International Journal of Production Research
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tprs20

Henry Ford vs. assembly line balancing

James M. Wilson[a]
[a] Adam Smith Business School, University of Glasgow, Glasgow, Scotland. UK.
Published online: 17 Sep 2013.

To cite this article: James M. Wilson (2014) Henry Ford vs. assembly line balancing, International Journal of Production Research, 52:3, 757-765, DOI: 10.1080/00207543.2013.836616

To link to this article: http://dx.doi.org/10.1080/00207543.2013.836616

International Journal of Production Research, 2014
Vol. 52, No. 3, 757–765, http://dx.doi.org/10.1080/00207543.2013.836616

Henry Ford vs. assembly line balancing

James M. Wilson*

Adam Smith Business School, University of Glasgow, Glasgow, Scotland, UK

(*Received 21 May 2013; accepted 13 August 2013*)

Ford's Assembly Line at Highland Park is one of the most influential conceptualisations of a production system. New data reveal Ford's operations were adaptable to strongly increasing and highly variable demand. These analyses show Ford's assembly line was used differently than modern ones and their production systems were more flexible than previously recognised. Assembly line balancing theory largely ignores earlier practice. It will be shown that Ford used multiple lines flexibly to cope with large monthly variations in sales. Although a line may be optimised to yield the lowest cost production, systems composed of several parallel lines may yield low cost production along with output and product flexibility. Recent research on multiple parallel lines has focused on cost effectiveness without appreciating the flexibility such systems may allow. Given the current strategic importance of flexibility, it should be included in such analyses as an explicit objective.

Keywords: assembly line balancing; empirical study; flexible flow shop; flexible manufacturing; capacity planning

1. Introduction

Assembly lines have been a significant development for managing operations – a mode that allows high-volume, low-cost, standardised production. These benefits are often offset by drawbacks: perceptions of Fordist assembly lines consider them to be rigid and inflexible (Abernathy 1978; Piore and Sabel 1984; Womack, Jones, and Roos 1990). Tolliday and Zeitlin's (1992) title 'Between Fordism and Flexibility' perfectly expresses this dichotomous perspective: that the two are on opposite poles. Our understanding of assembly lines is implicitly constrained by the theory surrounding assembly line balancing (ALB), describing how such systems *should* be designed for maximum efficiency.

The line balancing problem is well established in the Operations Research literature. Salveson (1955) first described and mathematically formulated the problem, and an extensive literature followed (Wild 1972; Erel and Sarin 1998; Boysen, Fliedner, and Scholl 2007) with many variants and extensions of the basic model. These analyses have focused on maximising line efficiency rather than their overall operational effectiveness or strategic use. Erel and Sarin (1998) observed that ALB theory was not widely used, but suggested this was because practising managers were unfamiliar with the relevant theoretical developments. They also noted that managers often considered broader issues than simple line optimisation; however, those issues were not explored.

One gap in the existing literature is its lack of interest in assembly line practice before Salveson's (1955) work; despite universal acknowledgement (Arnold and Faurote 1915; Ford 1924, 1926; Nevins and Hill 1954; George 1972; Hounshell 1984) of Ford's fundamental contribution in implementing these systems. If mentioned at all, Ford receives only cursory attention. A case study analysis of Ford's operations drawn from detailed accounting data (Raff 1996, 2003; Wilson 1998; Wilson and McKinlay 2010; Wilson 2011) complements the operations research literature and reveals how lines may be used more flexibly and strategically. This shows not only that Ford first informally used the objectives and logic that Salveson (1955) later formalised, but that Ford also used their lines more flexibly and as an integral element of their extended supply chain. The most notable result from Wilson and McKinlay (2010) and Wilson (2011) is the recognition that Ford used *multiple* parallel lines in a start–stop mode to adjust output to large demand fluctuations. Ford's lines were optimised both 'locally' as individual production systems; and also 'globally' as constituent sub-systems of Ford's larger, vertically integrated materials extraction, transportation, production, assembly, distribution and sales supply chain system (Ford 1926; Nevins and Hill 1954; Wilson 1995, 1996).

