. Everyone could agree they wanted the best outcome.

Pugh wrote three books,[29][30][31] the latter being the work of Clausing and Andrade. His Total Design Book, spawned several generations of books on design and analytical quality techniques. His work on "Concept Selection" (A Method of Controlled Convergence) was the basis for GM's Saturn project - everything done in one place. Convergence was also applied to identify market segments that were underserved, a highly intensive charting exercise that would result in converging on the underserved market segments. He is best known for his Pugh's Decision Matrix[32]. Just about all the important business and technical decisions that needed to be made could benefit from applying the technique.[33]

ISBN13 978-1-937115-42-5

When to Use a Decision Matrix:
- When a list of options must be narrowed to one choice
- When the decision must be made on the basis of several criteria
- After a list of options has been reduced to a manageable number by list reduction

Typical Situations:
- When one improvement opportunity or problem must be selected to work on
- When only one solution or problem-solving approach can be implemented
- When only one new product can be developed

Had Stuart Pugh lived longer, he would be mentioned in the same sentences as Edward Deming, Joseph Juran, Philip Crosby, and Kaoru Ishakawa for his contributions to the management of engineering, technology, science, and manufacturing.

The Next Wave

Pugh's work spawned a wave across industries and continents of academics, entrepreneurs, and corporate practitioners working on more precise analytical techniques that were generally applicable across industries. Older techniques were pulled out and tried again. Quality went in the direction of Cause & Effect Diagrams, Control Charts, Scatter Diagrams, QFD, and more. Engineering upped their game with QFD, FMEA and DfMEA. *What was different was that companies increasingly began to authorize large amounts of cross-functional employee time to proactively assess alternatives*, and to rigorously analyze problems to produce completed diagrams.

It was clear the separated specialties needed to be brought together again[34]. There is no greater statement of need than for management to approve "perpendicular time" vs. all hands focused on the value-added design-production processes. The IEEE foresaw management science would grow in electrical and electronic engineering, and formed the IEEE Engineering Management Society in 1951.[35]

Thought Leaders In DFA and DFM

Research underpinning this summary of early pioneers in DFA and DFM areas uncovered over fifty professionals who had a hand in the creation, development, maturation, or automation of the bodies of knowledge. When possible, the bodies of work of each individual was sought to roughly determine if there was at least half a career of dedication to DFA or DFM. Professionals that turned out to be all hat and no cattle were omitted.

The following is a summary of the folks that have cattle. In many cases they also had a hat, but not always. All come from three geographies: United States, United Kingdom, and Europe. Some were teachers and professors writing papers for academic publishing requirements, and teaching their students. Some were engineers in companies that perfected techniques that other companies found out about. Some were consultants who ended up doing great things with companies.

ISBN13 978-1-937115-42-5

A more complete bibliography of each thought leader will be compiled if additional follow-up research is done at a later date. For the purposes of this paper, the following professionals get a lot of credit for pushing DFA and DFM subject matter to the masses.

Each person had multiple areas of study. Only one or two area were picked for the list below. This list is by no means complete, nor is the research across geographies. Below are the people that could be vetted as of the writing of this paper.

Table 1
Thought Leaders at the Onset of DFA and DFM

Thought Leader	Birth-Death	Area of Contribution
Philip Barkan	1925 - 1996	Design for Manufacturability Curriculum at Stanford
Kenneth Wallace	1944 - 2018	Translate Seminal Work - Gerhard Pahl & Wolfgang Beitz
Daniel E. Whitney		DFA - Computer-Driven and Automated Assembly
David Anderson		DFM and Concurrent Engineering
Mogens Andreason		Design Process, Design for Assembly
Robert H. Sturges, Jr.		Design for Assembly, Fastenerless Assembly
Kevin Otto		Reverse Engineering, Designing In Uncertainty

While these people made great contributions of intellectual ideas and approaches, and their work was known on two or more continents, their work did not result in specific systematic approaches and tools that were widely adopted and became widespread across industries and continents. However, DFA and DFM would not have become widespread without them.

Corporate Thought Leaders In DFA and DFM

Research underpinning this summary of early corporate pioneers in DFA and DFM areas likely uncovered just about all companies that had an early hand in the creation, development, maturation, or automation of the bodies of knowledge. All the early adopter companies overtly marketed that they had created "tools" and gave them brands. In some cases, they openly shared some of the intellectual property. In other cases, you'd only get to see the front covers of documents to confirm they had such tools.

The following are all the companies with herds of cattle. In all cases they also had a hat. Why? Because marketing expertise that is real raises stock prices. The companies come from four geographies: United States, United Kingdom, Europe, and Japan.

