Introduction to Manufacturing Systems

T. Gutowski

2.810

Mfg Systems

1. Intro + Molly McLaughlin
2. Time & Rate: Stan Gershwin
3. Assembly: Dan Whitney
4. Process Control: Dave Hardt
5. Toyota Production System & Beyond
6. Summary + Michael Farid
7. Quiz 2: Nov 18

Outline

1. Matching manufacturing system to production objectives
2. Relationship between product design and manufacturing system
3. Inventing new manufacturing systems - history of 3 new systems

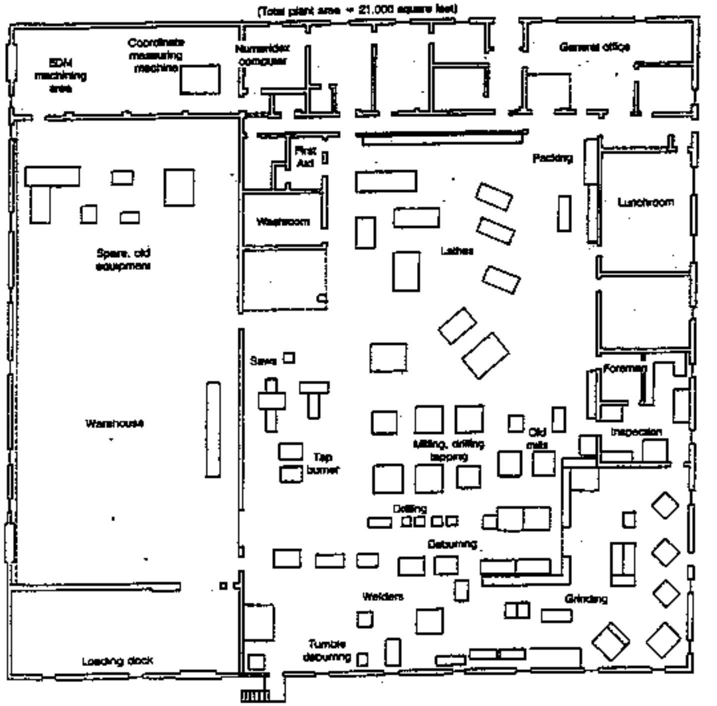
Readings

1. David A. Hounshell, From the American System to Mass Production, 1800-1932, The John Hopkins University Press, 1984. Introduction, Chapters 6 and 7
2. Boothroyd-Dewhurst Design for Assembly (DFA)
3. J T. Black The Factory with a Future Ch 2 & 4
4. James Womack, Daniel T. Jones and Daniel Roos, The Machine that Changed the World, 1990, Ch 3 and 4
5. Michael Maccoby, "Is There a Best Way to Build a Car?" HBR Nov-Dec 1997

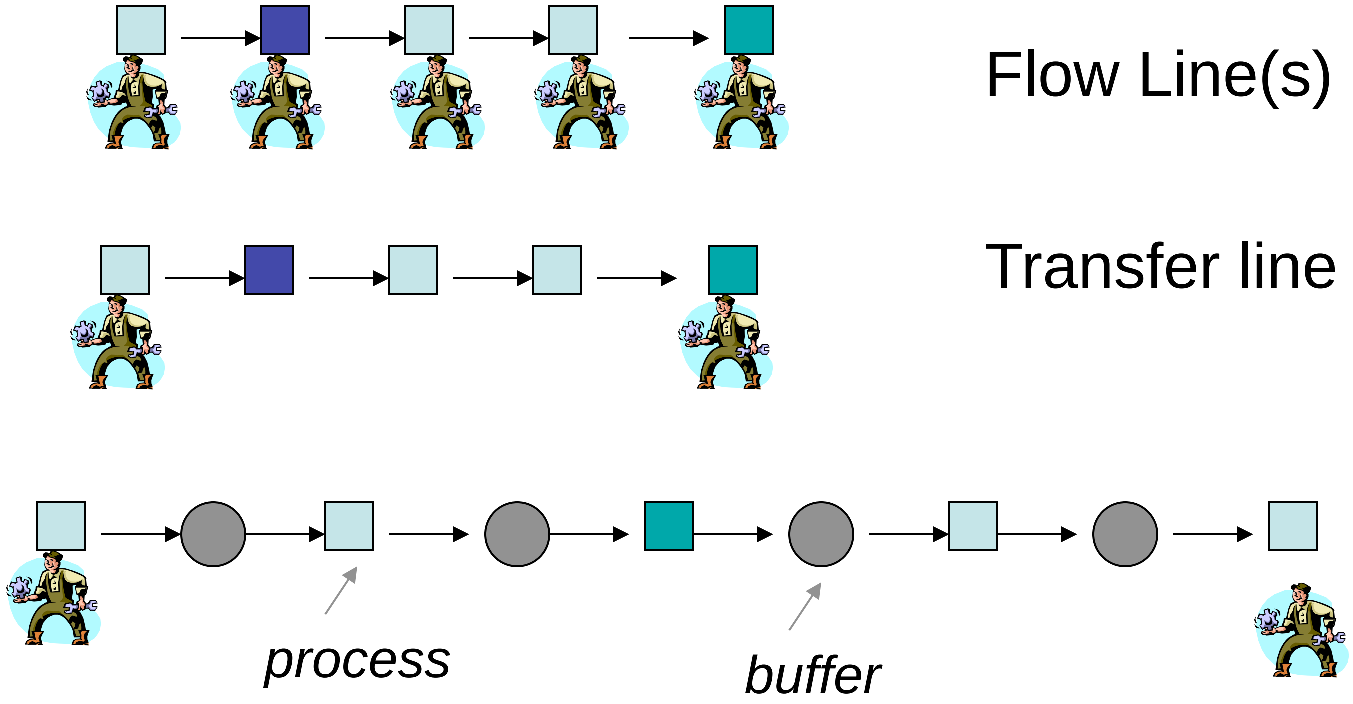
Manufacturing Systems

- job shop - machine arrangement by convenience
- flow line - dedicated resources for product(s)
- transfer line - automated work handling between process stations, “hardwired” flow pattern
- flexible manufacturing system (FMS) - flow pattern programmable
- Toyota Production System - production to demand
- Toyota Cell - One operator, multiple machines

Job shops - flexible, low volume



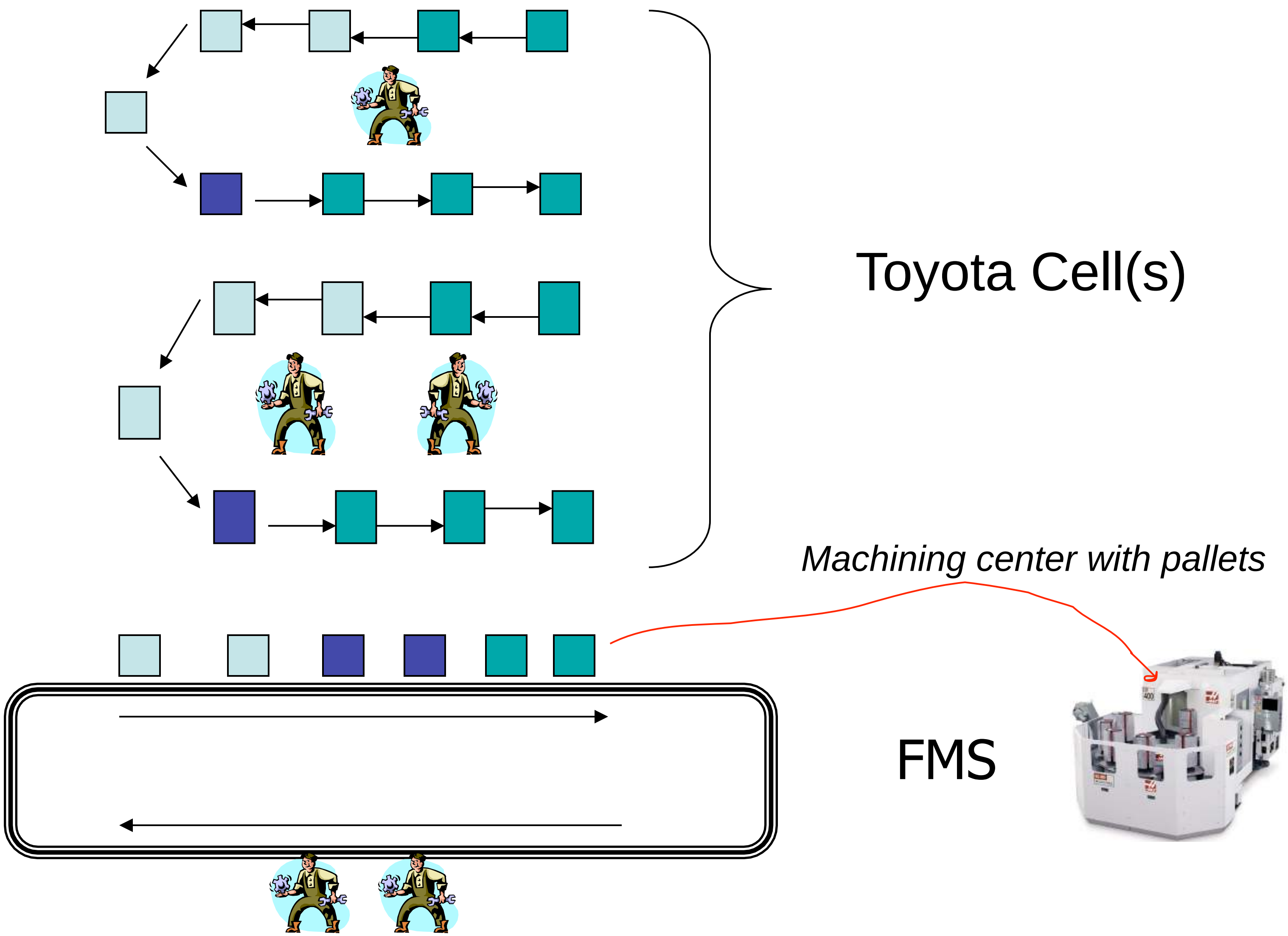
Example Mfg Systems



Flow Line(s)

Transfer line

Example Mfg Systems



Major Issues:

- Volume
- Variety
- Standardization
- Investment in Hardware

Production Volume

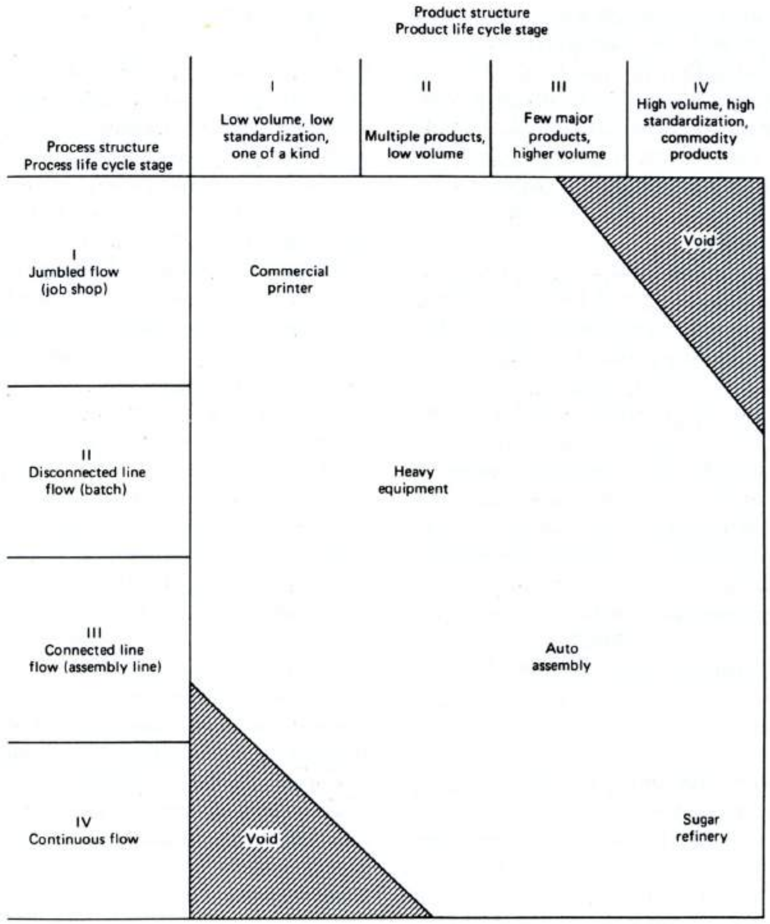


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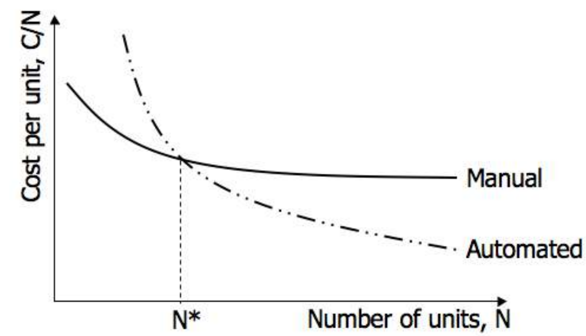
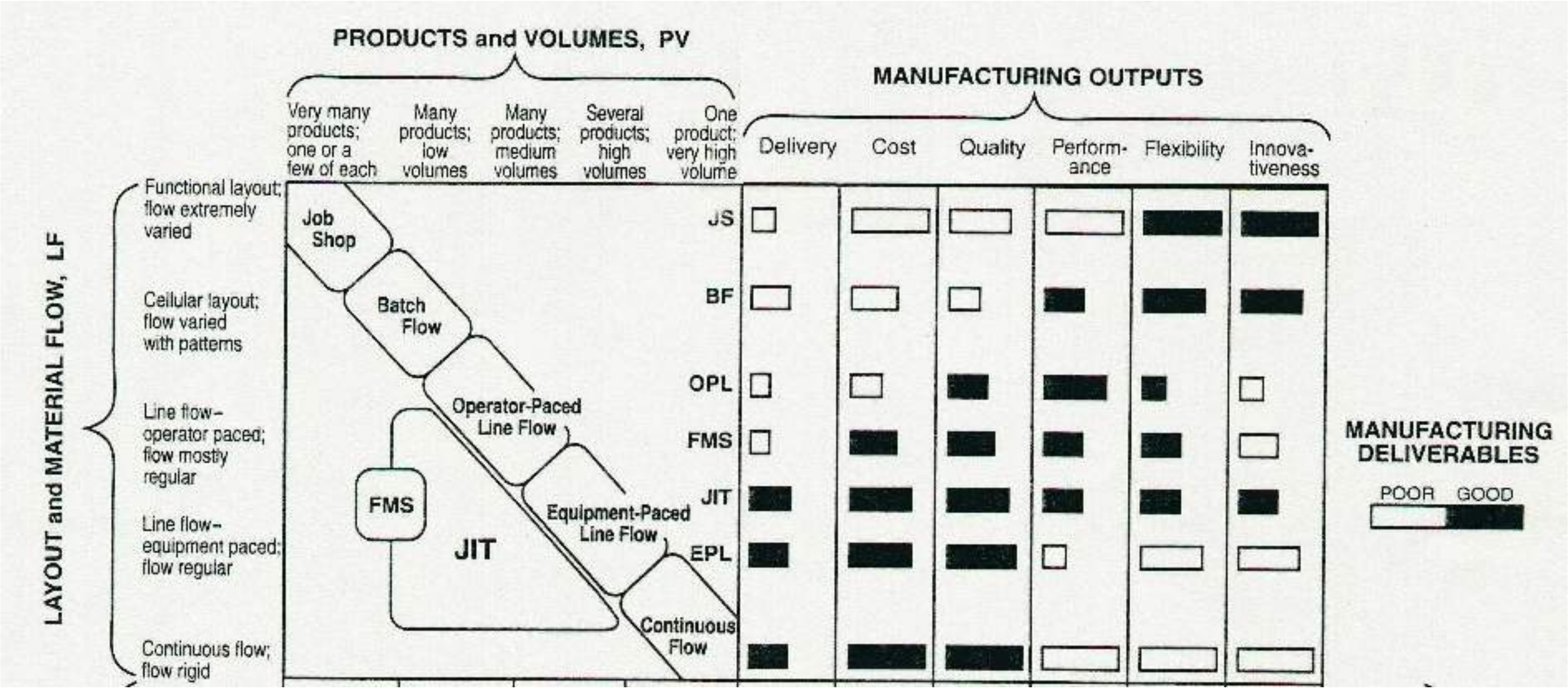
FIGURE 5. Matching Major Stages of Product and Process Life Cycles—The Product-Process Matrix

Number of Part Types



System Performance & Product Requirements



Ref J. Miltenburg Manufacturing Strategy

Machining Systems♪

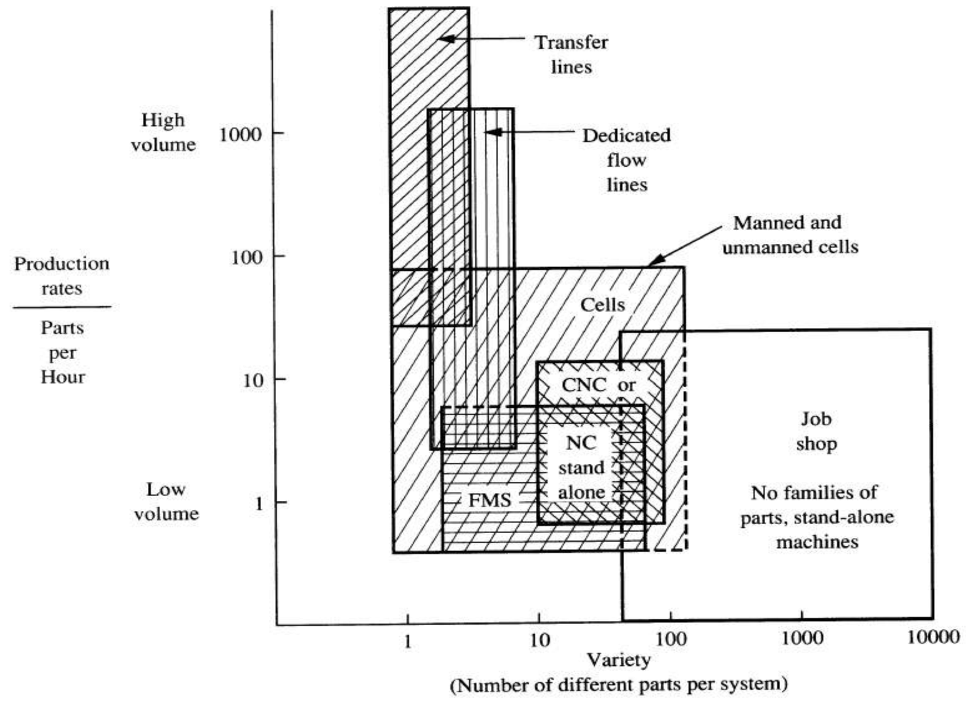


FIGURE 2-15
A comparison of different kinds of manufacturing systems with cells.