Research on the parallel assembly line balancing problem (PALBP) is a recent theme: Lusa (2008) provides a survey of contributions, though most focus on using parallel workstations rather than entirely separate lines. An overview of

*Email: james.wilson@glasgow.ac.uk

line balancing problems and solution approaches may be seen in Battaïa and Dolgui (2013); with independent lines especially considered by Süer (1998). That problem was subsequently formalised with solution procedures developed by Gökçen, Kürşad and Benzer (2006), Scholl and Boysen (2009) and Ozbakir et al. (2011). These treatments focus on maximising the efficiency of the lines, without regard to their role within an extended supply chain. They recognise that multiple lines will allow greater product variety, but none consider their ability to allow variations in output volume. Gökçen, Kürşad and Benzer (2006) also model lines having different cycle times and describe how those would be optimally solved. They do not explain why such an imbalance would be attractive, though that might possibly be a more efficient combination than identical lines. Ford's case reveals the strategic role of such layouts in increasing the organisation's ability to respond to demand changes in production volume and variety. Gunther et al. (1983, 209–210) suggest that ALB analyses would benefit from considering a broader range of objectives building models '… based on empirical evidence.'; noting that '… trying to apply a priori models to real world problems has not always been successful'. Those ideas have been applied to parallel lines by Kara, Gökçen and Atasagun (2010), but flexibility has not yet been treated as a goal within model formulations, as Wilson (2013) suggests a broader definition of organisational goals would require. Indeed, we will later argue that minimising the number of workstations explicitly limits a line's potential flexibility.

A related area is the more general study of flexible flow shops (Quadt and Kuhn 2007) in which a greater variety of products progress through several processing stages, each possibly having multiple processing machines. The stages may differ with some products not going through all processes, and the processing times may involve set-up times and costs for each product. In the ALB literature, the processes are more limited, usually with a strictly linear flow with no set-ups required and no (or little, within 'mixed model' formulations) product variation. Nevertheless, Agnetis et al. (1997) describe using flexible flow lines in automobile assembly whereby Automated Guided Vehicles (AGVs) relaxed the strict flow between stages in the line: that is, an item finishing processing in the first stage could then be moved to any idle processor in the next stage; and then from that processor to the next subsequent processor that was free. So, these flow lines were not strictly linear sequences of processors as usually defined as 'lines'. By thus decoupling the stages, the capacity of each could be better managed to meet production requirements. Agnetis et al. (1997) varied the production rates from 1100 up to 1800 units per day and showed that increasing the numbers of AGVs generally, and the number of processors at each stage would allow efficient production. They note (Agnetis et al. 1997, 362) that their approach is suited for a plant whose output grows over time – the initial investment in the line must be adaptable to the forecast demand growth. Plainly, any adaptations that accommodate long-term demand growth would also allow adjustments to shorter term and seasonal fluctuations. From this perspective, the line's flexibility is a function of the number of processors available at each stage; and, if shorter cycle times are to be achieved, it may be useful to allow a line to be extended with additional workstations, rebalancing thus giving each less work to do. Simply increasing the number of processors in each stage may increase stage throughput, but the underlying cycle time remains unaffected.

2. Production line management before Salveson

Salveson (1955) formalised existing practice by mathematically defining existing policies. He made no claim to identifying the objectives, or to being the first to recognise workload balancing, but shows how these informally handled problems could be addressed using operations research methods. Considering the overall production rate to determine a cycle time (daily output target/daily time available) and workstations required (work required per unit/cycle time) was already well established. The need for matching process capacity to overall throughput was clear from the very beginning of the industrial revolution.

This matching of capacity to demand can be seen in Evans's (1834) fully mechanised flour mill from 1785. This was a mechanically paced production system designed to operate without any human supervision, with wheat being mechanically moved, stored in buffers, moved again through grinding and cooling processes and then through sorting filters into storage. All these processes were designed to allow a smooth flow of material and mechanised processing. Evans's mill did not use any feedback or active control systems – not even speed governors as were developed for later steam-powered mills. Once set running, Evan's mill would continue without human intervention until it ran out of material or some problem arose (e.g. a blockage in the internal movement or processing, or a change in external water flow that powered the system).

Similarly, the Portsmouth Block Mill (Gilbert 1965; Cooper 1981–82, 1984) designed by Marc Isambard Brunel, Samuel Bentham and Henry Maudslay in 1802 was matched to both overall demand and to the batch processing requirements of constituent product lines. The sophistication of capacity management and production control can also be seen in Babbage's (1835, Section 331) observation of overlapping operations in the *London Times*' reporting of time-sensitive information. In those operations, reporters would physically send parts of parliamentary debate transcripts for typesetting before the debates being reported upon had concluded. Publication could then begin once the final part had been typeset, and was much faster than when their whole report needed typesetting.