ISBN13 978-1-937115-42-5

Table 2
Corporate Thought Leaders at the Onset of DFA and DFM

Corporate Leader	Area of Contribution
RCA	Price Systems
Sony	DAC - Design for Assembly/Disassembly Cost-Effectiveness
Hitachi	AEM - Assembly Evaluation Method
Fujitsu	PEM - Productivity Evaluation Method
IBM	ProPrinter 4201-001 Case Study
Xerox	PIC - Producibility Index Chart
Xerox	Pumpkin Books [Estimated 20+]
Westinghouse	Westinghouse Calculator - "Westinghouse Wheel"
Draper Labs	Automated & Computerized Assembly
Digital Equipment Corp.	DEC Standard 101 [Estimated 80+]

Note: This is probably the right place to insert another broad caveat to this paper as a whole. Much of what was evolving in Japan and Korea with thought leaders, publications, and corporate tools and case studies are not adequately included in this summation of DFA and DFM history at this time. The Toyota Production System was developed 1948-1975[36] *and began overtaking the world. DFA and DFM was embedded in every aspect of that TPS thinking. The maturation of TPS occurred in the same ten years as DFA and DFM also being ready for prime time, enabling their widespread adoption. There was certainly a great deal happening on the Pacific Rim that is not represented in this paper.*

The Advent of DFA and DFM Software

The environment in which the first commercially-developed software was to be developed was set. There is an old adage, "if you can't write it down you don't understand it." This is why detailed specifications are required to be written[37]. Software coding further raises the bar to a new level of exactness and consistency in a binary environment. This is logic underlying Digital Twins being done in advance, although the twin has other uses as well. Industry got great benefit from manual DFA and DFM techniques and adhering to their rules; not at a level of 80-20 however. DFA and DFM software would make the difference.

Two key contributors, not yet mentioned, were Corrado R. Poli[38] and Robert J. Graves[39] at UMass Amherst. Poli had been an anchor of the department for years, and eventually became Department Head. Graves' stay wasn't long, but he arrived in a key window of time, 1979-1981. He then departed to RPI and then Dartmouth. But Poli and Graves continued to collaborate for ten more years. They initially concentrated on the most important areas of the time for DFA and DFM: forging, stamping, and injection molding. In later years, Graves' interest in handling and logistics of physical products expanded their DFX repertoire. They co-authored a number of papers together, but research did not identify any books they wrote together. Each wrote many papers separately over time.

ISBN13 978-1-937115-42-5

Enter the industry disruptor from England to UMass Amherst. It was 1967. Geoffrey Boothroyd was smart, well trained, already respected for his work in the UK, knew Pugh, and had aspirations no one else was thinking about. To date, DFA and DFM had been a largely collegial environment between academia and industry in the United States. Europe was much more competitive at the time and the market was not near as big. Boothroyd had identified a center of excellence at UMass that matched his expertise, and was taking the technical approach that he believed would work. Automatic feeding and vibration feeding equipment was coming of age and it was a central topic of research at the time.

> Geoffrey Boothroyd was born in Radcliffe, Manchester, England on November 18, 1932. He obtained a Bachelor of Science in Engineering from the University of London in 1956, followed by a Doctor of Philosophy in 1962 and a Doctor of Science in 1974. Geoffrey Boothroyd, a renowned British educator and pioneer in the field of industrial and manufacturing engineering.[40]

In 1970, Boothroyd and Poli published their first major work together. The Handbook of Feeding and Orienting Techniques for Small Parts[41] was a seminal publication. The Handbook demonstrated the approach to the method and the ability to log data values that could be replicated, but it was not sufficiently refined to go mainstream. Laurence Merch, is mentioned here for completeness as a signed co-author of the Handbook but there is little mention of any involvement afterwards.

In 1976, a second seminal publication was published jointly between Boothroyd and a grad student, C. Ho., that he worked with for that year. The Coding System for Small Parts for Automatic Handling[42] was presented at a SME convention in Chicago which made it an official publication of research. Nothing can be found in the literature about C. Ho subsequently, or any additional involvement by him.

By 1979, the initial Handbook had been refined be useful for a great variety of small parts across industries. Many papers were written as the years progressed, but the Handbook[43] of 1970 is the only official publication of it that could be found. There were vague references to a second edition in 1979, but they couldn't be verified. It is known however, that the Handbook was an ongoing work-in-progress during the 1970s. By the late 1970s, this slice of the DFA and DFM emerging body of knowledge was now ready for prime time and could be sold and taught as a product or as a service. In the next five years it would be put into software.

This is when things get spicy in the history of DFA and DFM. Boothroyd's and Poli's professional aspirations were not the same, but they both had rights to the research in the Handbook.

National Science Foundation Grants

In parallel, but evidently separated from his work with Poli just described, Boothroyd had applied for a number of grants from the NSF beginning in 1974. The first four were prior to his joining with Professor Peter Dewhurst to form Boothroyd-Dewhurst, Inc. in 1980. The next two were in 1981, right after BDI was formed. For these first six NSF grants, the Principal Investigator was Geoffrey Boothroyd and the

Co-Principal Investigator remained UMass Amherst. For completeness, all ten NSF grants between 1974 and 1990 are listed here. Their collective impact will not be realized until the early 1990s.

In short, a great deal of the financial resources necessary to refine and evolve DFA and DFM to commercially available methods, references, and software were funded by the National Science Foundation.[44] The subjects of the grants give you a clear idea of their purpose.