Read J T. Black Ch 2 and 4

Comparison with Other Systems

Ref: J T. Black

46 THE DESIGN OF THE FACTORY WITH A FUTURE

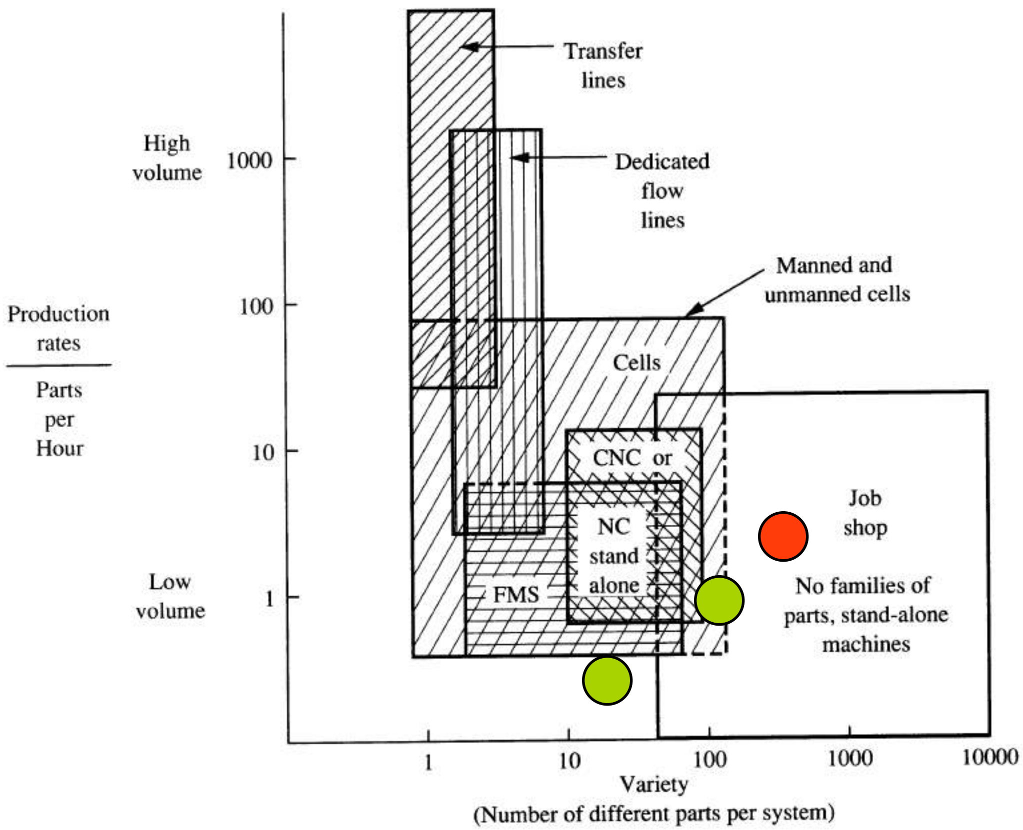


FIGURE 2-15
A comparison of different kinds of manufacturing systems with cells.

Company H

Other systems studied that use "Maxim Cells"

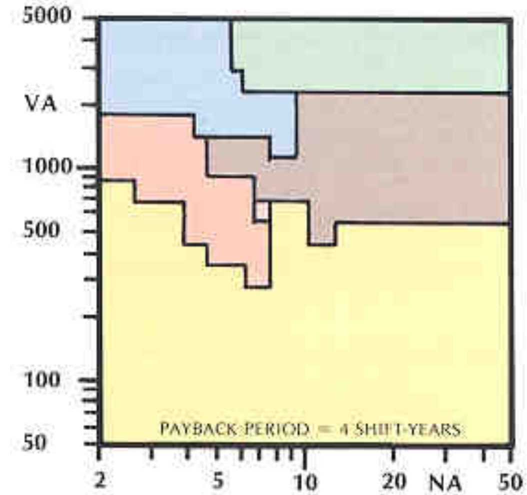
Economic Assessment Chart
Assembly Systems-Boothroyd/Dewhurst

Product with only one style
(NT/NA = 1)

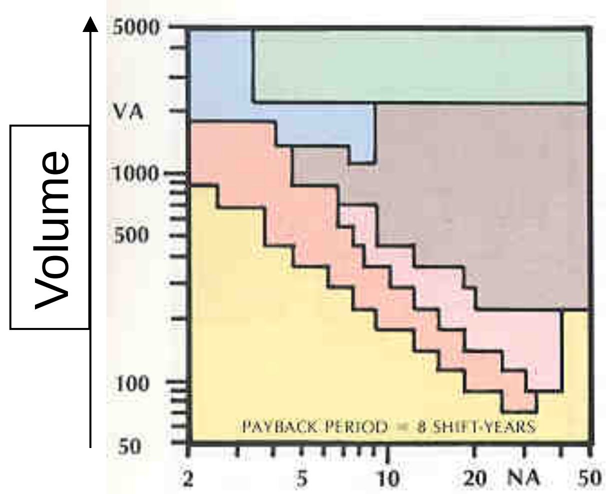
VA = annual production volume measured in thousands

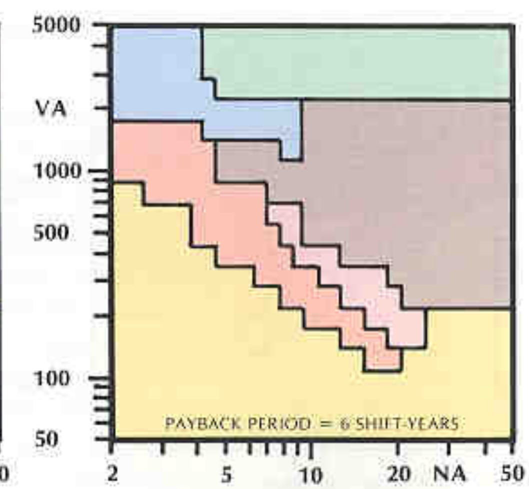
NA = number of parts in the assembly

NT = total number of parts from which various product styles can be assembled



- Special-purpose indexing
- Sp.-purt. Free-transfer
- Single-st. one robot arm
- Single-st. two robot arms
- Multi-station with robots
- Manual bench assembly





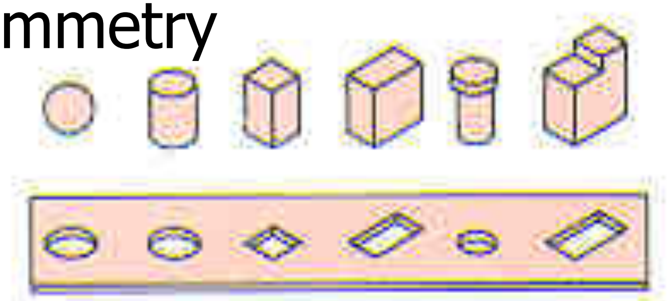
Time Estimation for Assembly

- Handling
  - pick up
  - orient
- Insertion
  - location (obstructed view? Self locating?)
  - hold down and resistance
  - securing method

DFA: see separate hand outs

Handling Issues

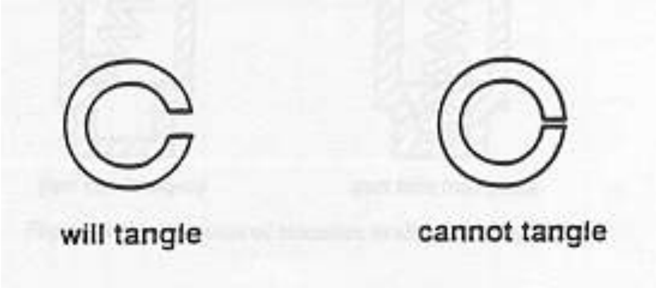
Symmetry



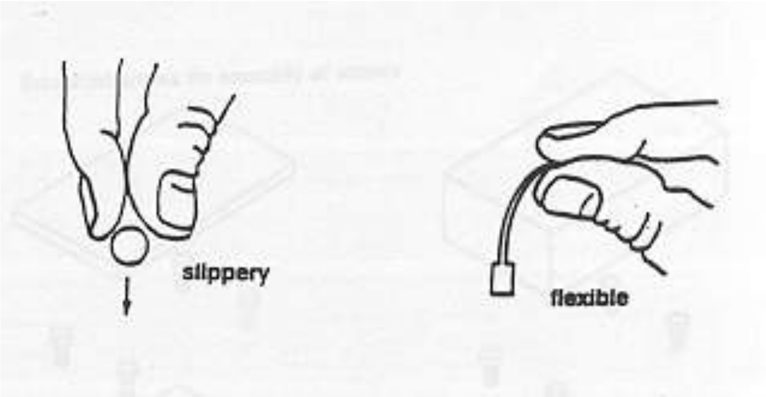
α	0	180	180	90	360	360
β	0	0	90	180	0	360

Size

Fragile/Sharp



Nest/Tangle



Slippery/Flexible

Ref Boothroyd, Dewhurst

B-D Manual handling chart

Handling difficulties: nest, tangle slippery, sharp…

MANUAL HANDLING—ESTIMATED TIMES (seconds)

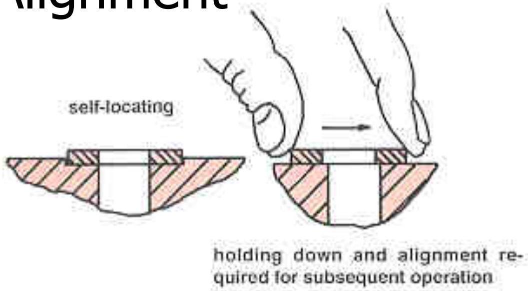
Key: ONE HAND

			parts are easy to grasp and manipulate					parts present handling difficulties (1)				
			thickness > 2 mm			thickness ≤ 2 mm		thickness > 2 mm			thickness ≤ 2 mm	
			size >15 mm	6 mm ≤ size ≤15 mm	size <6 mm	size >6 mm	size ≤6 mm	size >15 mm	6 mm ≤ size ≤15 mm	size <6 mm	size >6 mm	size ≤6 mm
			0	1	2	3	4	5	6	7	8	9
parts can be grasped and manipulated by one hand without the aid of grasping tools	$(\alpha+\beta) < 360°$	0	1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98
	$360° \leq (\alpha+\beta) < 540°$	1	1.5	1.8	2.25	2.06	2.55	2.25	2.57	3.06	3	3.38
	$540° \leq (\alpha+\beta) < 720°$	2	1.8	2.1	2.55	2.36	2.85	2.57	2.9	3.38	3.18	3.7
	$(\alpha+\beta) = 720°$	3	1.95	2.25	2.7	2.51	3	2.73	3.06	3.55	3.34	4

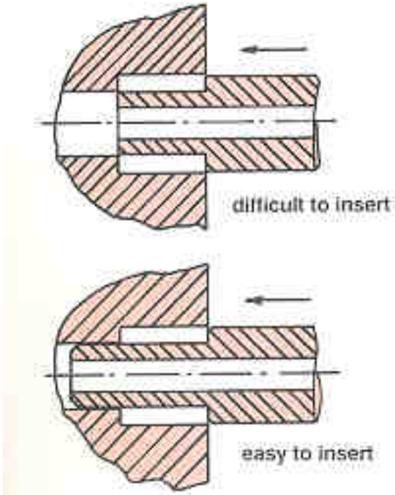
Ref Boothroyd, Dewhurst

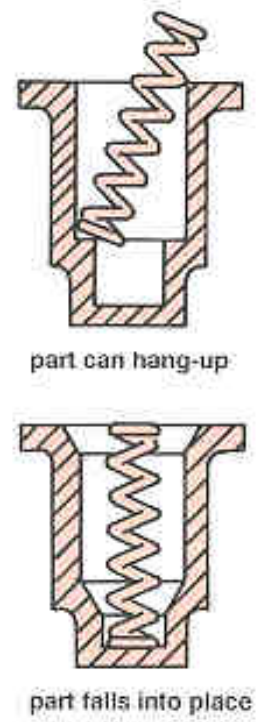
Insertion Issues

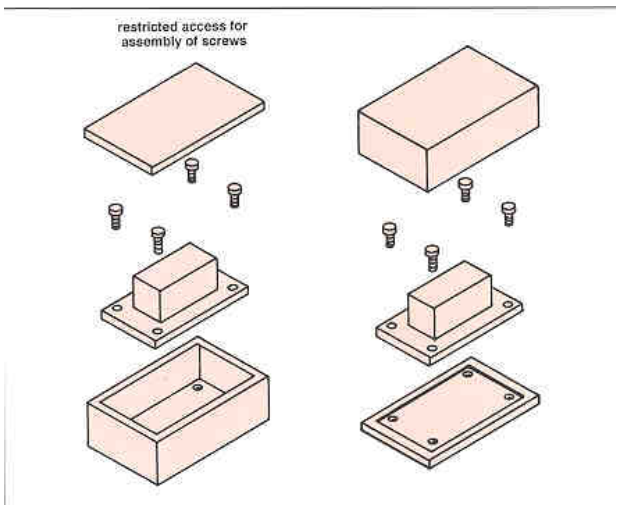
Alignment

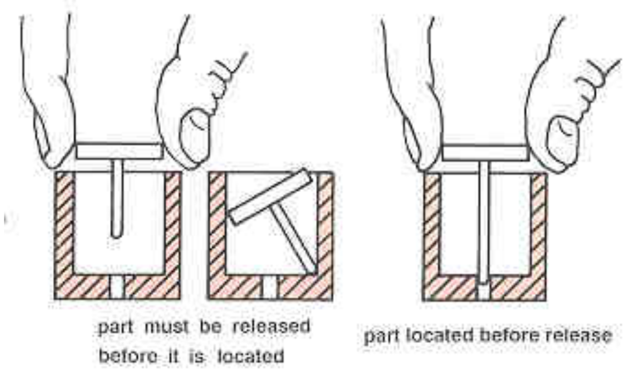


Insertion Force









Obstructed Access/View

Ref Boothroyd, Dewhurst

MANUAL INSERTION — ESTIMATED TIMES (seconds)

Key:

PART ADDED but NOT SECURED

			after assembly no holding down required to maintain orientation and location (3)				holding down required during subsequent processes to maintain orientation or location (3)			
			easy to align and position during assembly (4)		not easy to align or position during assembly		easy to align and position during assembly (4)		not easy to align or position during assembly	
			no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)
			0	1	2	3	6	7	8	9
addition of any part (1) where neither the part itself nor any other part is finally secured immediately	part and associated tool (including hands) can easily reach the desired location	0	1.5	2.5	2.5	3.5	5.5	6.5	6.5	7.5
	part and associated tool (including hands) cannot easily reach the desired location: due to obstructed access or restricted vision (2)	1	4	5	5	6	8	9	9	10
	part and associated tool (including hands) cannot easily reach the desired location: due to obstructed access and restricted vision (2)	2	5.5	6.5	6.5	7.5	9.5	10.5	10.5	11.5

PART SECURED IMMEDIATELY

			no screwing operation or plastic deformation immediately after insertion (snap/press fits, circlips, spire nuts, etc.)		plastic deformation immediately after insertion						screw tightening immediately after insertion (6)	
					plastic bending or torsion			rivetting or similar operation				
						not easy to align or position during assembly			not easy to align or position during assembly			
			easy to align and position with no resistance to insertion (4)	not easy to align or position during assembly and/or resistance to insertion (5)	easy to align and position during assembly (4)	no resistance to insertion	resistance to insertion (5)	easy to align and position during assembly (4)	no resistance to insertion	resistance to insertion (5)	easy to align and position with no torsional resistance (4)	not easy to align or position and/or torsional resistance (5)
			0	1	2	3	4	5	6	7	8	9
addition of any part (1) where the part itself and/or other parts are being finally secured immediately	part and associated tool (including hands) can easily reach the desired location and the tool can be operated easily	3	2	5	4	5	6	7	8	9	6	8
	part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily: due to obstructed access or restricted vision (2)	4	4.5	7.5	6.5	7.5	8.5	9.5	10.5	11.5	8.5	10.5
	part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily: due to obstructed access and restricted vision (2)	5	6	9	8	9	10	11	12	13	10	12

screws

Obstructed view

B-D Manual insertion chart

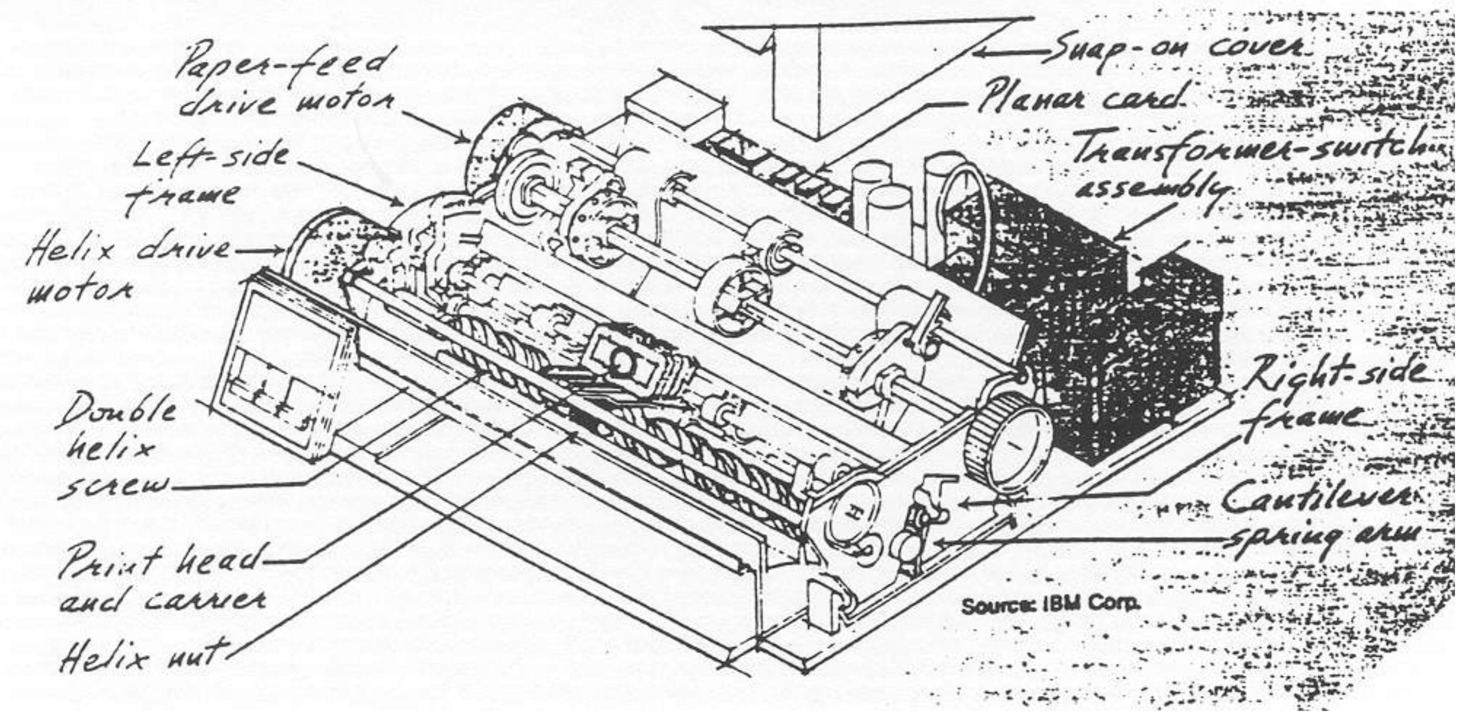
Ref Boothroyd, Dewhurst

Rules to reduce part count

- During operation of the product, does the part move relative to all other parts already assembled?
  - Only gross motion should be considered – small motions that can be accommodated by elastic hinges, for example, are not sufficient for a positive answer
- Must the part be of a different material than or be isolated from all other parts already assembled?
  - Only fundamental reasons concerned with material properties are acceptable
- Must the part be separate from all other parts already assembled because otherwise necessary assembly or disassembly of other separate parts would be impossible?