Thus, the general principles used by Ford to manage capacity were well established. Salveson's (1955) recognition of 'balance delay', or wasted time, as an objective; and then his development of a mathematical procedure for minimising it was a seminal contribution. He simply formalised existing, less rigorously implemented approaches. Salveson's industrial engineering contemporaries would have used manual and intuitive analyses for line balancing. But when Ford's managers were developing the line, they did not have any theory or experience to guide them. Observing the line would *visibly* show workers that were either idle or overworked, and the workload was then redistributed to improve the overall balance. Klann (1955) describes their experimental approach:

> By this time [1913] we had a fairly good record of our spacings, the men required, and where we required creepers for the men to lay on their backs so they could hook onto the chassis and be pulled along with the creepers so they could use both hands to work with instead of pulling the creeper along by hand. All this was recorded. We then set out to change operations, giving more work to some men and less work to others to even up our time, putting more men on the slow operations. …This was still all being turned by hand. This was in September or October of 1913. (Klann 1955, 69–70)

This was typical of Ford's approach that used an incremental, 'small wins' approach (Weick 1984) that was low cost, quick and easy to install (or undo if it did not work), and easily modified or improved.

This was most apparent in April, 1913 with their implementation of the first assembly line for flywheel magnetos. Arnold and Faurote (1915) describe an experimental line, with workers spread along the length of a workbench, with the division of work and number of workers/workstations varied as was the throughput and work speed; and even the height of the line changed to allow better ergonomics and material handling by workers at, and between their workstations. Ford's approach was empirical and based on understanding what each process needed to do for the whole line to be effective and efficient. But more importantly, Ford understood how the line itself fulfilled and complemented their other production and distribution activities. Ford's pragmatic, empirical approach contrasts significantly with the abstract, theoretical approaches of operations research analysts (Mitroff and Silvers 2010). In those approaches, imbalances in workloads would be resolved through task reassignments between workstations. Ford's understanding and *involvement* was deeper – not only could they reallocate work, they could also redesign the tasks to achieve a better balance and even, if necessary, redesign components and assemblies for more efficient production. Ford also deviated from modern practice in increasing the line's pace several times during the 1920s (Sward 1948; Meyer 1981; Wilson and McKinlay 2010; Wilson 2011), effectively reducing cycle times. Sward (1948) also notes that Ford used unbalanced feeder lines as implicit motivators – 'upstream' activities were run faster to create pressure on 'downstream' activities through work building up before them. Ford proactively combined product, process and job design with line balancing to achieve a better result than line balancing alone would yield. It is this wider context that assembly line theory since Salveson (1955) has lost.

3. Fundamental assumptions and reality

Assembly lines are now generally considered to be inflexible, and a fundamental assumption is that demand must be stable for their use. Theory and practice maximise efficiency by designing production systems with a defined throughput and limited ability to deviate from that. Wild (1972, 14) asserts: 'The term mass demand must be qualified; in particular, we must consider not only the level of demand, but also the continuity. … demand is both high and reasonably continuous'. An implicit assumption is that Ford's historic systems also suffered from this inflexibility. The aggregated annual data used by earlier analysts (Lewchuk 1987; Gibson and Mahmoud 1990; Williams, Haslam, and Williams 1992; Williams et al. 1993) obscured the details of Ford's operations. As Wilson and McKinlay (2010) have shown in Figure 1, the demand for automobiles was highly seasonal (O'Brien 1997), with significant month-to-month variations. Figure 2 shows that Ford's production closely followed sales and inventories were not used as buffers for isolating operations from sales fluctuations. The correlation statistics shown in Table 1 between sales and production are strong and positive, as are those for inventories and production. If a stable production policy was followed, the correlation between inventories and sales should be negative rather than positive. These strong correlations are seen:

> Because the link between contemporaneous sales and production is so strong, it seems likely that sales information was being gathered at intervals shorter than a month. That is, for example, a particular April's sales figures would not have had much impact on April's production if April's sales figures were not available until the end of the month. (O'Brien 1997, 209)

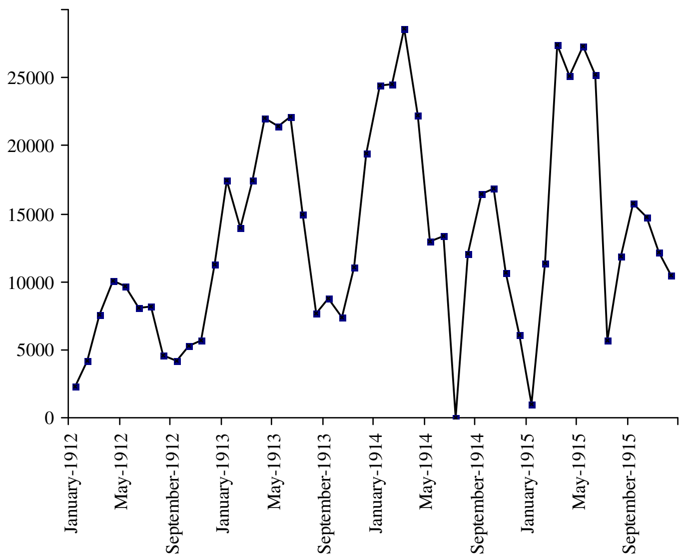

Figure 1. Monthly car sales.