1. Group Technology Applied to the Automatic Handling of Small Parts
Award Number:7412611; Principal Investigator:Geoffrey Boothroyd; Co-Principal Investigator:; Organization:University of Massachusetts Amherst;NSF Organization:CMMI Start Date: 07/01/1974; Award Amount:$372,300.00;

2. Fifth North American Metalworking Research Conference (Namrc-V)
Award Number:7710189; Principal Investigator:Geoffrey Boothroyd; Co-Principal Investigator:; Organization:University of Massachusetts Amherst;NSF Organization:CMMI Start Date: 05/15/1977; Award Amount:$3,000.00;

3. Design For Manufacturability
Award Number:7710197; Principal Investigator:Geoffrey Boothroyd; Co-Principal Investigator:; Organization:University of Massachusetts Amherst;NSF Organization:CMMI Start Date: 09/01/1977; Award Amount:$396,000.00;

4. Design For Manufacturability
Award Number:7909761; Principal Investigator:Geoffrey Boothroyd; Co-Principal Investigator:; Organization:University of Massachusetts Amherst;NSF Organization:CMMI Start Date: 09/01/1979; Award Amount:$150,000.00;

5. Workshop on Assembly and Inspection
Award Number:8115036; Principal Investigator:Geoffrey Boothroyd; Co-Principal Investigator:; Organization:University of Massachusetts Amherst;NSF Organization:CMMI Start Date: 05/15/1981; Award Amount:$5,525.00;

6. Economic Applications of Assembly Robots
Award Number:8111917; Principal Investigator:Geoffrey Boothroyd; Co-Principal Investigator:; Organization:University of Massachusetts Amherst;NSF Organization:CMMI Start Date: 09/01/1981; Award Amount:$361,425.00;

7. Economic Applications of Assembly Robots
Award Number:8514024; Principal Investigator:Geoffrey Boothroyd; Co-Principal Investigator:Peter Dewhurst; Organization:University of Rhode Island;NSF Organization:CMMI Start Date: 09/15/1985; Award Amount:$114,300.00;

8. Programmable Automation and Design for Manufacturing Economic Analysis
Award Number:8513930; Principal Investigator:Franklin Snyder; Co-Principal Investigator:Peter Dewhurst, Geoffrey Boothroyd, Phillip Ostwald, Jeffrey Funk; Organization:Westinghouse R&D Center;NSF Organization:CMMI Start Date: 09/15/1986; Award Amount:$488,543.00;

9. Selection of Manufacturing Processes and Materials for Component Parts
Award Number:8908214; Principal Investigator:Geoffrey Boothroyd; Co-Principal Investigator:Winston Knight, Peter Dewhurst; Organization:University of Rhode Island;NSF Organization:CMMI Start Date: 12/15/1989; Award Amount:$279,995.00;

ISBN13 978-1-937115-42-5

10. Design for Manufacturability and Assemblability Instructional Studio
Award Number:9051268; Principal Investigator:B. Lee Tuttle; Co-Principal Investigator:; Organization:Kettering University;NSF Organization:DUE Start Date: 05/01/1990; Award Amount:$43,740.00;

The "final report," which took place in 1981[45], upon which the subsequent grants were approved, could not be retrieved from the public archives of NSF reports for further investigative research as of the writing of this paper. All that could be ascertained was that there was a seminal final report written in 1981. In total, over all ten grants, Boothroyd and his colleagues obtained $2,184,788, which was a great deal of money in the 1970s and 1980s.

Red, White, & Black Books[46]

The other major source of funding came from Boothroyd- Dewhurst, Inc.'s ability to attract monies from corporations. Between 1983 and 1991, BDI evolved the original Handbook with Poli to be an entirely new data set that was the sole property of Boothroyd-Dewhurst. It took place across three successive publications of refined handbooks. Red in 1983. White in 1987. Black in 1989, which cited the first two books.

It is not known how much money was contributed by corporate supporters during the creation of these three versions. The research uncovered the actual Red and Black books. The White Book was not located as of the writing of this paper. Below are selected excerpts from the inside front pages of the two books that were located, the text below is replicated as it was written in the original work.

> Red Book [1983]
>
> The development of portions of this handbook was carried out in collaboration with the University of Salford Industrial Center, England (General Manager, B.D. Richardson, Project Managers K.C. Swift and A. H Redford).
>
> The work was mainly funded by NSF Grant APR77-10197. Additional financial support for this work has been provided by AMP, Inc. and Xerox Corp.
>
> Finally, the authors would like to thank Alan Redford for his helpful comments and the following individuals and companies (in alphabetical order) for their suggestions, financial support and continued encouragement: AMP, Inc. (Joe Sweeney and Ed Paukovitz); Digital Equipment Corp. (DoM Sambuto and Fred Kuenzig); Emhart Corp. (Gene Chartrand); GE Co. (Gerry Hock); IBM Corp. (Morris Krakinowski and Tim Karlberg); Philips (Jaap Boorsma); Siemens (J. Hauesler); University of Salford Industrial Center (Barry Richardson); Westinghouse Corp. (Tibor Csakvary); Xerox Corp. (SidneyLiebson).
>
> Black Book [1983, 1987, 1989]
>
> Work leading to this product design for assembly handbook, including development of databases and research in automatic and robot assembly, was

ISBN13 978-1-937115-42-5

undertaken with the aid of grants from the National Science Foundation and from industry.

Original studies of the design for high-speed automatic assembly classification systems were carried out with the close collaboration of Dr. Alan Redford of the University of Salford, England.

We wish to thank all of those graduate students who have participated in our design for assembly research programs. We would also like to express our gratitude to the NSF and the following companies who provided grants to support the research. AMP, Inc., Digital Equipment Corp., Ford Motor Company, General Electric Company, Gillette Company, IBM Corporation, Westinghouse Electric Corporation, and Xerox Corporation. Finally, our appreciation is due to the numerous companies and individuals who have provided encouragement during the past 10 years. - G. Boothroyd and P. Dewhurst, Wakefield, RI, November 1989

Boothroyd-Dewhurst, Inc. [BDI]

Between 1980 and 1991, BDI transformed itself from a start-up company of academic origins to a consultancy and specialized software provider that had caught the attention of all Fortune 500 companies.