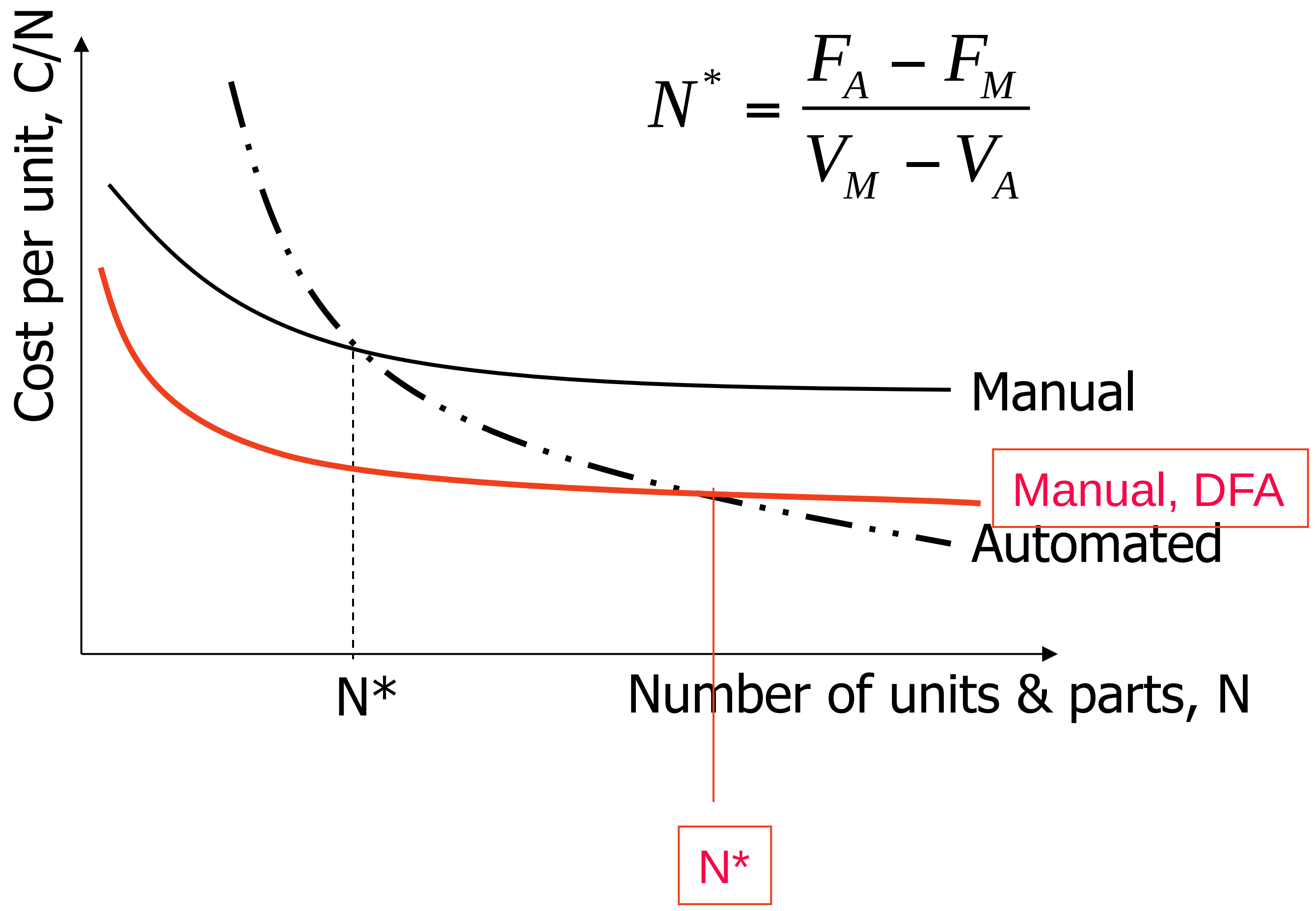
Ref Boothroyd, Dewhurst

IBM Proprinter



Competition from Japan - answered with robots and DFA

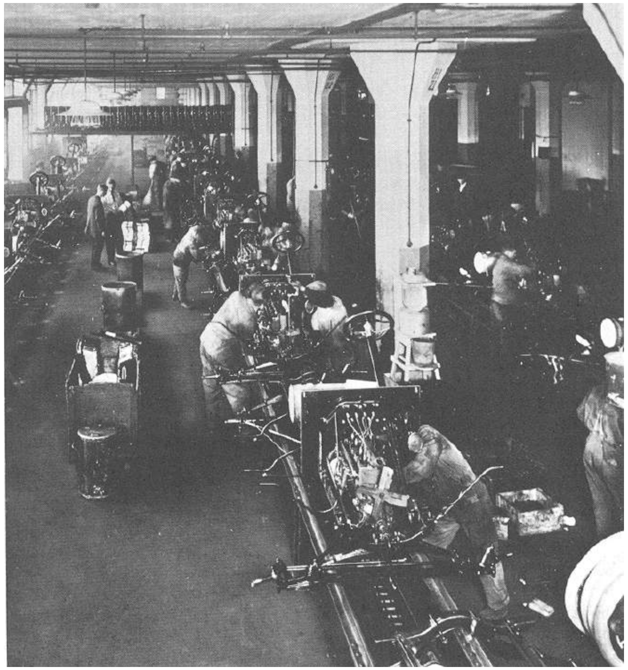
Economic Analysis, C = F + V·N♪



What conditions lead to a revolutionary new mfg system?

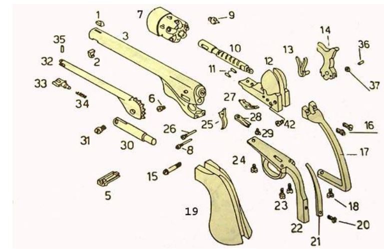
1. A Need
2. Financing
3. Workforce
4. Enabling technology

A Historical Review

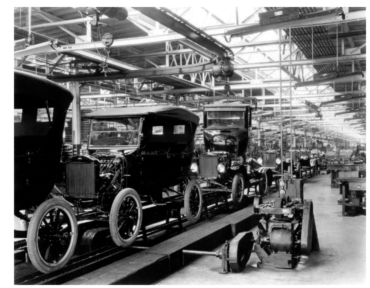


Ford's Moving Assembly Line

Inventing New Mfg Systems



- Interchangeable Parts
  - US Armories



- Mechanization of Production
  - Moving Assembly Line
  - Transfer Lines

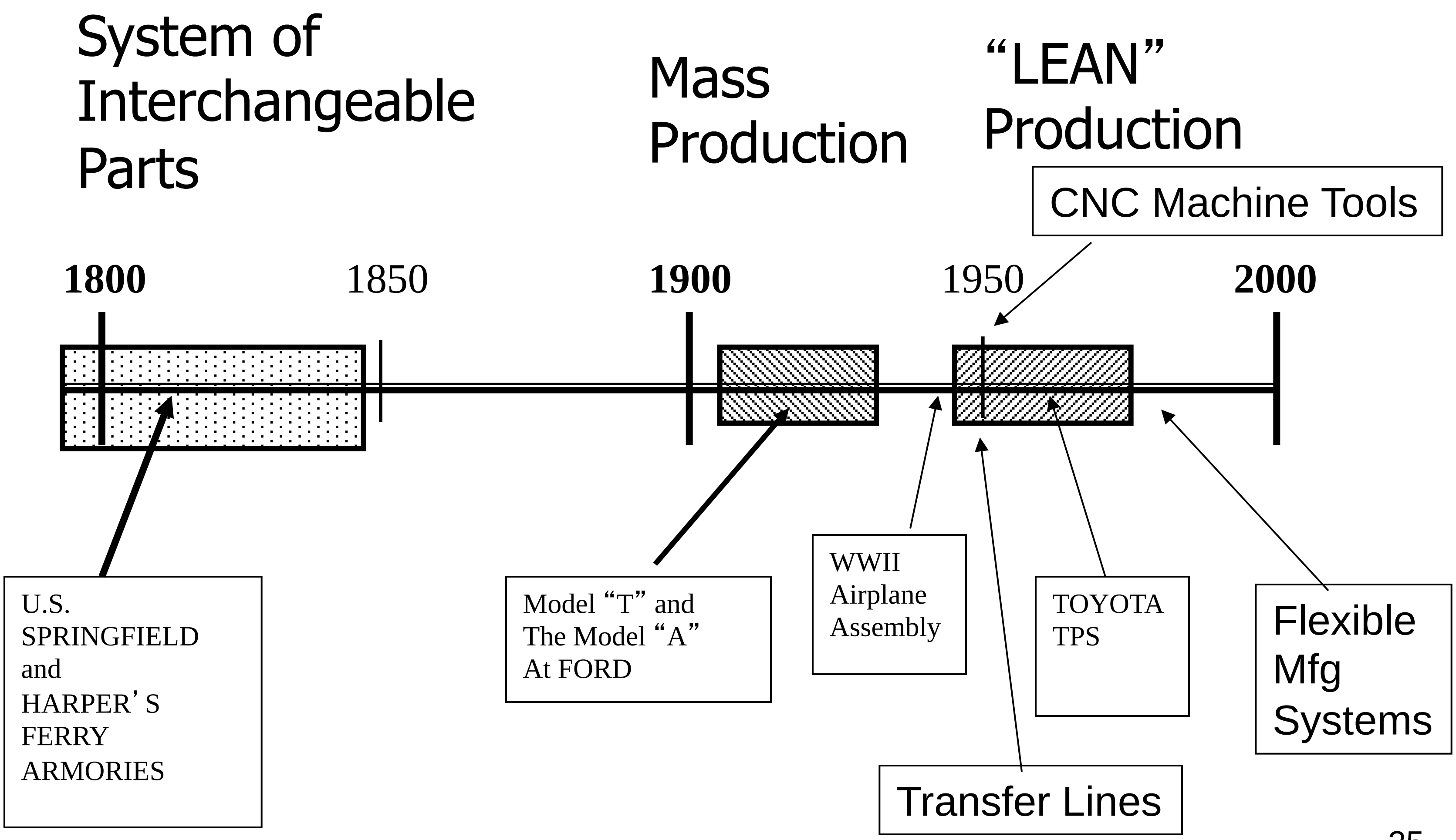
- Mechanical to Digital Control
  - CNC Machines
  - Flexible Mfg Systems (FMS)

- Production to Demand
  - Toyota Production System (TPS)

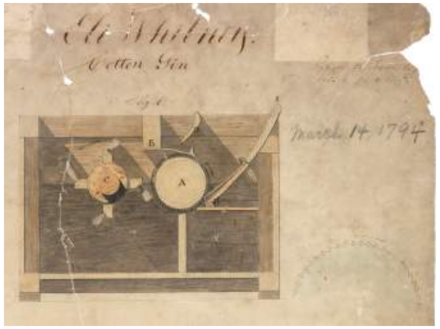
Reoccurring Issues

- Cost Effectiveness
- Social disruption
- Standardization Vs Flexibility
- Benefits and Costs of Inventory
- Work Scheduling/Control: centralized Vs Distributed

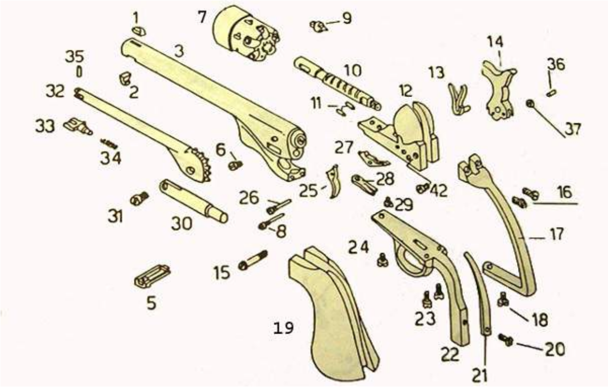
Historical Development of Major Manufacturing Systems from ~1800 to 2000



Who developed interchangeable parts?

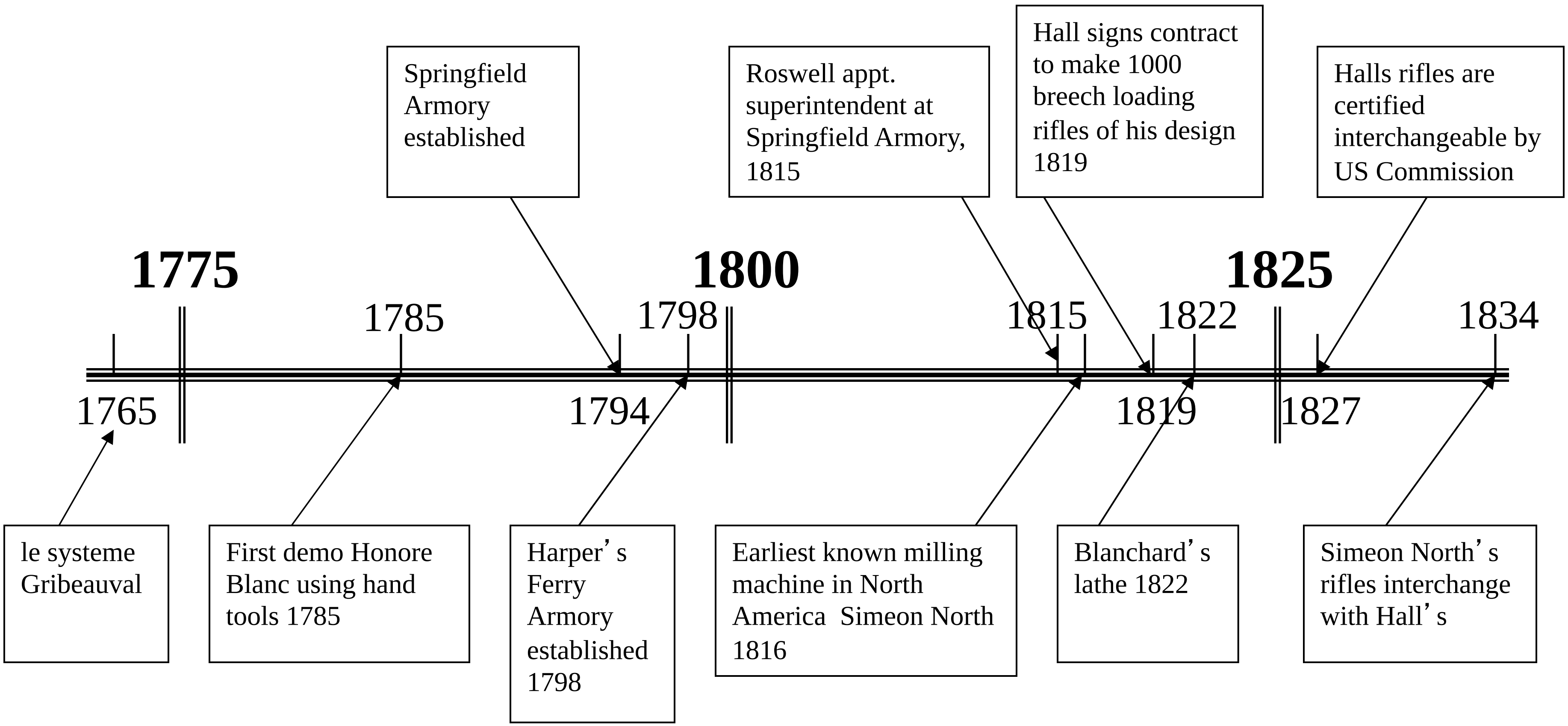


1. Eli Whitney?
2. Jean-Baptiste de Gribeauval?
3. Samual Colt ?
4. John H. Hall ?



Readings:David A. Hounshell, From the American System to Mass Production, 1800-1932, The John Hopkins University Press, 1984. Introduction, Chapters 6 and 7

Historical Developments for System of Interchangeable Parts



Development of the System of Interchangeable Parts at the U.S. Armories

Harper's Ferry Armory♪

Refs:

1. Merritt Roe Smith, Harper's Ferry Armory and the New Technology, Cornell University Press, 1977.
2. David A. Hounshell, From the American System to Mass Production, 1800-1932, The John Hopkins University Press, 1984.