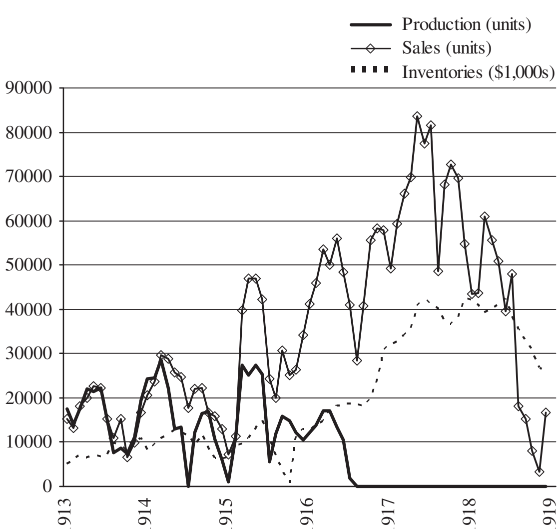

Figure 2. Production, sales and inventories.

This shows a conscious effort to coordinate production with sales and to pursue a 'chase demand' strategy closely. O'Brien (1997) maintains that Ford adjusted production based on reported sales from the previous 10 days: potentially two or three times *within* each month. Ford implemented mass production systems *despite* facing highly variable demand; and not, as commonly believed, under conditions that: 'Gradually, as Model T sales increased and as production schedules stabilised, Ford and his engineers and managers began to realise the profound impact of product design on their factory operations'. (Meyer 1981, 15) The assembly line did not wait for a stable market to emerge.

Wilson and McKinlay's (2010) most unexpected discovery was this large variability in production and sales – a variability that earlier, annualised data had completely obscured. Modern ALB and PALBP theory considers assembly lines to require a constant throughput. This discrepancy requires explanation: Ford not only used a supposedly inflexible production system in a highly variable environment, they *developed* it under those conditions. If Ford had a constant throughput consistent with an optimised line balance, then hours and staff would be stable and inventories of the finished product would buffer fluctuations in sales. Wilson and McKinlay (2010) find no evidence of this: inventories correlate positively with sales and production levels, hours and staff. If a stable production policy was followed, there would be a strong correlation between output, hours worked and staff with lower correlations of those to inventories

Table 1. Correlations.

0.9816	Correlation of production with sales from January 1910 to March 1914
0.8857	Correlation of production with staff from January 1910 to March 1914
0.8756	Correlation of production with total hours from January 1910 to March 1914
0.8900	Correlation of sales with staff from January 1910 to March 1914
0.8786	Correlation of sales with total hours from January 1910 to March 1914
0.8132	Correlation of production with direct hours from January 1910 to March 1914
0.9899	Correlation of staff with total hours from January 1910 to March 1914
0.7977	Correlation of production with inventory from January 1910 to March 1914
0.8294	Correlation of sales with inventory from January 1910 to March 1914

and sales; and negative correlation between inventory and sales as inventories would move counter-cyclically to sales to offset those variations. As Figure 2 shows, variations in inventory levels reflect those in sales, there are no observed attempts (i.e. inventories rising as sales fall, and *vice versa*) at using inventories as a buffer. O'Brien (1997) argues that Ford was unique in so closely matching their production to sales data: 'Ford pioneered in developing means of controlling inventory, receiving short-run feedback from dealers, and keeping production scheduling in line with sales' (O'Brien 1997, 200).

4. The line's strategic role and use

Ford used multiple assembly lines flexibly in contrast to the modern understanding of how they should function. The implications are that Ford better understood their system than have later users or theorists. Ford ran not just one assembly line to produce up to the required maximum capacity, or at some theoretical maximum 'efficiency', the company used as many as six with lower capacities in combinations suitable for achieving its maximum output, and fewer as required to meet demand when it varied. Klann (1955, 84) comments that some were 'temporary' and used for '… only 2 or 3 weeks at a time'. In the absence of established theory, Ford's multiple lines were not different conceptually from their use of multiple stationary assembly stands. Previously, the greater demand, the greater the number of static assembly stands: assembly lines were not conceptually so different that they were immune from coordinating capacity with demand. There was no *established* theory to restrict what Ford might think of doing, and modern ideas that demand must be stable for these systems to be effectively used are erroneous.