BDI took the generalized practice of always trying to have good design hygiene and minimize the part count in assemblies to a new level when they introduced the "Theoretical Minimum Part Count" which is now the industry standard. [The date this was first published could not be exactly determined.]

BDI created the first working formula for Design Efficiency[47].

BDI released the first DFA software to industry in 1983[48][49].

BDI released the first DFM software to industry in 1985[50]. Then pioneered the expansion of initial DFM applications across a wide variety of part types and production processes.

In 1985[51], Professors Boothroyd and Dewhurst at UMass Amherst moved to the University of Rhode Island and quickly involved Professor Winston Knight in their business. The trio would go on to set the standard for DFA and DFM for the next two decades until life's circumstances sent them in different ways.

BDI published its first book in 1988[52], which research indicates is a second edition of Boothroyd and Knight's first pre-BDI book together in

1975. Two more BDI books would follow. The next was coauthored by all three principals. The final was authored by Boothroyd solely.

Not everything was clear sailing yet though. It needed to be made certain that Poli did not have any claims that contradicted Boothroyd's assertion that his creation of the Red/White/Black Books now constituted proprietary BDI intellectual property and had evolved beyond having any of its IP roots from their seminal work in 1970. Poli had continued his own work after BDI formed, and was still actively applying and teaching and writing on his own DFA and DFM progress at UMass. By 1989, the stress of this lack of clarity on intellectual property claims came to a head and a law suit[53] which was filed by BDI on July 28, 1989. The straw that broke the camel's back is when one of Poli's grad students, Richard Adler, approached BDI about licensing BDI's software and porting it to Apple's Mac platform. When BDI declined his offer, he teamed up with his professor Poli and created software using Poli's data set. Together, the running open question on the actual independence of Boothroyd's current data sets that had evolved since joint Handbook in 1970, combined with the presence of a soon-to-be software competitor running on Poli's data set, was not an acceptable situation in BDI's view.

Making a highly intense two-year story short, in 1991[54], the United States District Court in Massachusetts ruled in BDI's favor that Poli had no claims and that Adler's Sapphire Design Systems Mac software constituted a violation of BDI's intellectual property as Adler had some access to BDI's software before "cloning" it on the Mac using Poli's data set. Sapphire was ordered to cease and desist. With this ruling, BDI put claims to its IP to rest and its first competitor out of business. Had these events not taken place in 1991, the make-up and composition of DFA and DFM market in the United States, England, and Europe would have certainly been different.

BDI Awarded National Medal of Technology and Innovation Management[55]

Research for this paper could not verify that there was any of type of tie to the timing of this, except to note that the US Government usually knows what's going on or is going to happen when they have an interest. In the same year the IP cloud went away, 1991, Boothroyd[56] and Dewhurst[57] were awarded the National Medal of Technology and Innovation Management by George H. W. Bush. As was the case for Christopher Dresser and his Industrial Engineering when the US Government asked him to write a report on the design of household goods in 1873, discussed earlier in this paper, the Award solidified BDI's DFMA® approach as a national asset and solidified the practices in the annals of corporate America and in companies around the world.

Honor Roll Contributors

Research findings identified a number of other academics, consultants, corporations, and authors that also contributed to the invention of DFA and DFM techniques; and/or their propagation across industries and continents. A paper on history would not be complete without including these contributors. Not yet for publication are a number people we are still researching as of the writing of this paper. More people will be included in subsequent versions of this initial "Honor Roll" List.[58]

Table 3
DFA and DFM Honor Roll

Honor Roll Actively Practicing		Honor Roll Deceased & Retired
Alan Redford University of Salford	**David G. Meeker** DEC, Compaq, HP, Bose, MIT, BU, Neoteric Product Design	**Alfonse Adler** University of California Deceased
Kenneth G. Swift University of Hull	**Christopher Tsai** Kodak, RIT, Global Productivity, BDI	**Gordon P. Lewis** Xerox, DEC, Datum 3D Deceased
Julian D. Booker University of Bristol	**William Devenish** Motorola, NEC, Nokia, Harris, FMC, Kohler, L3Harris, The Devenish Group	**F. James McWilliams** DEC, Compaq, HP, Sun Deceased
Steen Kahler & Thomas Lund University of Denmark	**Matthew Miles** Ingersoll Rand, Amphenol, Raymond, Dynisco, Markem, Ambri, Mission Technologies, VAVE Consulting Services	**A.J. Overton & David Nevela** DEC, Compaq, HP Deceased
Finn Fabricius Institute for Product Development (IPU) ListenWhy Engineering	**Robert A. Williams** HP, Agilent, Keysight, Nilfisk, Dry Development, Creative Design Solutions Consultants	**James L. Nevins** Draper Laboratories Deceased
Nicholas Dewhurst BDI	**Jonathan E. Freckleton** RIT	**Miles Parker** Parker Group Retired
John Breckenridge BDI	**Gerhard Pahl & Wolfgang Beitz** Technical University of Darmstadt	**William Branan** Motorola Retired
Brian Raposa BDI	**Jay P. Mortensen** Deloitte, Bethlehem Steel, Toyota, Raytheon, Mercury Marine, Maytag, Rexnord, KPMG, LG	**Vincent P. Render** Ford Retired
	Michael E. Corbett Deere, IBM, Gaileo, Zymark, Invacare, PinDot, Jaior, Corbett Engineering	**Michael F. Carter** General Motors Retired

The Cat Inevitably Gets Out of The Bag

When capabilities are developed, that have widespread impact and clear ROI, whether they be technical or process or software innovations, time takes its toll and competitive offerings emerge. That is the nature of a capitalistic marketplace. The absence of detailed research on early activities in Japan and Korea; and certainly capabilities and offerings have become more widespread now, has already been noted.