Development of the System of Interchangeable Parts at the U.S. Armories

Refs:
1. Merritt Roe Smith, Harper's Ferry Armory and the New Technology, Cornell University Press, 1977.
2. David A. Hounshell, From the American System to Mass Production, 1800-1932, The John Hopkins University Press, 1984.

Springfield MA & Harper's Ferry VA US Armories

- Roswell Lee
- Scarcity of trained gunsmiths
- Very good transportation
- Puritan ethics
- Good schools
- Rapid adoption of new technology

- James Stubblefield
- Who's who of gunsmiths
- Paternalistic society
- Poor transportation
- Poor public schools
- Poor adoption of new technology

Ref Merritt Roe Smith

U.S. Model 1816 Musket produced at the Springfield and Harper's Ferry Armories by craft method

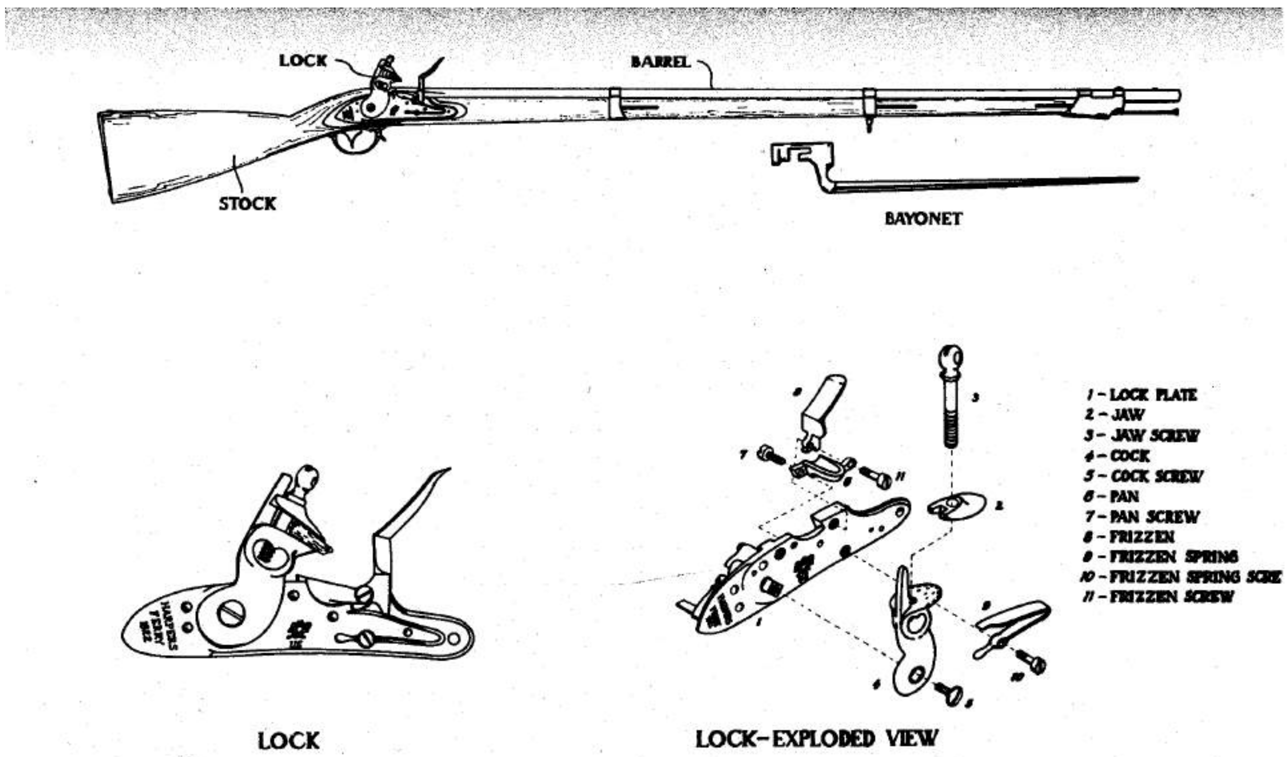
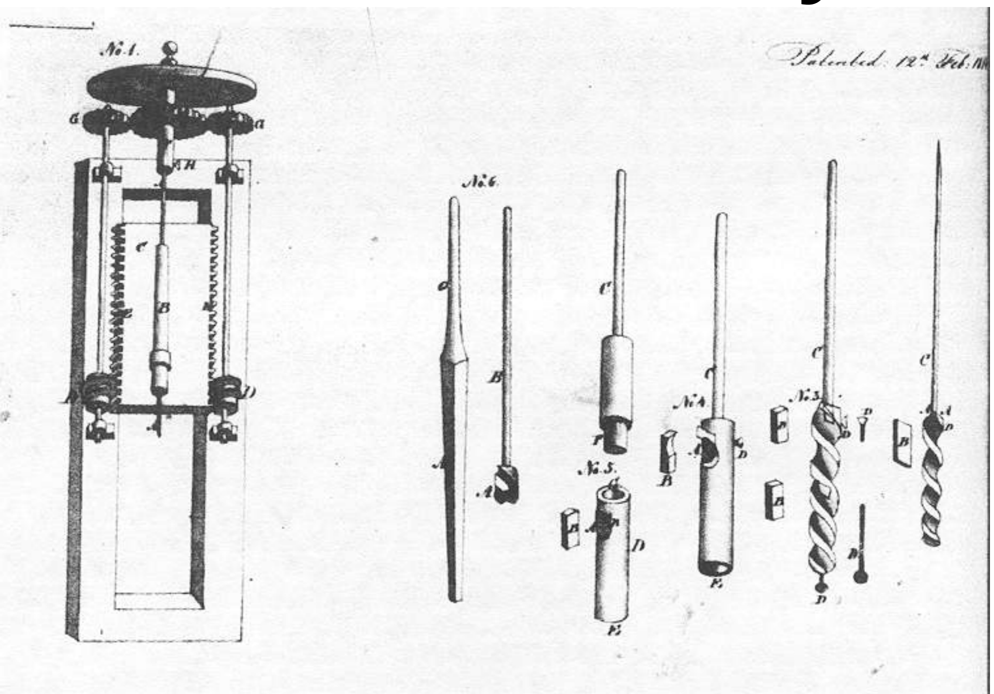


Figure 2. U.S. Model 1816 musket. For views of the tumbler, bridle, sear, and other interior parts of the lock mechanism, see Figure 14 Drawing by Steve Foutz. Photograph by Christopher Duckworth.

By employing the "European system" of division of labor
The armories could produce ~10,000 muskets/yr w/ ~250 workers

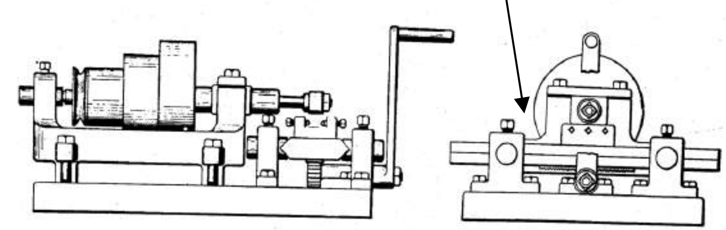
Technology development in early America



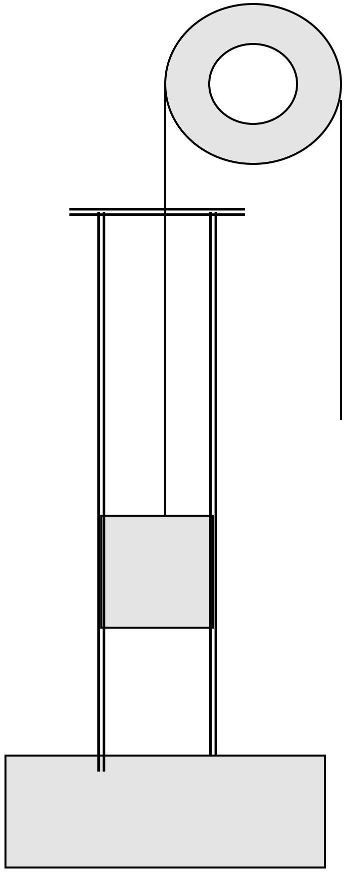
Machine for boring gun
Barrels with various
Augers from 1814 U.S. patent
application

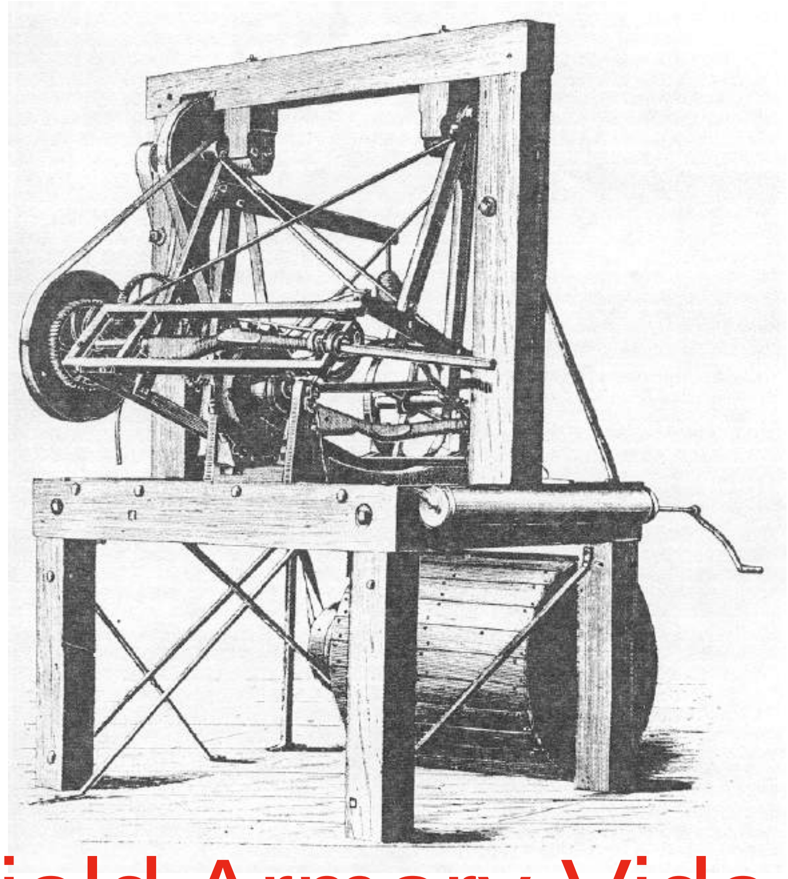
“Earliest known milling
Machine in America”
circa 1816 by Simeon North

Ref Smith



Rendering of early drop press used at Philadelphia lamp Factory in 1833 and Thomas Blanchard's eccentric lathe for turning gun stocks circa 1819





Springfield Armory Video

Blanchard's reply to Roswell Lee's letter of Jan 1819 requesting a demonstration of his new process at the National Armory

"Yours of the 21 ultame. come safe to hand – you wished me to wright you respecting macenory – I conclude you meen a machine I have recently invented for turning gun stocks and cuting in the locks and mounting. Doubtless you have heard concerning it But I would inform you that I have got a moddle built for turning stocks and cuting in the locks and mounting. I can cut a lock in by water in one minute and a half, as smooth as can be done by hand. The turning stocks is very simple in its operation and will completely imatate a stock made in proper shape. I shal bring the moddle to Springfield in the course of three weeks – I shal want your opinion of its utility." (ref. Merritt Roe Smith p 128)

John Hall's Breech loading rifle, produced at Harper's Ferry from 1823 to 1841

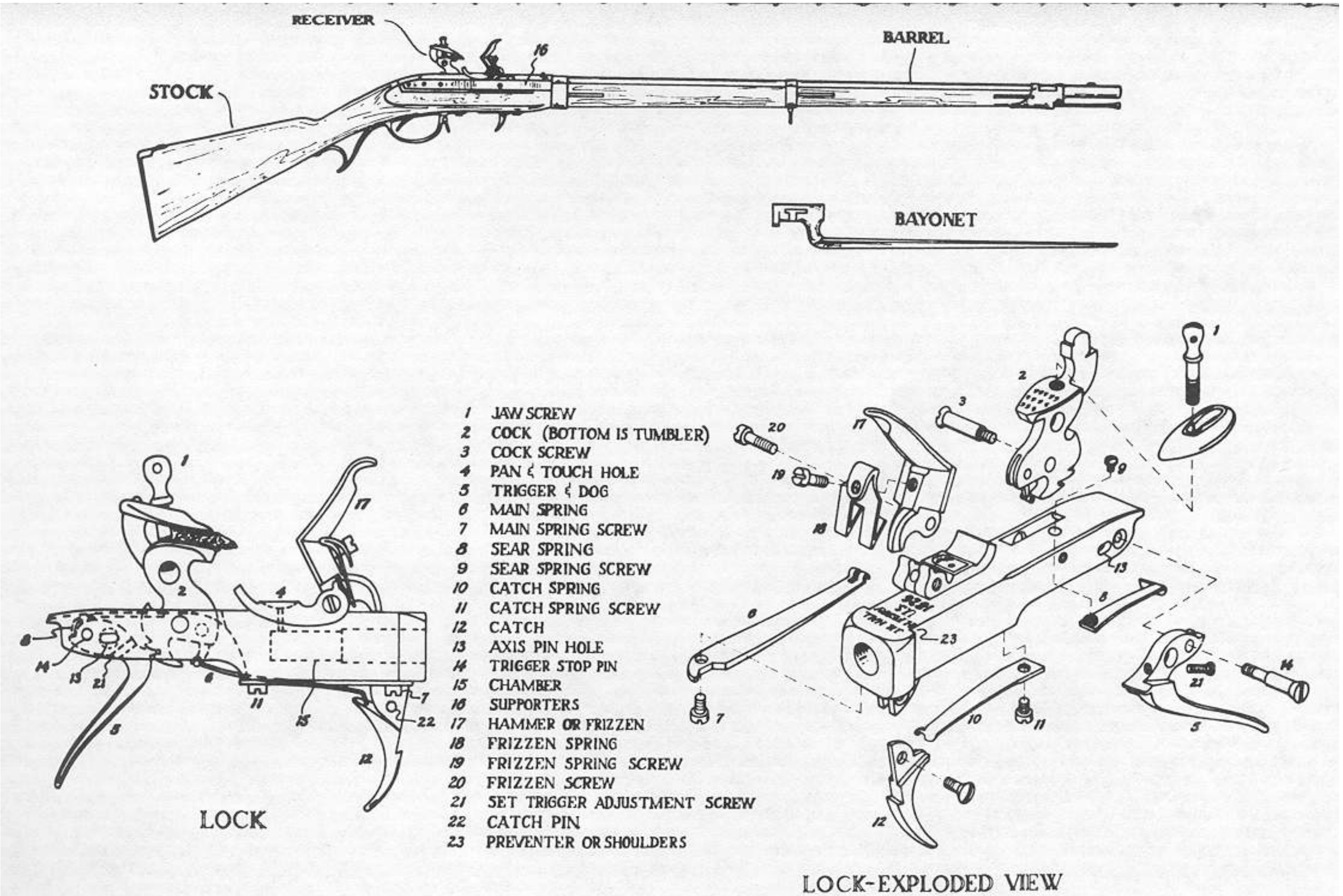


Figure 10. U.S. Model 1819 Hall rifle, the staple product of the Rifle Works at Harpers Ferry from 1823 to 1841. Drawing by Steve Foutz. Photograph by Christopher Duckworth.

Invented in 1811, certified interchangeable in 1827 by military commission

John Hall’s Breech loading rifle, produced at Harper’s Ferry from 1823 to 1841

Invented in 1811, certified interchangeable in 1827 by military commission

Fixturing of Parts – as described by John H. Hall to the Secretary of War in 1840

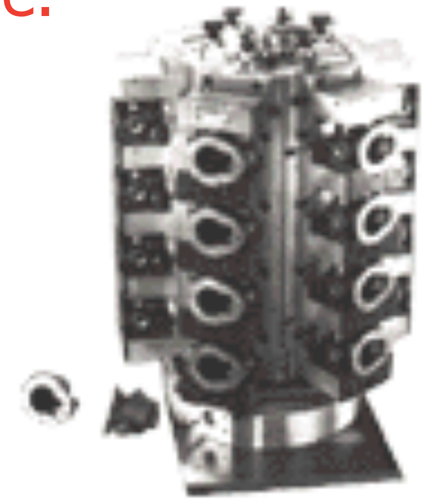
"In making a part of an arm like a prescribed model, the difficulty is exactly the same, as that which occurs in making a piece of Iron exactly square. In such a case, a man would Square the 2d. side by the 1st, the 3d. by the 2d. and the 4th by the 3d., but on comparing the 4th side with the 1st, it will be found that they are not square; the cause is that in squaring each side by the preceding side, there is a slight but imperceptible variation and the comparison of the 4th with the 1st gives the sum of the variations of each side from a true square. And so in manufacturing a limb of a gun so as to conform to a model, by shifting the points, as convenience requires, from which the work is gauged & executed, the slight variations are added to each other in the progress of the work, so as to prevent uniformity. The course which I have adopted to avoid this difficulty, was to perform & gauge every operation on a limb, from one point called *a bearing* so that the variation in any operation could only be the single one from that point".

Ref. Merritt Roe Smith "Harper's Ferry Armory and the New Technology", U. Cornell Press, 1977, p. 227.

Fixturing Principles from John Hall;

Principle: Fixture Part from a single reference or “bearing”

Corollary: Once fixtured, perform as many operations as possible.