Multiple lines gave Ford a degree of flexibility not previously recognised. Having four lines available in 1914 allowed Ford to match output closely to demand. Wilson and McKinlay (2010) show that four lines were sufficient to meet the maximum monthly demand that year, that two lines produced enough for the lowest demand periods; and three lines matched the average monthly demand. Ford's multiple lines allowed them to respond to the practical demands of matching their production activities to sales. Ford Times (1914) describes the assembly line's flexibility:

> … no matter whether the factory is turning out 1000 or 2000 cars per day the time of building an individual car is in no way affected … When it's desired to build more cars, *more conveyors are put into operation*, or those in service are run a greater number of hours each day, that's all. [emphasis added]

Wilson and McKinlay (2010) maintain that Ford's flexible use of the assembly line is supported by multiple mutually supporting data-sets and analyses: employee numbers, hours worked, cars sold, numbers produced and inventories, contemporary reports, worker's comment, corporate history establishing their existence, and corroborated by other modern research.

5. Deskilling's full importance

Recognising the variability of Ford's production and capacity changes makes capacity change costs a new, important factor in system design and modelling. With stable operations, such costs could be ignored, but Ford's starting and stopping lines involved costs. The role of deskilling to increase production volume is well understood. A finer division of tasks allowed greater specialisation and increased productivity. The greater fragmentation of tasks also facilitated line balancing since these smaller tasks could be more evenly spread across workstations. Reducing the 'lumpiness' of the tasks being assigned made the problem less difficult. Ford benefited from increased productivity through both a faster and a more regular, steady flow. Wilson and McKinlay (2010) go further and argue that the line's operations *dictated* those of the factory overall. Variations in assembly were necessarily matched by variations in feeder lines and parts production, and by deliveries from suppliers. Consequently, Ford also deskilled their upstream production work by using ‘farmer machines’ that a worker straight off the farm could operate with minimal training and supervision (Biggs 1984). The whole system was designed for flexibility as well as, and perhaps even more than, high volume, low cost manufacturing.

Deskilling reduced Ford’s capacity change costs. When tasks were very narrowly defined, training and other staff assimilation costs were reduced to virtually nothing. Staff could be hired and fired as required. Organisationally, Ford could promote favoured workers to supervisory positions when demand grew and more line workers were needed; and then, when demand reduced again, could be returned to their normal line tasks. This staff flexibility was also eased by Ford’s rapid growth since good performance in a temporary supervisory position could lead to a more permanent posting in the near future. Ford’s personnel office reputedly had the capability of hiring nearly 600 people per day, further highlighting the organisation-wide capacity for managing operational variations (Boudie 1958). Ford employed an average of 12,145 people monthly in 1914, ranging from a minimum of 9694 in July to a maximum of 13,971 in February. The personnel office seemingly had the capacity for moving from the minimum staffing level up to the maximum (13,971 − 9694 = 4277) within just seven days’ time given they could process 600 people a *day*. This implies that the smaller within month adjustments could be made within just a day or two, so Ford probably had more difficulty in adapting its material flows than in adjusting the workforce size. In 1914, Ford unilaterally increased wages significantly (the ‘$5 day’) with most analysts like Meyer (1981) attributing this as compensating staff for more intensive work on the line. However, considering the new information about Ford’s flexible operations and variability in employment, it particularly seems that such high wages were an incentive ensuring workers would be *immediately* available when required for any tasks needed.

Ford’s organisational capabilities fully supported the flexible use of multiple lines. Gökçen, Kara and Atasagun (2010) observe that one principle of Toyota’s system was ‘Shojinka’ – being the ability to adjust a production line to meet varying demand by varying staff numbers and assignments. Studies that maximise labour utilisation on multiple lines (Gökçen, Kürşad, and Benzer 2006, Gökçen, Kara, and Atasagun 2010, Kara, Gökçen, and Atasagun 2010, Ozbakir et al. 2011) do so by assigning some staff to tasks on adjacent lines; that is, a worker would spend some time working on an item on line 1, then reposition themselves on line 2 and work there until done with that line’s item, switching back and forth between the two lines.

Ford’s system design adapted to the sales variability. The work was designed so that it could be easily performed at speed, and workers quickly trained to take on work they had not previously done. The production systems as well as the staff were adapted to the need for flexibility with simple, low-cost materials handling and production equipment used where possible.