By the mid 1990s, Lucas Engineering in the UK, an engineering consultancy, had developed DFA and DFM Capabilities. Research indicates some software, but it was more of a set of individual tools than an integrated suite. Unknown. But, it was a natural extension of their long standing base business in engineering.

Galorath Incorporated, a defense contractor for years that was focused on software cost minimization and management, expanded its software platform to include hardware assemblies and part costs - and some analytical capabilities.

Two small consulting firms developed offerings in the field, Munro & Associates and Huthwaite Innovation Institute. Huthwaite had been in business for years, much of it was benchmarking. DFA and DFM are benchmarks in their own right, a product at a time. This too was a natural extension. Huthwaite used manual techniques, or assisted companies with their thinking that had licensed BDI's software. It was a small part of his business. Munro was more serious about focusing more specifically in the area,

ISBN13 978-1-937115-42-5

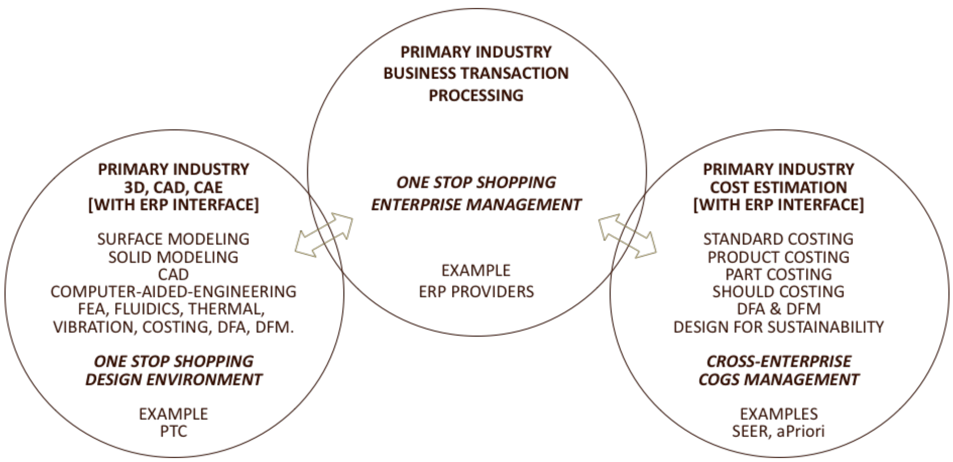
and specifically on the automotive industry. Munro achieved a great deal with the Big 3 in Detroit and their suppliers. Research indicates he has evolved a proprietary software offering over the years.

In all though, "The BDI Case Study" is a masterclass in how a small company can own a market segment or an industry. Boothroyd, Dewhurst, and Knight created great value with their DFMA® and managed to hang on to it when surrounded on all sides by pirates and giants.

The Cat Naturally Gets Out of The Bag

Another decade would pass though before "structural" natural competitors began to emerge. For DFA and DFM, competition would naturally emanate from three primary sources. Just as with Lucas, Galorath, and Huthwaite, offerings would be natural extensions of existing and established businesses and/or their software platforms.

Figure 1
Other Industries Extend Software Platforms To Incorporate DFA and DFM[59]



The decision making process will be to select from the DFA and/or DFM body of knowledge, the capabilities that best augment their current offerings. This will be true for all three "natural competitor industries." They will be selective to their own interests, often thought through as getting the next ring of functionality around the current base offering. They will likely not implement full-on capabilities. A number of years have already passed if there are intentions to do so. The goal of all three though is to extend their platforms to achieve "one stop shopping" for their customer bases.

4th Industrial Revolution [1990-2060]

Many peg the 4th IR as beginning in 2016. This is when Klaus Schwab first pronounced it so as part of the World Economic Forum.[60] Modern literature seems to be supporting this time of 4IR beginning.

3D Printing

The digital age more likely began in the 1990s as the usage of CAD, solid modeling, email, and cell technology became widespread. The first digital 3D printers were also invented in the 1990s. Now, 25 years later, the evolved production capabilities of Additive Manufacturing have yielded a new field for formalized DFA and DFM practices. Evolving steadily now for twenty five years, recent DFAM[61] and DfAM acronyms now represent an emerging set of matured practices for 3D printing. Additive manufacturing has now achieved equal status[62][63][64] to traditional production technologies such as stamping, extrusion, molding, and forging and it needs its own DFA and DFM. Unique tables of optimization values and tailored software algorithms need to be developed. Some of the rules guiding DFA and DFM will need to be modified as well. One of the reasons 3D made it to the legitimate manufacturing process table, is that it eliminated many of the constraints of traditional processes. In the final analysis, it will be its own unique take on DFM and DFA.