Locating feature for machining of forged crankshaft

Interchangeable Parts at U.S. Armories circa 1800-1860

Key points:

1. Military need and financing
2. Enabled by machine tool industry developments in the U.S.
3. Division of labor and piece rate accounting
4. Transition from “master” model of part to engineering drawing of part disrupts social structure in shop.
5. Maintenance of tolerance requires gauging and gauge blocks, this also disrupts social structure.
6. Cultural and leadership differences at Springfield and Harper’s Ferry Armories greatly affect rate of new technology adoption.
7. John Hall designs and builds breech loading rifle - first demonstration of interchangeable parts.
8. Cost effectiveness of new system in doubt for decades, slow and painful transistion to commercial products e.g. sewing machines, harvesting machines and bicycles

The Ford Motor Co. and Mass Production

Finally after the Models A, B, C, F, K, N, R, and S came the Model "T" in 1908. Here are Henry and Edsel Ford in the last Model T produced in 1927.

Refs:
David A. Hounshell, From the American System to Mass Production, 1800-1932, The John Hopkin's University, Press, 1984.
Karl Williams, Colin Haslam and John Williams, "Ford versus "Fordism, The Beginning of Mass Production?" appeared in Work, Employment and Society, December 1992.

Ford

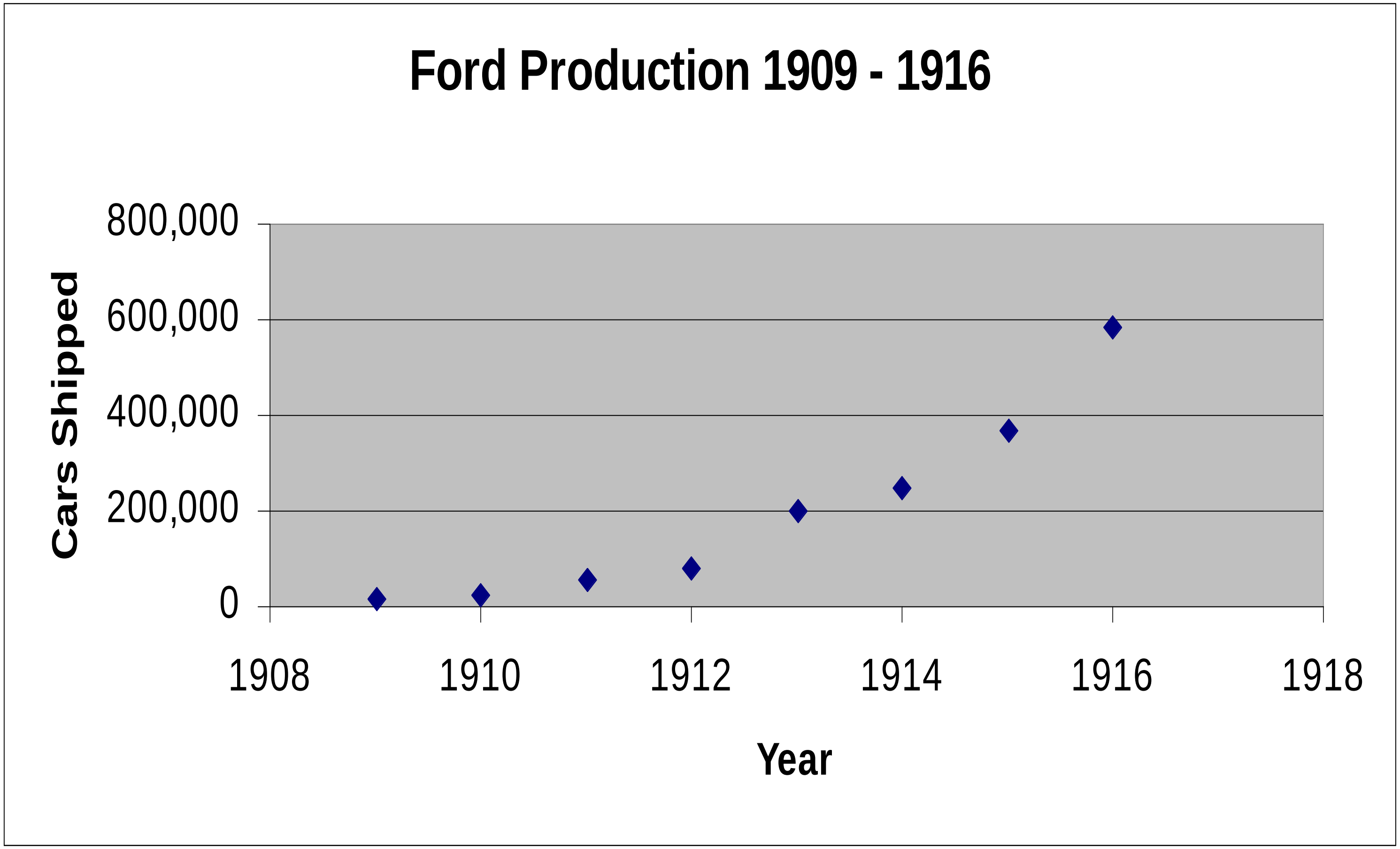
Model T from 1908 to 1927, more than 15 million produced.
177 cu in (2.9L)
20hp, 13-21 mpg

Model A from 1927 to 1931, almost 5 million produced.
201 cu in (3.3L)
40 hp
25-30 mpg

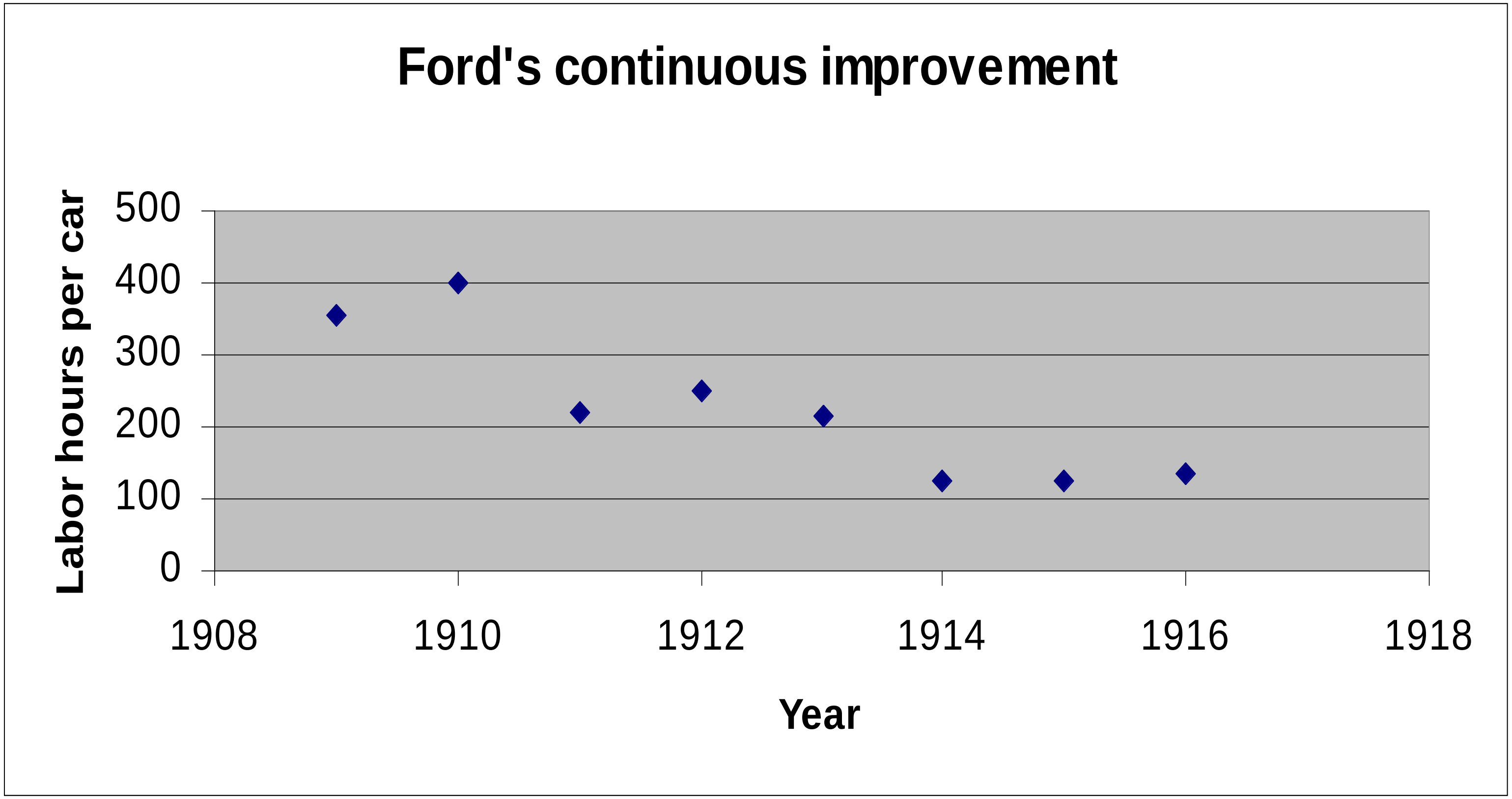
1927 Chevrolet
Best selling car in US for that year

Roomy interior!
Not black!
Also inline 4
171 cu in (2.8L)
20 hp

Ford’s early production was increasing as fast as he could build cars



Ford’s response………

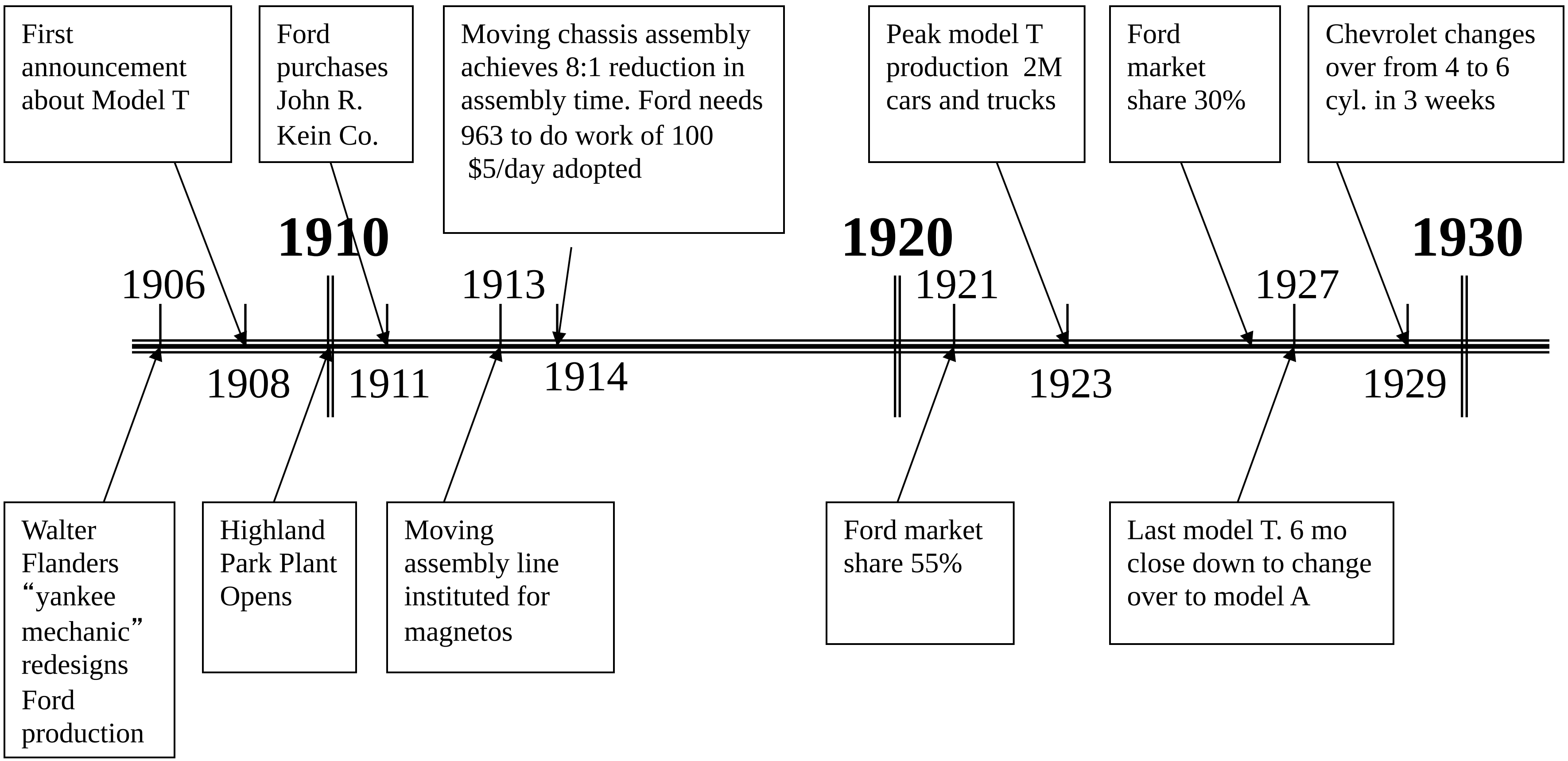


Ford's continuous improvement 1909-1916

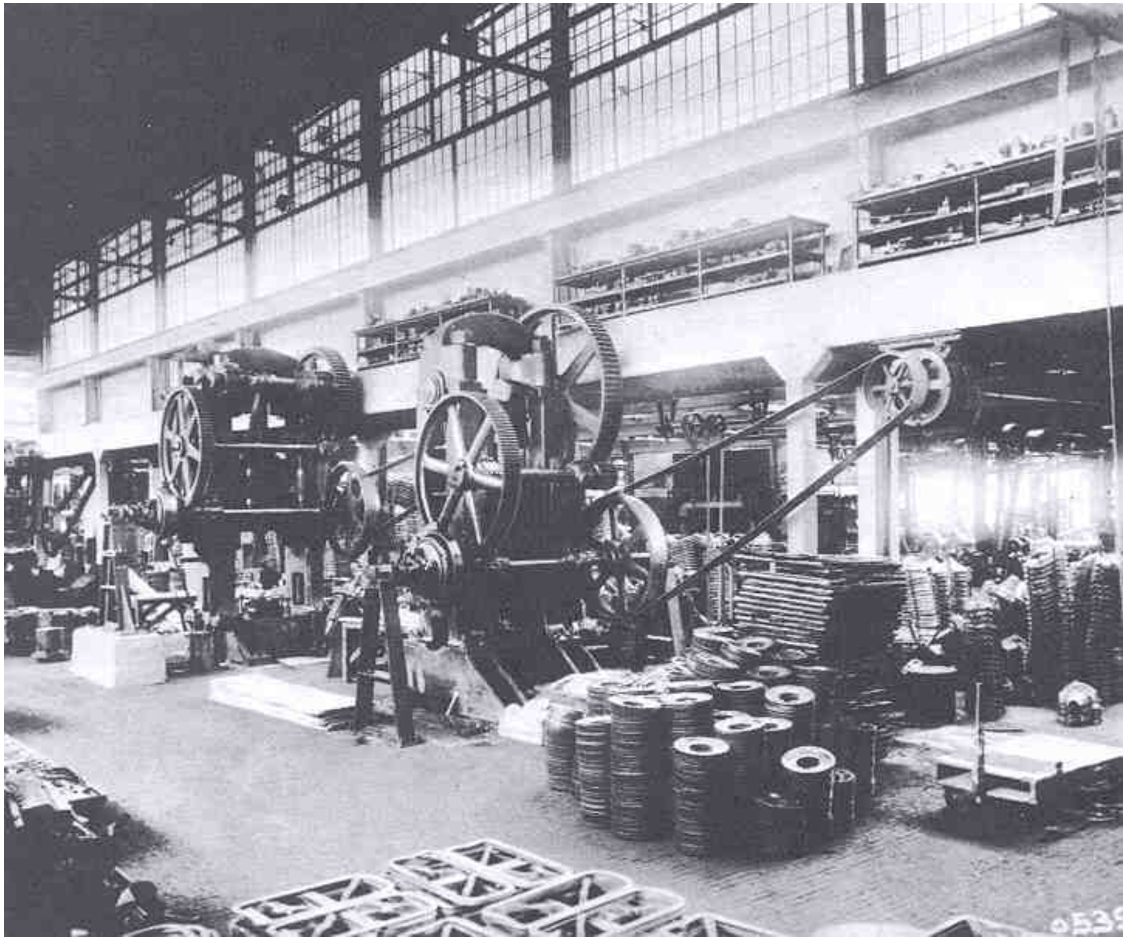
	Cars Shipped (i)	**Number of employees (ii)**	**Cars per man year (iii)**	**Labor hours per car (iv)**
1909	13,941	1,655	8.4	357
1910	20,738	2,773	7.5	400
1911	53,800	3,976	13.5	222
1912	82,500	6,867	12.0	250
1913	199,100	14,366	13.9	216
1914	249,700	12,880	18.8	127
1915	368,599	18,892	19.5	123
1916	585,400	32,702	17.9	134

70% reduction

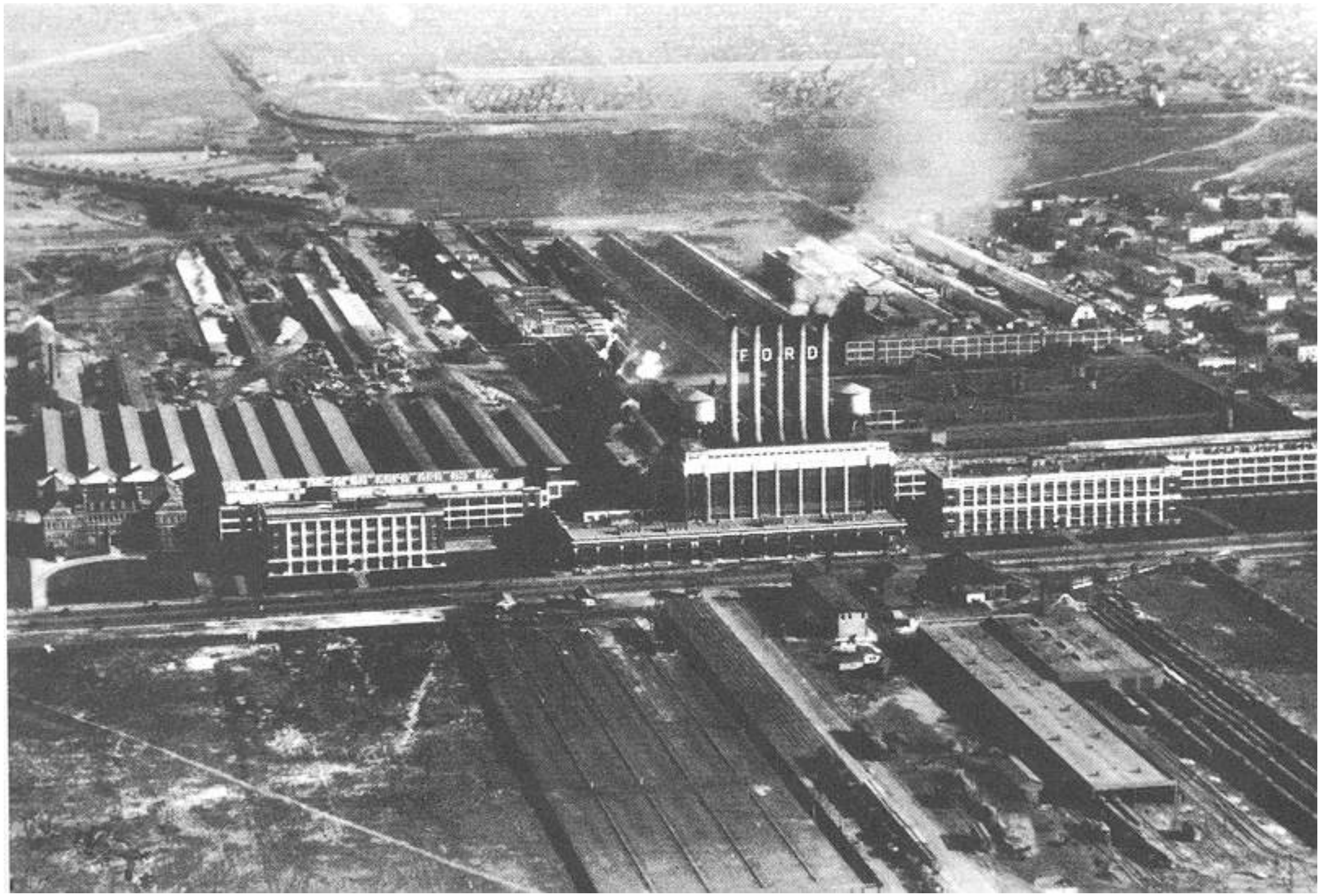
Historical Development of Mass Production at Ford.