6. Implications for future research

Theoretical models have ignored the need for flexibility despite the criticisms cited earlier. This historical case shows that the underlying assumption that demand is steady is not necessary. Ford’s multiple lines provided flexibility not recognised by either the general operations research literature (Erel and Sarin 1998; Boysen, Fliedner, and Scholl 2007) or historians (Hounshell 1984; Lewchuk 1987, Williams, Haslam, and Williams 1992; Williams et al. 1993). The limited literature on the PALBP (Gökçen, Kürşad, and Benzer 2006; Scholl and Boysen 2009; Ozbakir et al. 2011) only mentions flexibility in terms of product variety and facilitating maintenance. Agnetis et al. (1997) discuss output flexibility that was apparently forced on a company when its sales fell below expectations and its line needed to adapt when output fell or demand grew. Flexibility was not then an initial design objective but a reaction to operational and marketing needs. Such concerns should arguably be a theoretical design consideration. Ford’s lines were a subsystem within their larger supply chain: their concern was global performance, rather than optimal use of the line alone. Future research should include flexibility as a specific concern – the ability to adapt to variations in demand may be more important than small improvements in line ‘efficiency’ minimising balance delay.

Gökçen, Kürşad and Benzer (2006) note that the ALB problem generally deals only with single-sided lines; i.e. where a workstation consists of just one set of tasks undertaken on one ‘side’ of a line. In Özcan, Gökçen and Toklu (2010) two-sided formulation, workstations undertaking different sets of tasks may exist on the ‘other’ side of the line. They note a number of advantages: shorter lines, reduced materials handling costs and reduced tool and fixture costs. A common cycle time would be needed to coordinate any shared resources between the two parallel lines. Ford’s practice shows their line operated on four ‘sides’: some staff would ride on the cars doing their work, while others worked beneath the cars in pits, or on trolleys that were attached to, and pulled along with the cars (see Klann 1955 above). These practices further complicate the model since such ‘workstations’ moved with the work. Since a worker could ride along (or beneath on a roller trolley) with the car as it moved past other, fixed workstations that 'workstation' effectively overlapped them, and its cycle time might be a multiple of that given the fixed workstations. Thus; from a modelling perspective, a subset of activities may be assigned to a workstation with a fuzzy cycle time limit subject to an additional time for staff to move from ending points back to the starting position. Solutions to ALB problems are computationally difficult (Ozbakir et al. 2011), and extending models to include Ford's practices would further complicate them. Ford's empirical approach yielded manifestly effective solutions to the 'local' problem of balancing their lines while also satisfying their 'global' issues of coordinating those operations with sales, and reflecting production needs backwards through their upstream supply chain.

There are major implications for theorists, modellers and managers. Although an assembly line's capacity is inflexible just as every other piece of capital equipment, its *use* can be flexible. Salveson (1955) hypothesised that one benefit of his procedure was that it allowed lines to be rebalanced more easily to accommodate variations. An analytical process would allow lines to be redesigned to match demand as it varied (or to differing staff availability) so that the system functioned as efficiently as possible. Systems have always needed to adapt to demand or staff fluctuations and Salveson (1955) sought to facilitate those responses, but in practice line rebalancing seldom occurs in response to short-term fluctuations. Current ALB and PALBP design systems may be used for these short-term layout and operational needs as well as their more common intermediate and strategic applications.

One current source of flexibility could be found through running lines for longer or shorter periods. Overtime might be used to run a line an additional hour to increase nominal output by 2.5% (assuming a standard 40 h work week). Adding an additional day could increase capacity by 20%, and an added shift could add a nominal 100%. The variability in output from a supposedly 'fixed' facility is considerable: from a 'normal' one shift run for a five-day work week (40 h nominal output) up to three shifts run continuously for seven days (168 h nominal output). Scheduling can allow a flexibility that the design cannot; but it has to be recognised that the base design provides the foundation on which later adjustments (both increases and decreases) are based. Thus, designs that more readily allow rebalancing may be preferred to less flexible ones.

Ford used multiple, parallel lines. If more intensive capacity utilisation from multiple shifts or overtime is unattractive, these may provide alternatives. Ford used lines that were identical. This made managing them easier but it also involved relatively large capacity changes. However, there is no theoretical requirement that all lines be the same. One possibility would be to design a line to satisfy a minimum specified or baseline demand at the lowest cost when run 'normally'; and to have supplementary lines used for those periods when the demand is greater than may be effectively accommodated through more intensive, overtime use. Line balancing could then optimise both the 'base' level of production and consider various capacity increments and the most effective designs for overall performance. Gökçen, Kürşad and Benzer (2006) describe a model for lines with different cycle times, and this historical study shows that their model, as well as the other PALBP analyses, are potentially of more than just theoretical interest. Ironically, some of the most recent developments in PALBP research are justified by the oldest assembly lines. Adding flexibility as an explicit design parameter for ALB research more generally would extend the usefulness and relevance of that research.