3D Printing is not just one thing either. There are several different processes and each have their constraints. New materials are being invented regularly, and each have their constraints. In the beginning it was about plastics, then plastic composites, then composites that were borderline plastics, and now metals[65]. Like resins, each different type of 3D-printed metal has its own issues. As printing beds grow in bed size and geometry, a next level-up of a total assembly becomes possible. It is easily argued that 3D printing, unto itself, will grow to be as large and varied as all traditional DFA and DFM applications.[66]

Structural Biomaterials

Soon there will be "structural bio-materials" and "bio-plastics" There will be manufacturing, out of the test tube and ready for volume production. Their designs, production processes, and constraints will be yet again different. New tables and new-to-the world software applications will need to be developed. Supporting libraries will need to include the Periodic Table, approved organic and inorganic molecules, compound degradation rates of heat, light, and effects of several forms of EMI and magnetism imparted by production activities. That will be a new world of materials.

Environmental Goals

On a different vector, one that has been discussed and practiced in some corners since the 1990s is now evolving more rapidly because of the things that are going today that are becoming societal issues. Europe is ahead of the United States in thinking the problem, as there are very few places remaining to dump junk.[67] Recyclability needs will increasingly influence designs. Design for Recyclability may optimize Design for Disassembly, in contrast to today's Design for Assembly. Design for the Environment and Design for Sustainability are the forerunner for what will be a complete relook at many products and product categories.

Extending the thought just a bit more, structural biomaterials and bioplastics may enter the picture on a larger scale if they are also designed to degrade naturally without harm to the environment. Initial offerings in fast food packaging industry, in both plant-based materials and bioplastics, have come into the market this past year.[68] Likely industrial applications are ahead. More widespread packaging and items that get consumed in production or logistics processes are obvious candidates.

ISBN13 978-1-937115-42-5

Micro/Nano, Zero Gravity, and AI

Design for Micro and Design for Nano are already making their way out of the lab, and will be on the corporate radar in another twenty years[69]. As the world heads toward 2060, Design for Zero Gravity is in sight. We'll have to be able to do it, before we live it. By then, as well, the final step in the sequence of manual vs. semi-manual vs. automated assembly will have come of age. We're already changing certain designs just from the presence of the IoT and IIoT[70]. Imagine what AI will bring. AI Assembly and AI manufacturing will have its own set of capability constraints. It will redefine what automation means. So far in history, automation has been about increasing speed and removing labor without losing quality. Will AI manufacturing again be about speed? Any Designing for AI Manufacturing will certainly need its own set of tables. All these areas are smiling problems for the moment.

Summary

The purpose of this paper is to summarize the known history of the evolution of Design for Assembly and Design for Manufacturability. To do so, a three-hundred year period was examined and postulated.

As an early proponent and sometimes practitioner of the techniques since the 1980s, and watching traditional DFA and DFM refine and mature, it became clear that a history was being lost to the ages. A quarter of the pioneers are no longer with us. A quarter are retired or otherwise left the field. A quarter are in the twilight years of their useful career. A quarter remains. Without strong leadership, adaptation to the times, and fresh inventions in the field that keep pace with new materials and new processes, DFA and DFM risks becoming another check the box item in product development and cost reduction plans. Most design-assisting tools are only capable of incremental change and improvement. DFA and DFM can bring about radical change and improvement, sure they take a little more time and concentration.

Much has been accomplished. DFA and DFM have contributed to the well being of the human experience, and to corporate bottom lines since their inception. It is incumbent on those that remain to carry the torch forward. Bodies of knowledge take 60-100 years to mature. DFA and DFM are at best middle-aged at the advent of this 4th Industrial Revolution. There are many new things soon to come. That is the history of all four industrial revolutions. DFA and DFM will be no different.

* *

A Note About The Author: Bradford L. Goldense NPDP, CMfgE, CPIM, CCP, LSME, IEEELM is president of GGI. Founded in 1986, the consulting - market research - executive education company is recognized across geographies for expertise in R&D, advanced and product development, innovation, and the metrics that drive corporate performance. Mr. Goldense has worked with 200 of the Fortune 1000 and over 750 global manufacturing locations. Over 500 companies have attended GGI Summits and Masterclasses discussing strategy, innovation, and metrics topics. Mr. Goldense holds over two hundred copyrights. GGI is based in Dedham, Massachusetts. www.goldensegroupinc.com

* *

CITATIONS OF THIS PAPER

Goldense, Bradford L., "Design for Manufacturing & Assembly Across 3 Industrial Revolutions [White Paper], The 2024 International Forum on Design for Manufacture and Assembly, Boothroyd-Dewhurst, Inc., Providence, Rhode Island, USA, June 18, 2024, 25 Pages, GGI ISBN13 978-1-937115-42-5.