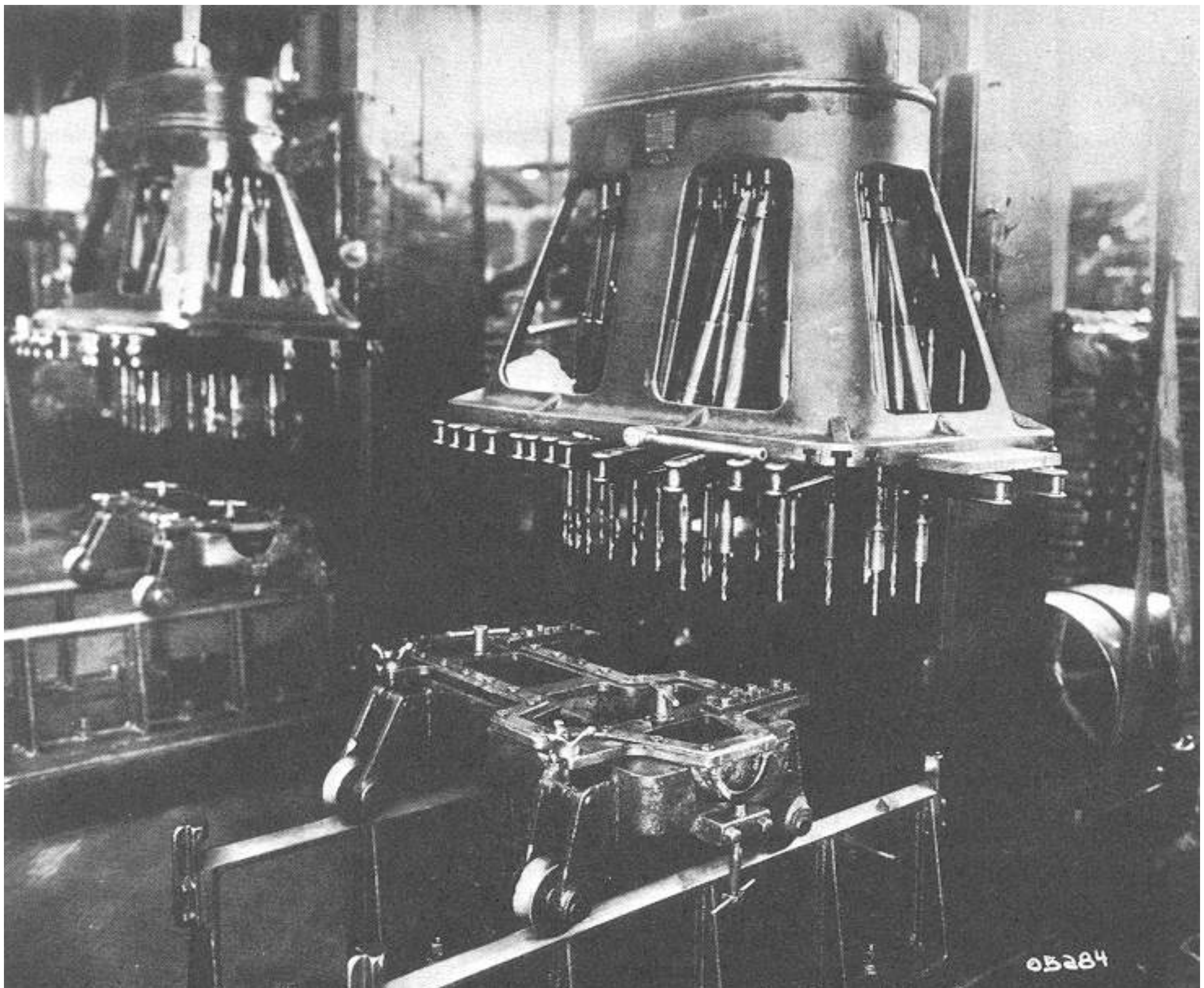
"Punch Press operations, Highland Park plant 1913 Much of Ford's punch press machinery came from John R. Keim Company from Buffalo, which Ford purchased in 1911 and moved to Detroit." Ref. Hounshell



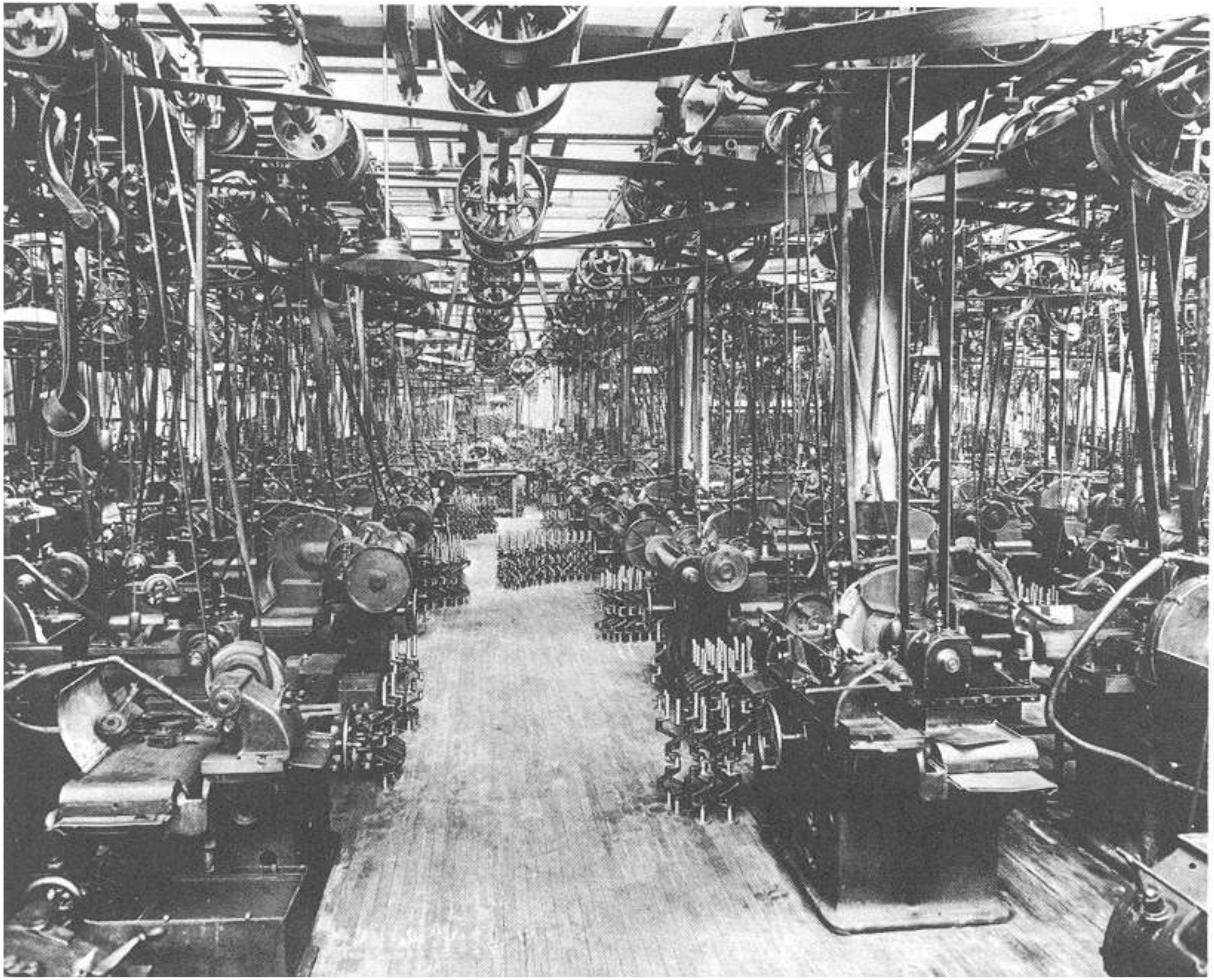
Ford's Highland Park Plant where the moving assembly line was first developed for automobiles in 1913



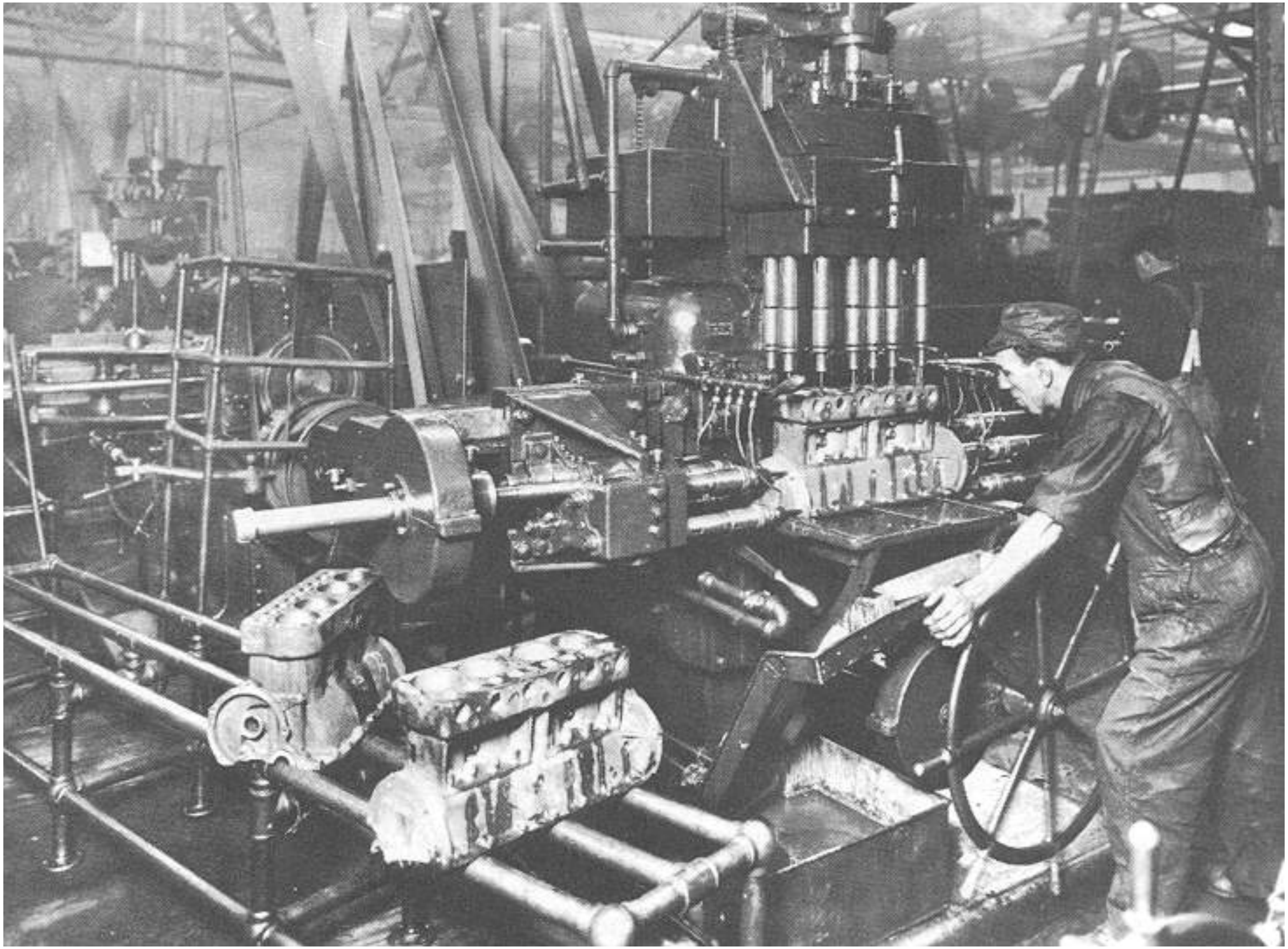
Multiple spindle drilling of the crankcase, notice the quick-change fixturing.