7. Conclusions

The implications of this historical case study are that modern systems could be designed for more flexible use. Lines are now more capital intensive than in Ford's time, so the degree of flexibility available to Ford is unlikely to be reproducible. Employment and labour practices are also generally more restrictive than in Ford's time, though the increasing use of part-time and agency-supplied temporary workers may reintroduce a degree of staffing flexibility. Despite these possible restrictions, systems design should nevertheless consider normal production variation and accommodate it. All too often the operations research models developed emphasise narrowly defined variants or relatively slightly improved solution procedure (Mitroff and Silvers 2010). Multiple lines could provide flexibility as they did for Ford. Although Ford's lines were all identical, there is no reason that lines necessarily should be. Imbalanced lines could be considered in which producing the minimum demand is optimised, and then suitable additions to that; or additional lines, up to the maximum, designed so that the overall costs are minimised for a desired effectiveness in matching production to sales. In an increasingly competitive environment, line balancing also needs to consider the line's role within the supply chain and how production needs to adapt to unexpected fluctuations. Flexibility as well as efficiency needs explicit consideration.

Acknowledgements

The author acknowledges the financial support of the Carnegie Trust for the Universities of Scotland, and the Benson Ford Research Centre and the archivists of the Ford Motor Company for granting access to their records.

References

Abernathy, W. J. 1978. *The Productivity Dilemma Roadblock to Innovation in the Automobile Industry*. Baltimore, MD: Johns Hopkins University Press.

Agnetis, A., A. Pacifici, F. Rossi, M. Lucertini, S. Nicoletti, F. Nicolò, G. Oriolo, D. Pacciarelli, and E. Pesaro. 1997. "Scheduling of Flexible Flow Lines in an Automobile Assembly Plant." *European Journal of Operational Research* 97: 348–362.

Arnold, H. L., and F. L. Faurote. 1915. *Ford Methods and the Ford Shops* (Reprinted 1972). New York: Arno Press.

Babbage, C. 1835. *On the Economy of Machinery and Manufactures*. London: Charles Knight.

Battaïa, O., and A. Dolgui. 2013. "A Taxonomy of Line Balancing Problems and their Solution Approaches." *International Journal of Production Economics* 142 (2): 259–277.

Biggs, L. 1984. *Beat of the System*. BBC 2 Broadcast and BBC Educational and Training Video, London. Accessed May 7, 2013. www.youtube.com/watch?v=JgvYGi5J-Cg

Boudie, A. 1958. *Interview*. Accession 65, Box 7J; Archives, Benson Ford Research Center. Dearborn, MI: Henry Ford Museum & Greenfield Village.

Boysen, N., M. Fliedner, and A. Scholl. 2007. "A Classification of Assembly Line Balancing Problems." *European Journal of Operational Research* 183 (2): 674–693.

Cooper, C. C. 1981–82. "The Production Line at Portsmouth Block Mill." *Industrial Archaeology Review* 6: 28–44.

Cooper, C. C. 1984. "The Portsmouth System of Manufactures." *Technology and Culture* 25: 182–225.

Erel, E., and S. C. Sarin. 1998. "A Survey of the Assembly Line Balancing Procedures." *Production Planning and Control* 9 (5): 414–434.

Evans, O. 1834. *The Young Mill-wright & Miller's Guide* (Reprinted 1989). New York: Arno Press.

Ford, H., and collaboration with S. Crowther. 1924. *My Life and Work*. London: William Heinemann.

Ford, H., and collaboration with S. Crowther. 1926. *Today and Tomorrow*. London: William Heinemann.

Ford Times 1914. *Cutting down costs* 8 (2): 75–77.

George, Claude S., Jr. 1972. *The History of Management Thought*. Englewood Cliffs, NJ: Prentice-Hall.

Gibson, J. E., and N. Mahmoud. 1990. "The Moving Assembly line: Real Productivity Improvements Produced." *Journal of Manufacturing and Operations Management* 3 (4): 293–307.

Gilbert, K. R. 1965. *The Portsmouth Block-making Machinery*. London: Her Majesty's Stationery Office.

Gökçen, H., A. Kürşad, and R. Benzer. 2006. "Balancing of Parallel Assembly Lines." *International Journal of Production Economics* 103: 600–609.

Gökçen, H., Y. Kara, and Y. Atasagun. 2010. "Integrated Line Balancing to Attain Shojinka in a Multiple Straight Line Facility." *International Journal of Computer Integrated Manufacturing* 23 (5): 402–411.

Gunther, R. E., G. D. Johnson, and R. S. Peterson. 1983. "Currently Practiced Formulations for the Assembly Line Balance Problem." *Journal of Operations Management* 3 (4): 209–222.

Hounshell, D. 1984. *From the American System to Mass Production 1800–1932*. Baltimore, MD: The John Hopkins University Press.