FOOTNOTES

[1] Goldense, Bradford L., "Adapting the "Master-Apprentice Model" to the 21st Century," Machine Design, Penton Publishing, Cleveland, Ohio, USA, Volume 91, Number 1, January 2019, Page 96, ISSN 0024-9114.
[2] "Industrial Design," Wikipedia: https://en.wikipedia.org/wiki/Industrial_design.
[3] "History of the Steam Engine," Wikipedia: https://en.wikipedia.org/wiki/History_of_the_steam_engine.
[4] "History of the Steam Engine," Wikipedia: https://en.wikipedia.org/wiki/History_of_the_steam_engine.
[5] Max Roser and Hannah Ritchie (2023) - "How has world population growth changed over time?" Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/population-growth-over-time' [Online Resource].
[6] "Planer," Wikipedia: https://en.wikipedia.org/wiki/Planer_(metalworking).
[7] "Milling," Wikipedia: https://en.wikipedia.org/wiki/Milling_(machining).
[8] "Shaper," Wikipedia: https://en.wikipedia.org/wiki/Shaper.
[9] "Lathe," Wikipedia: https://en.wikipedia.org/wiki/Lathe.
[10] "Industrial Revolution," Wikipedia: https://en.wikipedia.org/wiki/Industrial_Revolution.
[11] "Portland Cement," Wikipedia: https://en.wikipedia.org/wiki/Portland_cement
[12] "Industrial Revolution," Wikipedia: https://en.wikipedia.org/wiki/Industrial_Revolution.
[13] "History of Engineering," Wikipedia: https://en.wikipedia.org/wiki/History_of_engineering
[14] "Industrial Design," Wikipedia: https://en.wikipedia.org/wiki/Industrial_design.
[15] "Christopher Dresser," Wikipedia: https://en.wikipedia.org/wiki/Christopher_Dresser#Partial_bibliography.
[16] Goldense, Bradford L., "The Powers of Product Design," Machine Design, Penton Publishing, Cleveland, Ohio, USA, Volume 91, Number 3, March 2019, Page 80, ISSN 0024-9114.
[17] Goldense, Bradford L., "A History of Product Design," Machine Design, Penton Publishing, Cleveland, Ohio, USA, Volume 91, Number 4, April 2019, Page 96, ISSN 0024-9114.
[18] "Industrial Design," Wikipedia: https://en.wikipedia.org/wiki/Industrial_design.
[19] Urwick, Lyndall F. & Wolf, William B., *The Golden Book Of Management,* American Management Associations, New York, NY, USA, Expanded Edition, Copyright © 1956, 1984, Pages 79-85.
[20] "Model T," History: https://www.history.com/topics/inventions/model-t#section_1.
[21] "Henry Ford's Greatest Achievements and Inventions," World History Edu: https://worldhistoryedu.com/henry-fords-greatest-achievements-and-inventions/.
[22] Urwick, Lyndall F. & Wolf, William B., *The Golden Book Of Management,* American Management Associations, New York, NY, USA, Expanded Edition, Copyright © 1956, 1984, Pages 95-98.
[23] Urwick, Lyndall F. & Wolf, William B., *The Golden Book Of Management,* American Management Associations, New York, NY, USA, Expanded Edition, Copyright © 1956, 1984, Pages 136-140.
[24] Margolin, Victor, "*The United States in World War II: Scientists, Engineers, Designers*," MIT Press, Vol. 29, No. 1 (Winter 2013), pp. 14-29.
[25] "Systems Engineering," Wikipedia: https://en.wikipedia.org/wiki/Systems_engineering.

[26] Goldense, Bradford L., "A History of Design for Manufacturing and Assembly," Machine Design, Endeavor Business Media, Nashville, Tennessee, USA, January 7, 2022, https://www.machinedesign.com/automation-iiot/article/21213546/a-history-of-design-for-manufacturing-and-assembly, ISSN 0024-9114.
[27] "Information Age," Wikipedia: https://en.wikipedia.org/wiki/Information_Age.
[28] "Stuart Pugh," Wikipedia: https://en.wikipedia.org/wiki/Stuart_Pugh.
[29] Stuart Pugh, Don Clausing, Ron Andrade, (24 April 1996). Creating Innovative Products Using Total Design. Addison Wesley Longman. ISBN 0-201-63485-6.
[30] Pugh, S. (February 1991). Total Design: Integrated Methods for Successful Product Engineering. Addison-Wesley. ISBN 0-201-41639-5.
[31] S.Pugh, B.Hollins, (March 1990). Successful Product Design: What to Do and When. Butterworth-Heinemann. ISBN 0-408-03861-6.
[32] SlideTeam: https://www.slideteam.net/blog/top-7-pugh-matrix-templates-with-samples-and-examples.
[33] American Society for Quality: https://asq.org/quality-resources/decision-matrix.
[34] "Goldense, Bradford L., "A History of Design for Manufacturing and Assembly," Machine Design, Endeavor Business Media, Nashville, Tennessee, USA, Volume 94, Issue 2, February/March 2022, Pages 12-16, ISSN 0024-9114.
[35] IEEE: https://www.ieee-tems.org/governance/.
[36] "Toyota Production System," Wikipedia: https://en.wikipedia.org/wiki/Toyota_Production_System.
[37] Goldense, Bradford L., "Back To A Better Future: Product Definition," **Machine Design**, Penton Publishing, Cleveland, Ohio, USA, Volume 88, Number 6, June 2016, Page 72, ISSN 0024-9114.
[38] "Corrado Poli," Facebook: https://www.facebook.com/corrado.poli/.
[39] "Dartmouth Engineering: https://engineering.dartmouth.edu/community/faculty/robert-graves#.
[40] Dignity: https://www.dignitymemorial.com/obituaries/bradenton-fl/geoffrey-boothroyd-11611483.
[41] Boothroyd, G., Poli, C.R., and Murch, L.E., *Handbook of Feeding and Orienting Techniques for Small Parts*, University of Massachusetts, Amherst, MA, 1970. [A Seminal Work]
[42] Boothroyd, G. and Ho, C., *Coding System for Small Parts for Automatic Handling*, SME Paper ADR76-13, Assemblex 111. Chicago, October 1976.
[43] Boothroyd, G., Poli, C., Merch, L., "Handbook of Feeding & Orienting Techniques for Small Parts," 1979, Department of Mechanical Engineering, University of Massachusetts. [Unable To Verify 1979 Reference]
[44] National Science Foundation "Award Search," NSF: https://www.nsf.gov/, Award Search.
[45] Boothroyd, G and Wilson, W.R.D., Design for Manufacturability, NSF Final Report. University of Massachusetts, Amherst, MA, 1981.
[46] The original works were accessed using Journalistic Reporter's Privilege. Selected texts are accurately excerpted and reproduced as written from the inside front pages of the original published works.
[47] Boothroyd, Geoffrey and Dewhurst, Peter and Knight Winston, *Product Design for Manufacture and Assembly*, Marcel Dekker, Inc., New York, New York, 1994, Page 8.
[48] DFMA® Software: https://www.dfma.com/backgrd.asp.
[49] First DFA Software Published, Perplexity: https://www.perplexity.ai/search/when-was-first-6mn2kj13Q0CfXsCEa6se_g.
[50] First DFM Software Published, Perplexity: https://www.perplexity.ai/search/when-was-first-hREr5wPzRK2jRA0J69s8Qw.
[51] URI: https://web.uri.edu/engineering/departments/mcise/2024/03/manufacturing-pioneer-and-uri-professor-geoffrey-boothroyd-passes-away/.