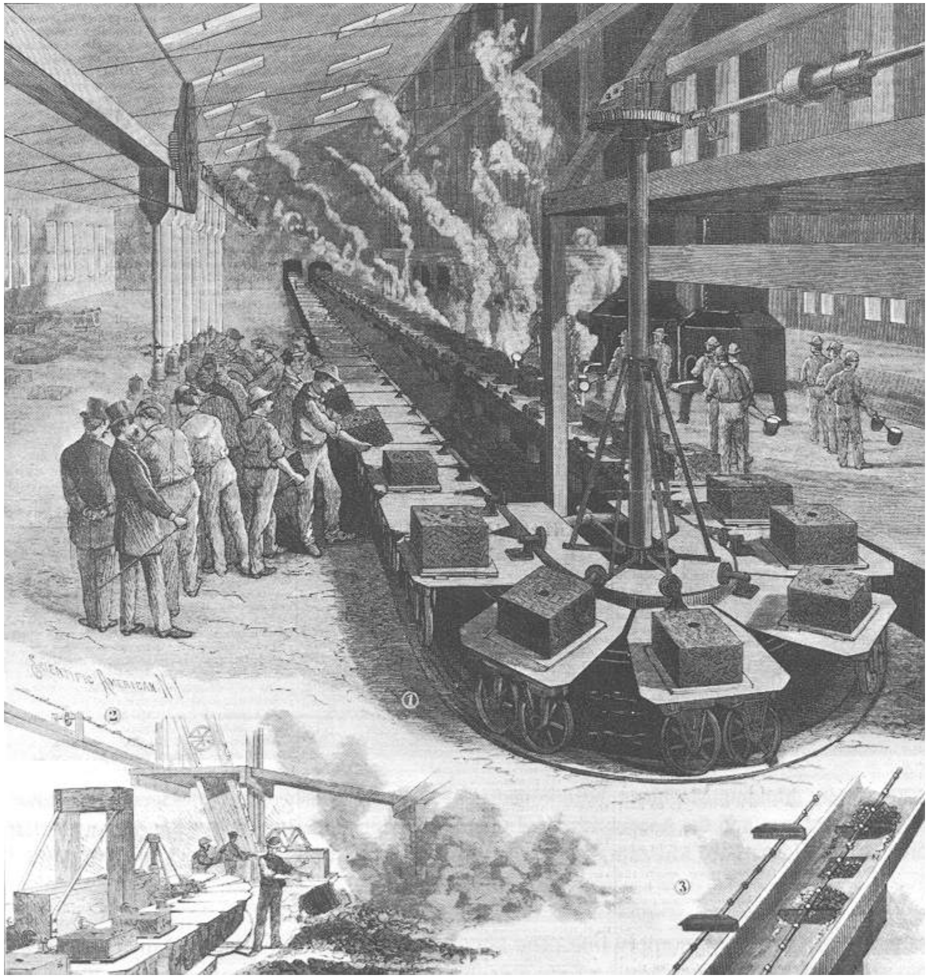
Ford Crankshaft Grinding Machines 1915



Multi-spindle drilling and reaming of engine blocks

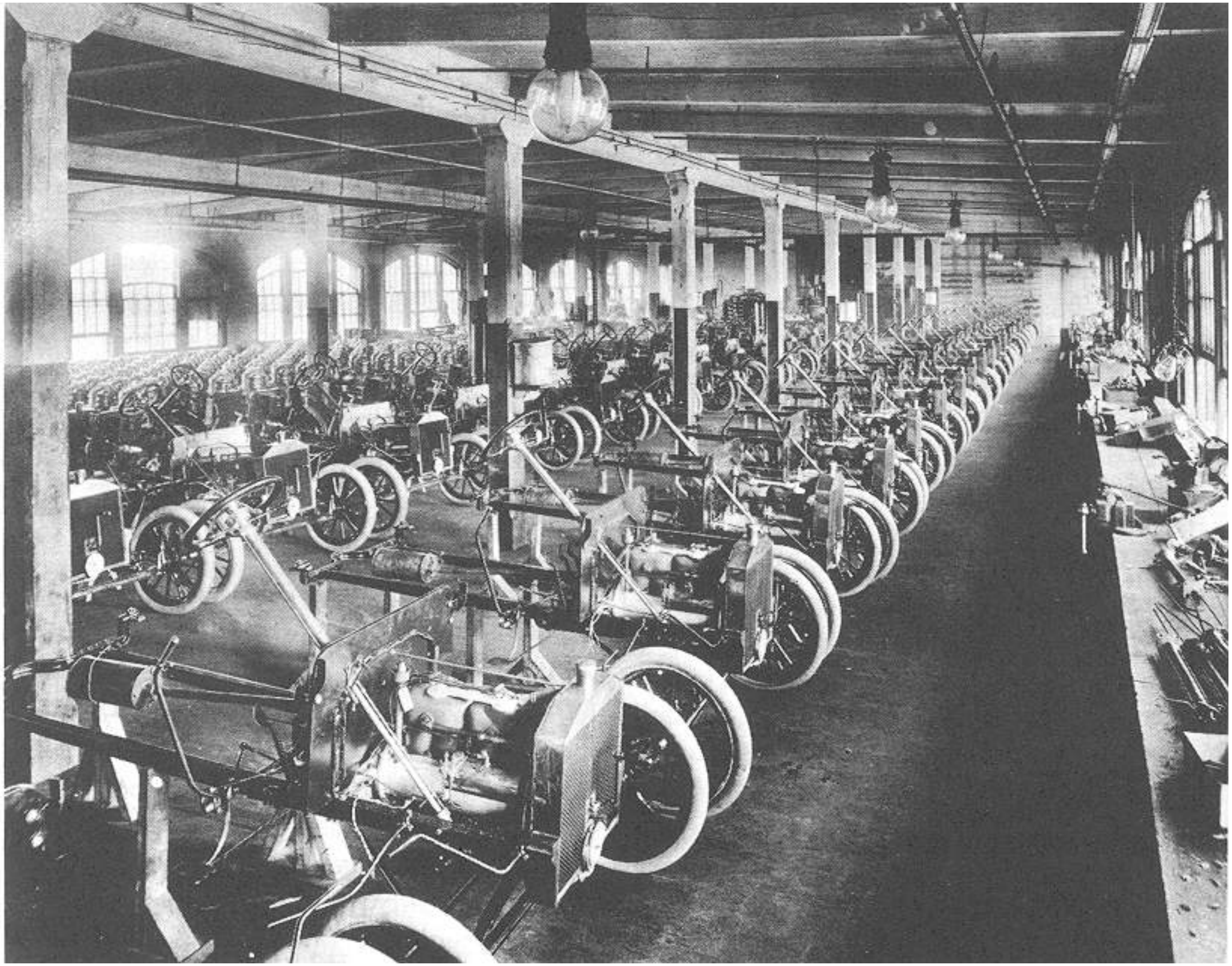


Westinghouse Foundry in 1890
Machine made molds are moved past pourer
on conveyor system. A similar system was used at Ford



THE FIRST OPERATION TO BE CONVERTED TO THE MOVING ASSEMBLY LINE WAS THE THE MAGNETO ASSEMBLY IN 1913

Static Assembly of the Model "N"
At the Piquette Avenue Factory 1906



HIGHLAND PARK

THE CONVERSION
OF THE CHASSIS
FROM STATIC (12.5 hr)
TO MOVING (93 min)
RESULTED IN
AN 8:1 IMPROVEMENT.
WITHIN 18 MO.
ALL ASSEMBLIES
AND SUBASSEMBLIES
WERE CONVERED TO
MOVING ASSEMBLY.

http://silodrome.com/ford-model-t-assembly-line/

General view of "the line" Highland Park 1914
This is the assembly line that assembled a car in 93 minutes

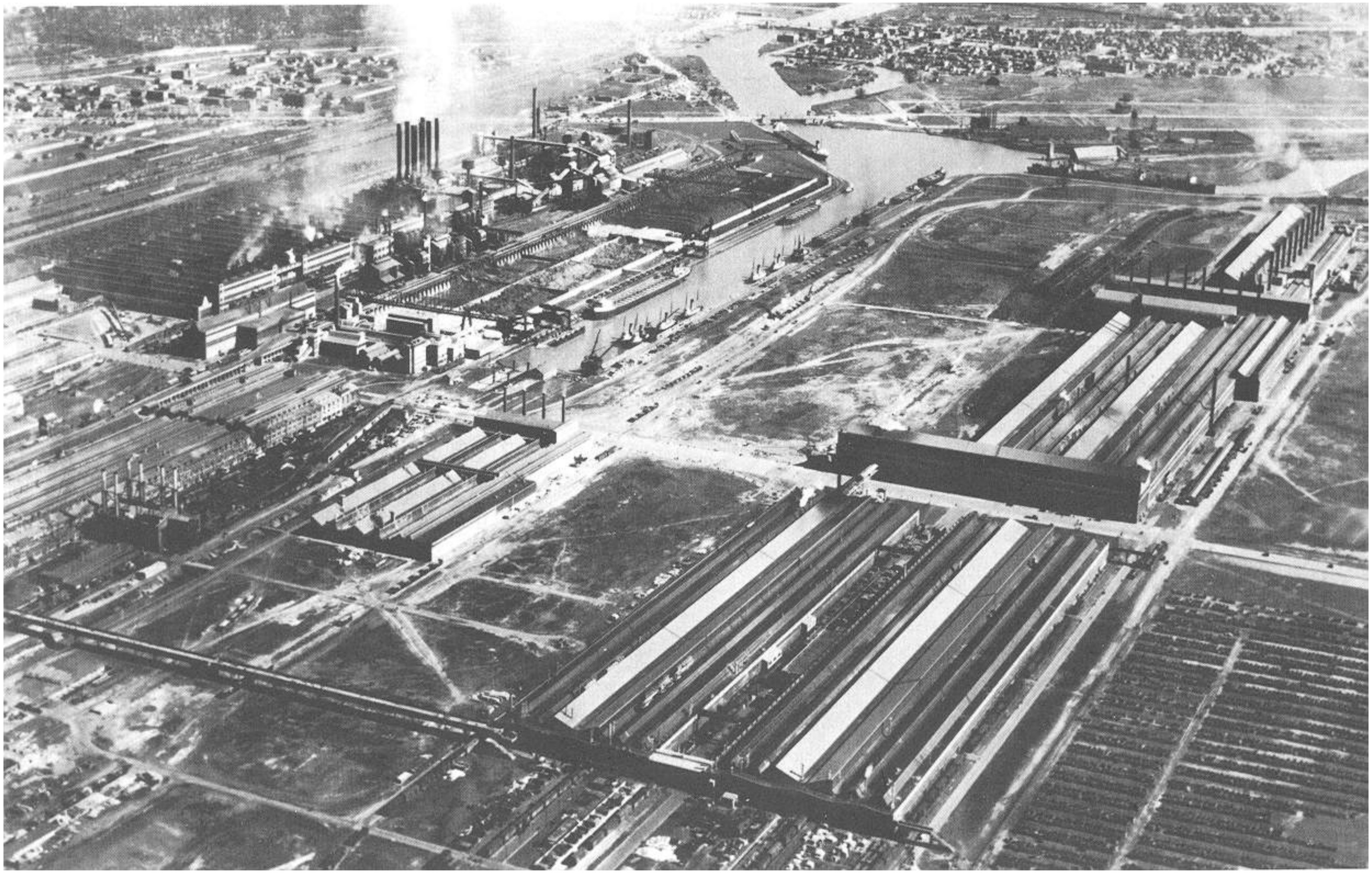
...However, Ford' s turnover rate increased dramatically. In 1914 Ford needed To hire 963 people To fill 100 jobs

FORD MODEL T VIDEO

http://www.youtube.com/watch?v=S4KrIMZpwCY

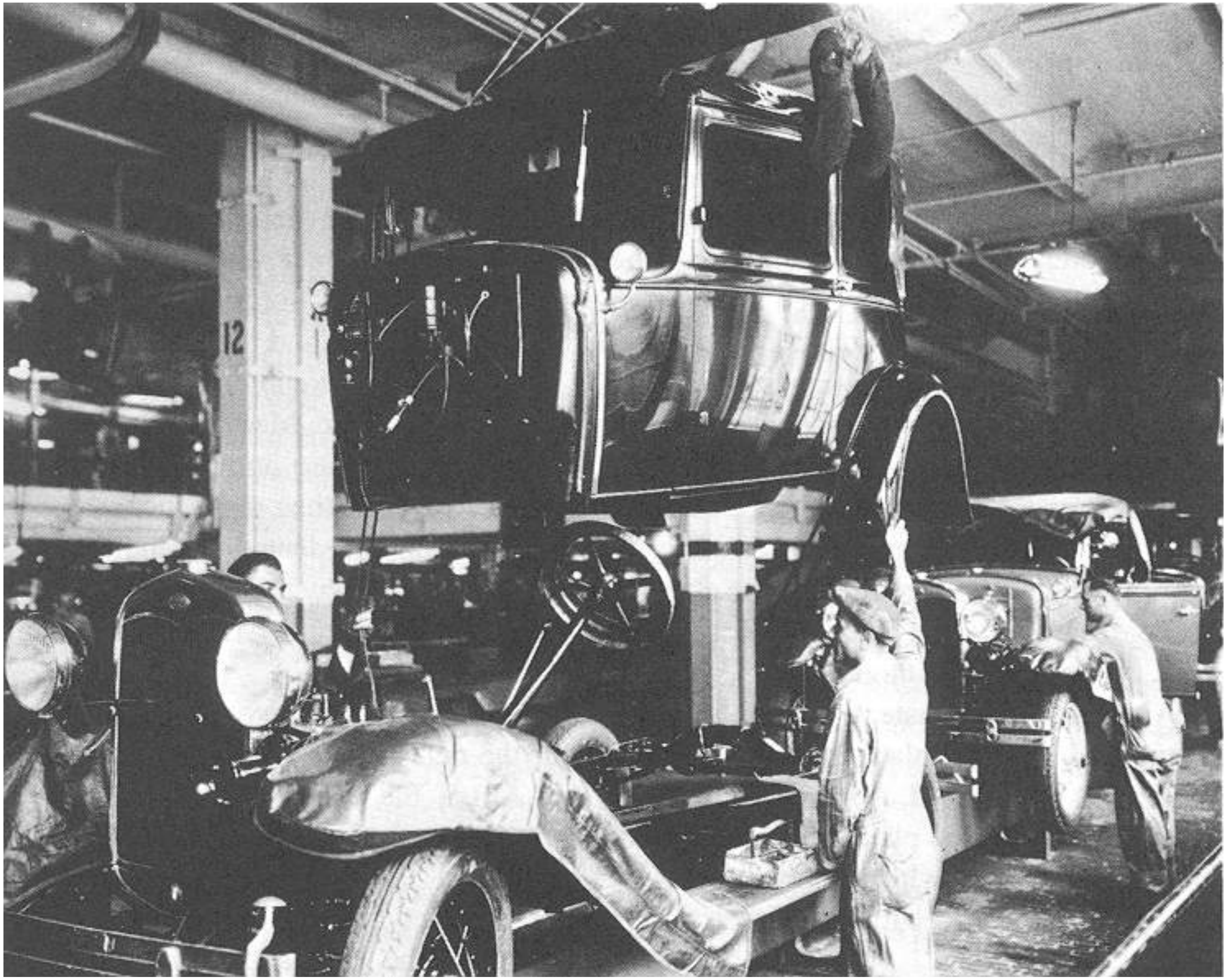
Crowd wanting to apply for $5/ day jobs at Ford 1914

Ford's River Rouge Plant; 27 miles of conveyor, the epitome of vertical integration.



1927 change over to model "A". 1949 strike. Now the site of Bill Ford's Heritage program

Lowering the body onto the Model “A”. Those curved lines contributed to manufacturing problems which delayed the changeover



Ford Service men in action May 26, 1937

photographer Scotty Kilpatrick, Detroit News

Labor leaders Walter Reuther and Richard Frankensteen after beatings by Harry Bennett's "service" men at the "battle of the overpass".

May 26, 1937 at the Ford River Rouge Plant.

photographer Scotty Kilpatrick, Detroit News

"The photos taken by the Detroit News photographer Scotty Kilpatrick on the overpass did not qualify for a Pulitzer Prize because there was no such category at the time. But they caused the Pulitzer committee to institute a prize for photography and in 1942 Detroit News photographer Milton (Pete) Brooks won a Pulitzer for this of a beating on a Ford picket line. Ironically, it shows picketers beating a Ford Motor Co. security man."

Ref "Rear View Mirror"
Detroit News

Mass Production at Ford, 1907-1932

Keypoints:

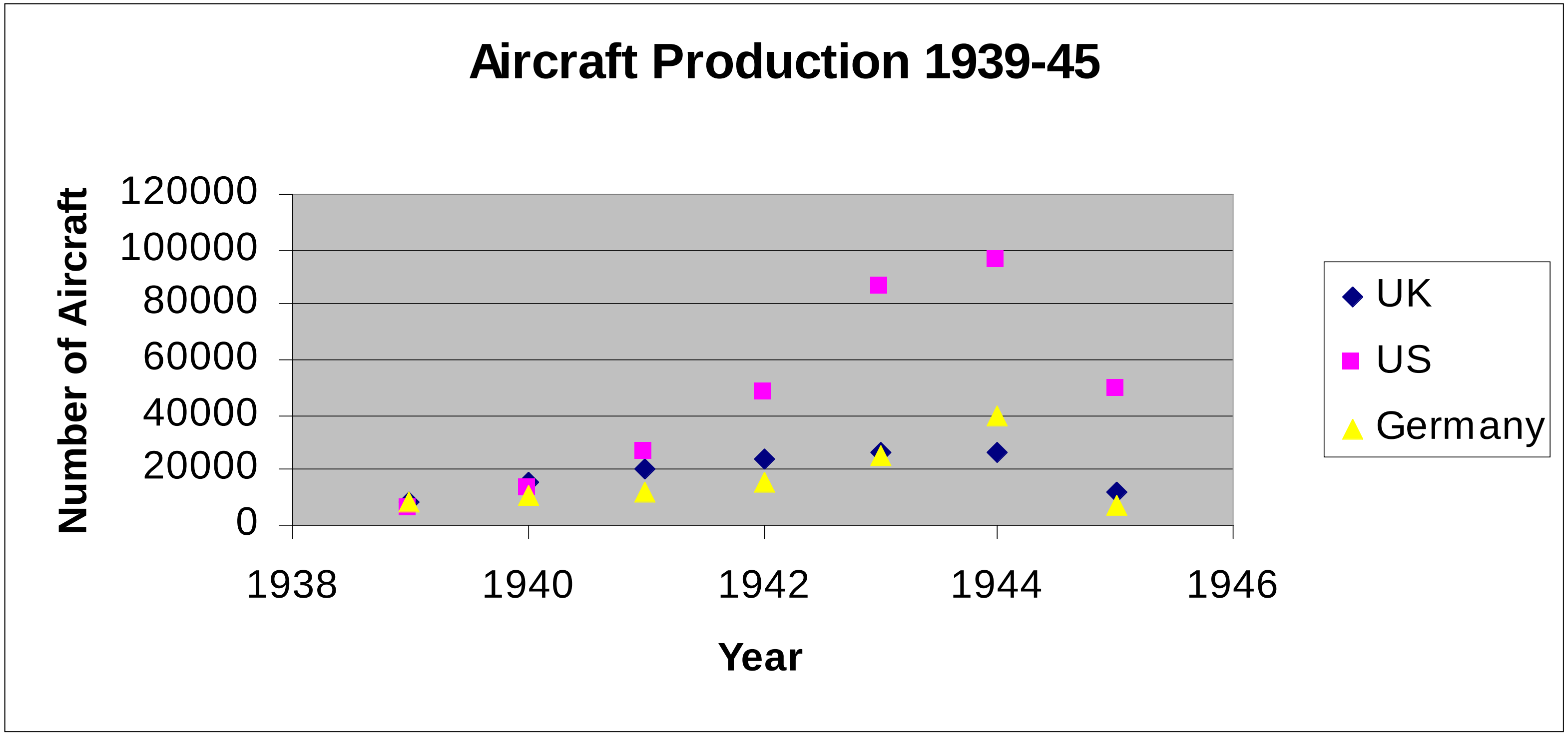
1. "In mass production there are no fitters" - Henry Ford.
2. Stamping plays important role in providing low cost high precision parts.
3. Constant improvement, division of labor, standard work, flat organization. Moving assembly line (1913) comes from other examples in industry. Work pace is increased and turnover rate increases. In late 1913, to add 100 workers Ford needed to hire 963 people. $5/day pay is instituted to address this problem.
4. Vertical integration is taken to limits at River Rouge. End of previous cost cutting strategy, conveyor system limits flexibility, labor strike moves Ford to build new plants at other locations.
5. Conversion from Model T to Model A is too late and extremely painful, occasions 6 month shut down and great upheaval.
6. GM introduces yearly model change 1925-1932.

Common elements between Ford and “lean”

- Elimination of Waste
- Equipment Placed in the Sequence of Operations
- Reduced Inventory
- Production to Demand not to Stock
- Continuous Improvement
- Flat Organization

Charlie Chaplin in "Modern Times" 1936

High Volume Aircraft Production during WWII, 1939 - 1945



Refs:

1. Johnathan Zeitlin, "Flexibility and Mass Production at War: Aircraft Manufacture in Britain, the United States and Germany, 1939-1945", published in The Society for the History of Technology.
2. Don Sherman, "Willow Run", published in Air and Space, August/September 1992.
3. Joshua Stoff, "Picture History of WWII American Aircraft Production", published by Dover Publications, 1993.

How did they do it?

year	UK	US	Germany
1939	7904	5,859	8,295
1940	15,049	12,864	10,247
1941	20,094	26,277	11,776
1942	23,672	47,836	15,049
1943	26,263	85,898	24,809
1944	26,461	96,318	39,807
1945	12,070	49,761	7,540

16:1 !!!