Kara, Y., H. Gökçen, and Y. Atasagun. 2010. "Balancing Parallel Assembly Lines with Precise and Fuzzy Goals." *International Journal of Production Research* 48 (6): 1685–1705.

Klann, W. C. 1955. *Reminiscences*. Accession 65, Box 21, Folder 10, Archives, Benson Ford Research Center. Dearborn, Mi: Henry Ford Museum and Greenfield Village.

Lewchuk, W. 1987. *American Technologies and the British Vehicle Industry*. Cambridge: Cambridge University Press.

Lusa, A. 2008. "A Survey of the Literature on the Multiple or Parallel Assembly Line Balancing Problem." *European Journal of Industrial Engineering* 2 (1): 50–72.

Meyer, S., III 1981. *The Five Dollar Day*. Albany, NY: State University of New York Press.

Mitroff, I. I., and A. Silvers. 2010. *Dirty Rotten Strategies: How We Trick Ourselves and Others into Solving the Wrong Problems Precisely*. Stanford, CA: Stanford University Press.

Nevins, A., and F. Hill. 1954. *Ford: The Times, The Man, The Company*. New York: Scribner.

O'Brien, A. P. 1997. "The Importance of Adjusting Production to Sales in the Early Automobile Industry." *Explorations in Economic History* 34 (2): 195–219.

Ozbakir, L., A. Baykasoglu, B. Gorkemli, and L. Gorkemli. 2011. "Multiple-colony Ant Algorithm for Parallel Assembly Line Balancing Problem." *Applied Soft Computing* 11 (3): 3186–3198.

Özcan, U., H. Gökçen, and B. Toklu. 2010. "Balancing Parallel Two-sided Assembly Lines." *International Journal of Production Research* 48 (16): 4767–4784.

Piore, M. J., and C. F. Sabel. 1984. *The Second Industrial Divide*. New York: Basic Books.

Quadt, D., and H. Kuhn. 2007. "A Taxonomy of Flexible Flow Line Scheduling Procedures." *European Journal of Operational Research* 178: 686–698.

Raff, D. 1996. "Productivity Growth at Ford in the Coming of Mass Production: A Preliminary Analysis." *Business and Economic History* 25 (1): 176–185.

Raff, D. 2003. *What Happened at Highland Park?*. Washington, DC: National Bureau of Economic Research.

Salveson, M. E. 1955. "The Assembly Line Balancing Problem." *Journal of Industrial Engineering* 6 (3): 18–25.

Scholl, A., and N. Boysen. 2009. "Designing Parallel Assembly Lines with Split Workplaces: Model and Optimization Procedure." *International Journal of Production Economics* 119: 90–100.

Süer, G. A. 1998. "Designing Parallel Assembly Lines." *Computer and Industrial Engineering* 35 (3–4): 467–470.

Sward, K. 1948. *The Legend of Henry Ford*. New York: Rinehart.

Tolliday, S., and J. Zeitlin. 1992. *Between Fordism and Flexibility*. Providence, RI: Berg.

Weick, K. E. 1984. "Small Wins." *American Psychologist* 39 (1): 40–49.

Wild, R. 1972. *Mass Production Management*. London: John Wiley & Sons.

Williams, K., C. Haslam, and J. Williams. 1992. "Ford versus 'Fordism': The Beginning of Mass Production." *Work, Employment and Society* 6 (4): 517–555.

Williams, K., C. Haslam, J. Williams, A. Adcroft, and J. Sukhdev. 1993. "The Myth of the Line: Ford's Production of the Model T at Highland Park, 1909–16." *Business History* 35 (3): 66–87.

Wilson, J. M. 1995. "Henry Ford's Just-in-Time System." *International Journal of Operations and Production Management* 15 (12): 59–75.

Wilson, J. M. 1996. "Henry Ford: A Just-in-Time Pioneer." *Production and Inventory Management Journal* 36 (2): 26–31.

Wilson, J. M. 1998. "Measuring Myths: Cost Reductions and the Model T; The Assembly Line and Other Sources." *Production and Operations Management Society Conference*, Santa Fe, NM.

Wilson, J. M. 2011. "Reconsidering Ford's Highland Park Assembly Line: New Data vs. Old Ideas." *Academy of Management Best Papers Conference Proceedings*, San Antonio, TX.

Wilson, J. M. 2013. "Flexible Fordism as a Business Model." *The Association of Business Historians Conference*, Preston, England.

Wilson, J. M., and A. McKinlay. 2010. "Rethinking the Assembly Line: Organisation, Performance and Productivity in Ford Motor Company, c. 1908–27." *Business History* 52 (5): 760–778.

Womack, J. P., D. Jones, and D. Roos. 1990. *The Machine That Changed the World*. New York: Scribners.