[52] Boothroyd, Geoffrey and Knight, Winston A, *Fundamentals of Machining and Machine Tools*, 2nd Edition, CRC Press, Taylor & Francis Group, 1989.
[53] Justia: https://law.justia.com/cases/federal/district-courts/FSupp/783/670/1362309/.
[54] Justia: https://law.justia.com/cases/federal/district-courts/FSupp/783/670/1362309/.
[55] BDI: https://www.dfma.com/backgrd.asp.
[56] National Medals.org: https://nationalmedals.org/laureate/geoffrey-boothroyd/.
[57] National Medals.org: https://nationalmedals.org/laureate/peter-dewhurst/.
[58] Goldense, Bradford L., "Design for Manufacturing & Assembly Across 3 Industrial Revolutions [Presentation], The 2024 International Forum on Design for Manufacture and Assembly, Boothroyd-Dewhurst, Inc., Providence, Rhode Island, USA, June 18, 2024, Page 36, GGI ISBN13 978-1-937115-43-2.
[59] Goldense, Bradford L., "Design for Manufacturing & Assembly Across 3 Industrial Revolutions [Presentation], The 2024 International Forum on Design for Manufacture and Assembly, Boothroyd-Dewhurst, Inc., Providence, Rhode Island, USA, June 18, 2024, Page 38, GGI ISBN13 978-1-937115-43-2.
[60] "Fourth Industrial Revolution," Wikipedia: https://en.wikipedia.org/wiki/Fourth_Industrial_Revolution.
[61] Goldense, Bradford L., "DFAM: Design for Additive Manufacturing Arrives," Machine Design, Penton Publishing, Cleveland, Ohio, USA, Volume 90, Number 10, October 2018, Page 72, ISSN 0024-9114.
[62] Goldense, Bradford L., "The Five Types of Manufacturing Processes," Machine Design, Penton Publishing, Cleveland, Ohio, USA, Volume 87, Number 9, September 7, 2015, Page 88, ISSN 0024-9114.
[63] Goldense, Bradford L., "The 6 Types of Manufacturing Processes," Machine Design, Penton Publishing, Cleveland, Ohio, USA, Volume 90, Number 8, August 2018, Page 64, ISSN 0024-9114.
[64] Goldense, Bradford L., "The 6 Types of Manufacturing Processes: The Impact of AM," Machine Design, Penton Publishing, Cleveland, Ohio, USA, Volume 90, Number 9, September 2018, Page 112, ISSN 0024-9114.
[65] Goldense, Bradford L., "Metal AM: Metal Additive Manufacturing Hits Critical Mass," Machine Design, Penton Publishing, Cleveland, Ohio, USA, Volume 90, Number 7, July 2018, Page 72, ISSN 0024-9114.
[66] Goldense, Bradford L., "A Future of Product Design," Machine Design, Penton Publishing, Cleveland, Ohio, USA, Volume 91, Number 5, May 2019, Page 80, ISSN 0024-9114.
[67] "GD Europe," https://www.gd-europe.com/greendot/about-green-dot/.
[68] Sustainoverse: https://sustainoverse.com/biodegradable-food-containers/.
[69] Goldense, Bradford L., "The Importance of Product Design," Machine Design, Penton Publishing, Cleveland, Ohio, USA, Volume 91, Number 2, February 2019, Page 64, ISSN 0024-9114.
[70] Goldense, Bradford L., "The Five Types of Manufacturing Processes," Machine Design, Penton Publishing, Cleveland, Ohio, USA, Volume 87, Number 9, September 7, 2015, Page 88, ISSN 0024-9114.