- Division of labor
- Redesign for mfg
- Interchangeable parts
- Pre-fabrication strategy
- Moving assembly line

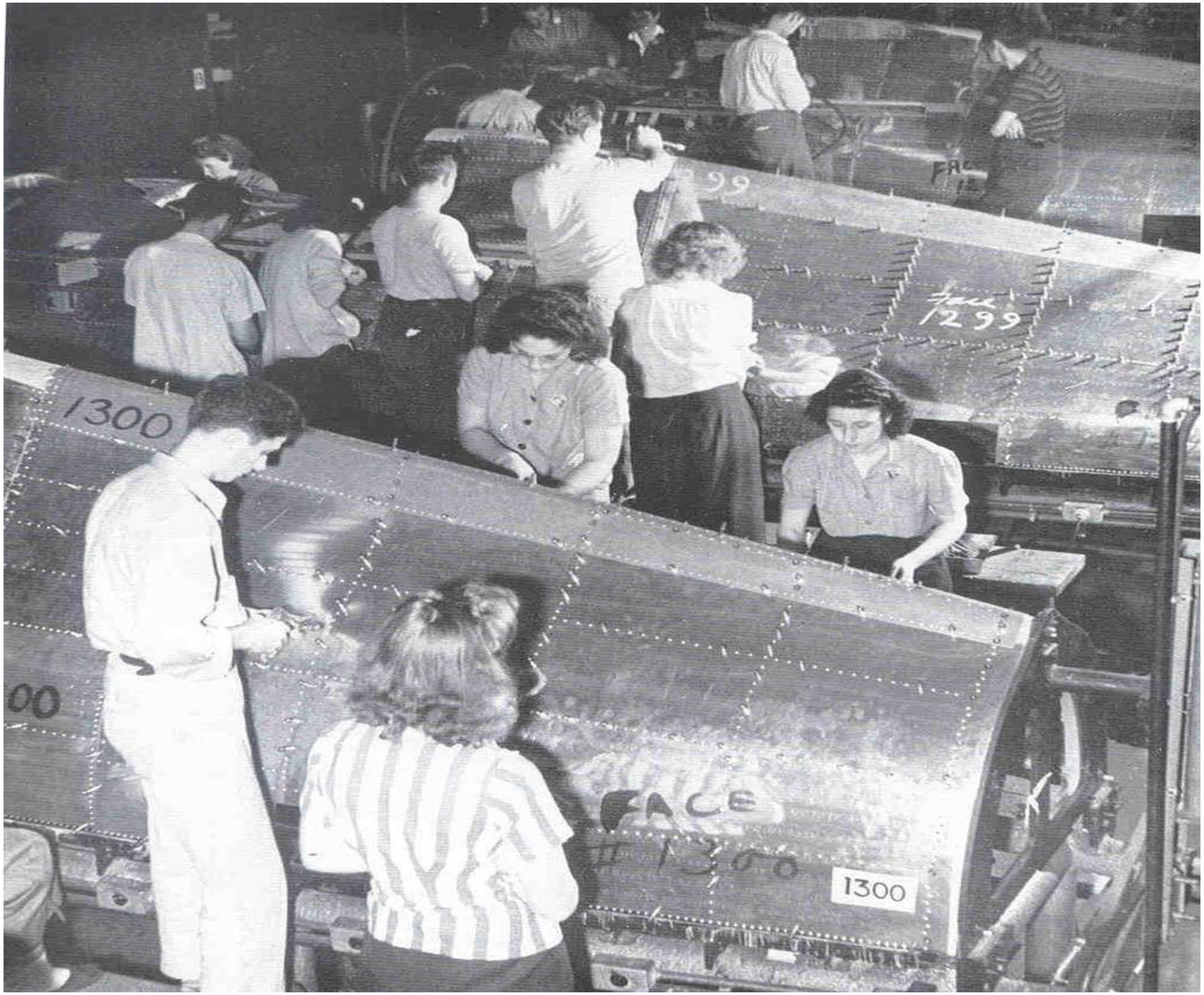
B-24 Assembly line in Ft. Worth

Consolidated, later General Dynamics, 4000 ft long

C-47 (DC-3) line in Long Beach 1944

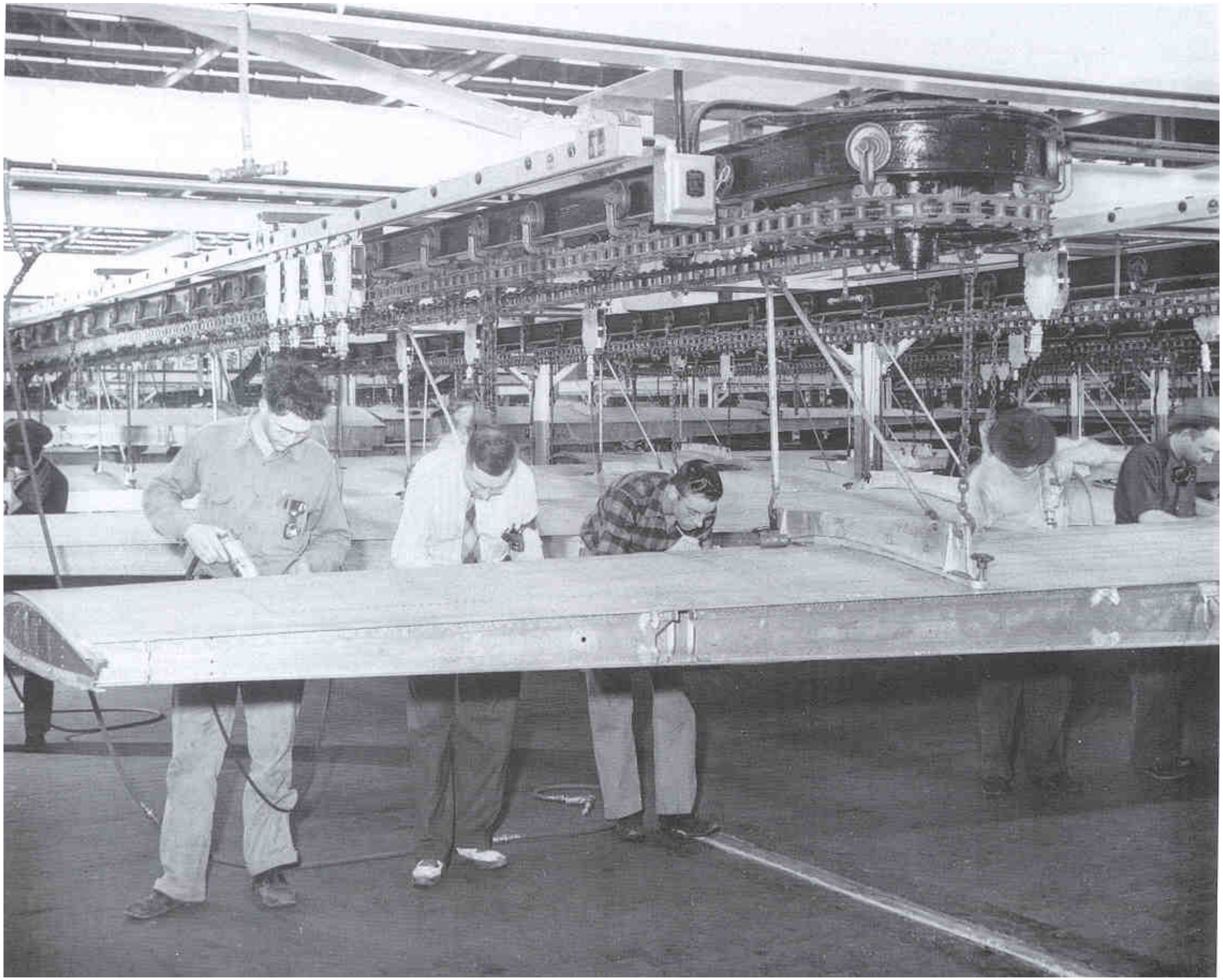
Moved every 5 minutes

P-47 fuselage riveting



Division of Labor

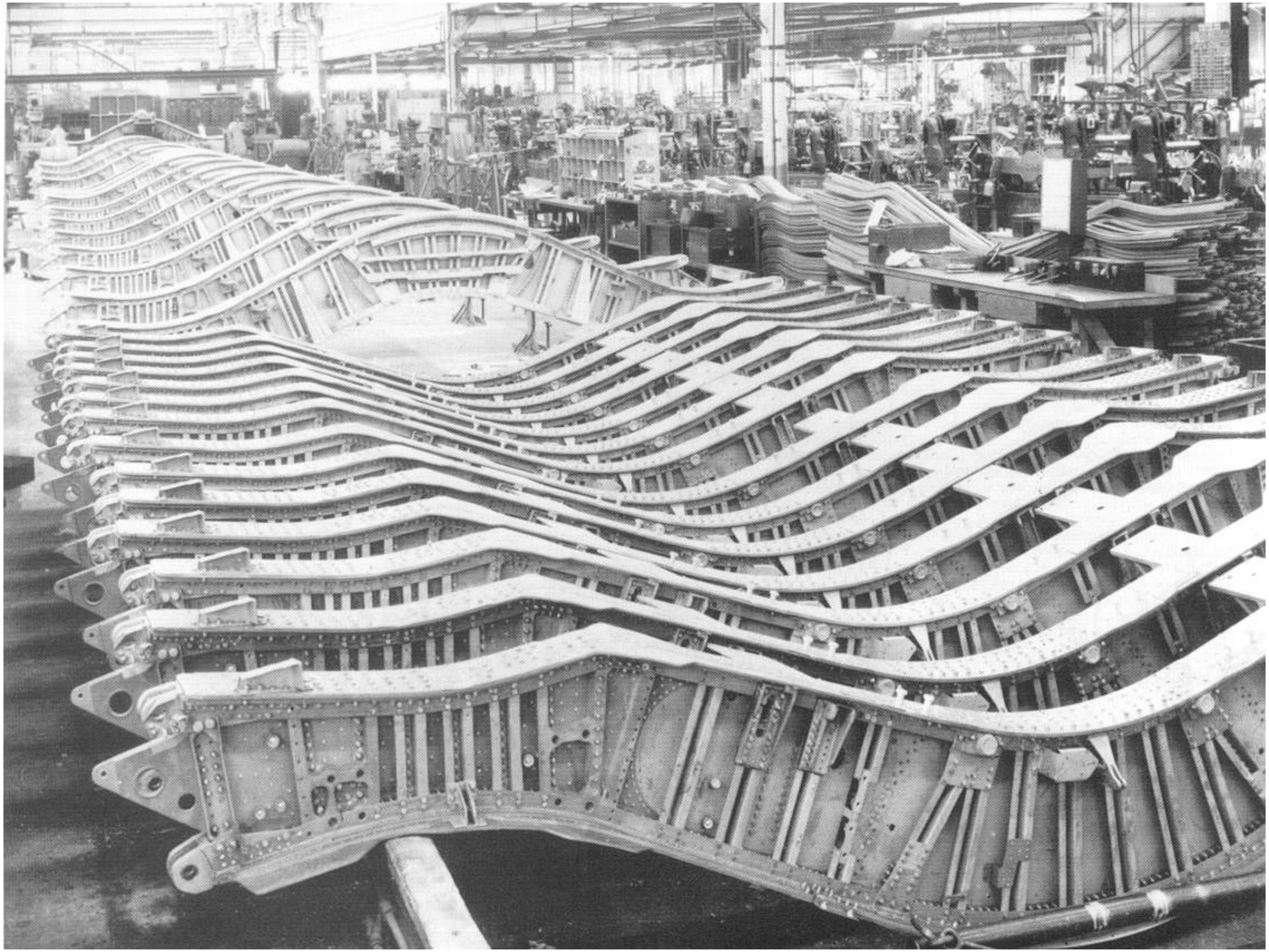
B-24 (skin riveting) assembly line in San Diego



B-17 “precompletes” for Boeing’s “multiline” production

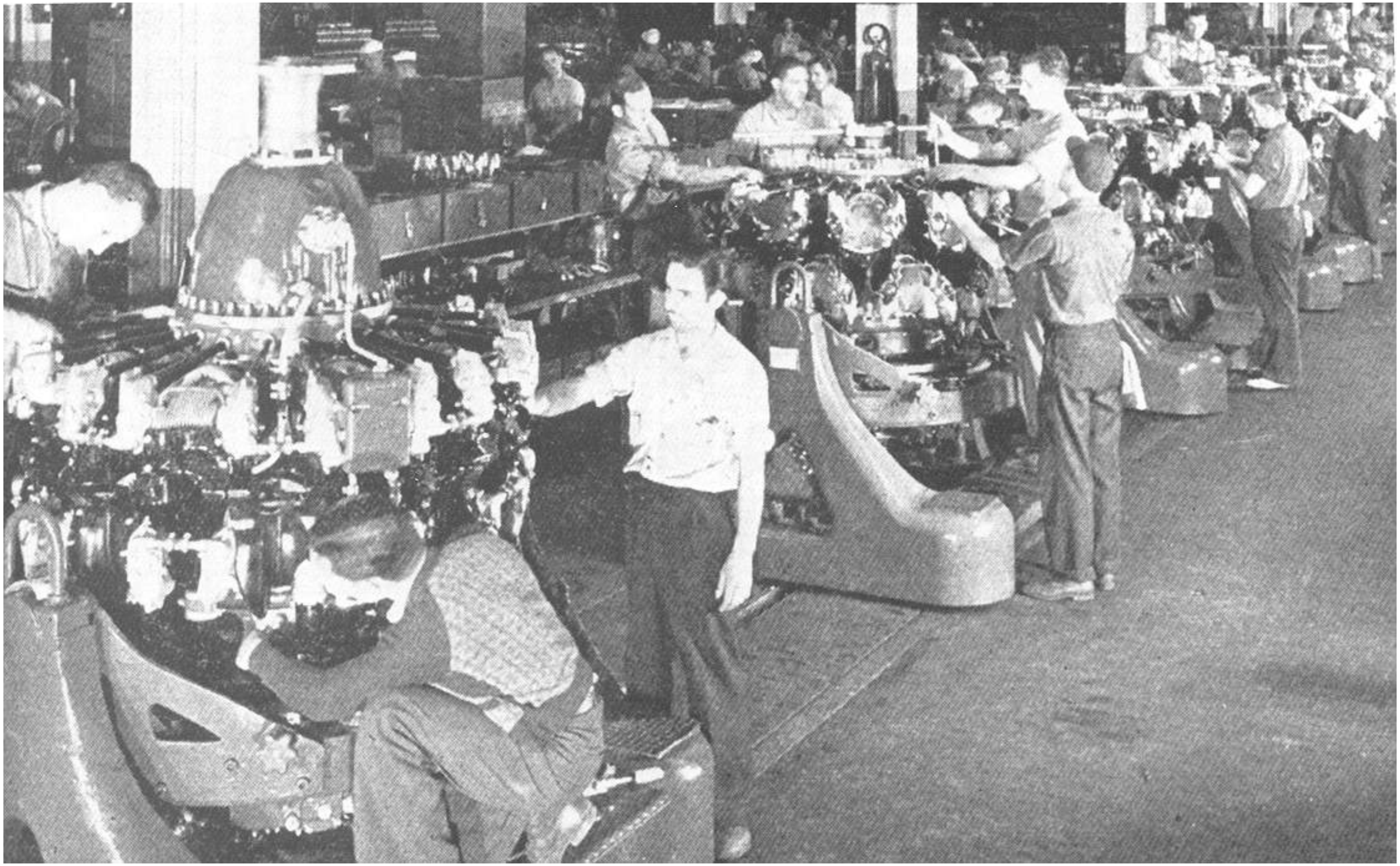
Saves room, improves access to interior

Vought F4U “Corsair” main spars for wing center sections



13 ft propeller, 2000 hp engine

Assembly of Pratt and Whitney R-2800 (2000hp, 2800 cu in) Engine at the Ford Dearborn Plant in 1944



Willow Run - Will it run?

Ford's Willow Run plant - 10 mo delay, but in 1944 produced 453 airplanes in 468 hrs

High Volume Aircraft Production during WWII, 1939 - 1945

Keypoints:

1. Mass production techniques applied to military products including; division of labor, redesign for casting and forging, interchangeable parts, and moving assembly line.
2. Ford's Willow Run plant called "will it run?" due to long startup delay. Many of Ford's tools not used, "retrospective" modification required at separate plant.
3. Experience with automotive and aircraft companies with military aircraft production shows aircraft companies better suited to introduce new system in both U.S. and England.
4. "multiline" production developed at Boeing.
5. Continuous learning and the learning curve documented.
6. Strategy to introduce change into the line; U.S. & U.K.

What conditions lead to a revolutionary new mfg system?

	Interchange-able parts	Mass Production	TPS/Lean
Need	field repairs,	Mobility alternative	Re-build after WWII
Financing	U.S. Gov' n	Ford reinvests	Japanese Banks
Workforce	Scare Yankees	Yankee mechanics, immigrants	Survivors of WWII
Enabling Technology	Mechanization of machining	Interchange-able parts, moving assembly & stamping	Many

Reoccurring Issues-Summary

Issue	US Armories	Ford	Toyota
Cost Effectiveness	Doubtful for long time	immediate	Long time
Social disruption	Two armories	$5/day & Harry Bennett	Avoid strike
Standardization & flexibility	standardization	More standardization	Still more…
Benefits & costs of inventory	Not mentioned	Vertical integration & low inventories	JIT, low inventories…
Work Scheduling/ control	Central	Centralized control	Push Vs pull - some local control

Additional References

1. Merritt Roe Smith, Harper's Ferry Armory and the New Technology, Cornell University Press, 1977
2. Johnathan Zeitlin, "Flexibility and Mass Production at War: Aircraft Manufacture in Britain, the United States and Germany, 1939-1945", published in The Society for the History of Technology.
2. Don Sherman, "Willow Run", published in Air and Space, August/ September 1992.
3. Joshua Stoff, "Picture History of WWII American Aircraft Production", published by Dover Publications, 1993
4. Kenneth N. MaKay, The Evolution of Manufacturing Control - What Has Been, What will Be. Working paper 2001