Henry Ford vs. assembly line balancing

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1. Introduction

Assembly lines have been a significant development for managing operations-- a mode that allows high-volume, low-cost standardized 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 (Erel and Sarin, 1998; Boysen, Fliedner and Scholl, 2007; Wild, 1972) with many variants and extensions of the basic model. These analyses have focused on maximizing 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 practicing managers were unfamiliar with the relevant theoretical developments. They also noted that managers often considered broader issues than simple line optimization; 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;

George, 1972; Hounshell, 1984; Nevins and Hill, 1954) 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; and 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 formalized, 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 optimized 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).

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 work-stations rather than entirely separate lines. An overview of 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 formalized with solution procedures developed by Gökçen, Kürşad and Benzer (2006), Scholl and Boysen (2009) and Ozbakir, Baykasoglu, Gorkemli and Gorkemli (2011). These treatments focus on maximizing the efficiency of the lines, without regard to their role within an extended supply chain. They recognize 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 organization'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, et al. (2010) but flexibility has not yet been treated as a goal within model formulations, as Wilson (2013) suggests a broader definition of organizational goals would require. Indeed, we will later argue that minimizing 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 work stations, 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) formalized existing practice by mathematically defining existing policies. He made no claim to identifying the objectives, or to being the first to recognize 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 work stations 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 Oliver Evans's (1834) fully mechanized 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 mechanized 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 (Cooper, 1981-2, 1984; Gilbert, 1965) designed by Marc Isambard Brunel, Samuel Bentham and William 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, §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 type-setting before the debates being reported upon had concluded. Publication could then begin once the final part had been typeset, and was much faster than if their whole report needed type-setting.

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 minimizing it was a seminal contribution. He simply formalized 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 (1914) describe an experimental line, with workers spread along the length of a work bench, with the division of work and number of workers/work-stations 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 work-stations. 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 Silver, 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 maximize 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 (Gibson and Mahmoud, 1990;

Lewchuck, 1987; Williams, et al. 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 were 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)

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 stabilized, Ford and his engineers and managers began to realize 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.

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Wilson and McKinlay's (2010) most unexpected discovery was this large variability in production and sales -- a variability that earlier, annualized 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 optimized line balance then hours and staff would be stable, and inventories of 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 were followed there would be strong correlation between output, hours worked and staff with lower correlations of those to inventories 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 is erroneous.

Multiple lines gave Ford a degree of flexibility not previously recognized. 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. The ***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; with corporate history establishing their existence; and collaborated by other modern research.

5. Deskilling's Full Importance

Recognizing 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 specialization 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. Organizationally, 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 organization-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 13971 in February. The personnel office seemingly had the capacity for moving from the minimum staffing level up to the maximum (13971 – 9694 = 4277) within just 7 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 organizational capabilities fully supported the flexible use of multiple lines. Gökçen, et al. (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 maximize labor utilization on multiple lines (Gökçen, et al., 2006, Gökçen, et al., 2010, Kara, et al., 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 recognized by either the general operations research literature (Erel and Sarin, 1998; Boysen, Fliedner and Scholl, 2007) or historians (Hounshell, 1984; Lewchuck, 1987, Williams, et al., 1992; Williams, et al., 1993). The limited literature on the PALBP (Gökçen, Kürşad and Benzer, 2006; Scholl and Boysen, 2009; Ozbakir, Baykasoglu, Gorkemli and Gorkemli, 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 sub-system 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" minimizing balance delay.

Gökçen, et al. (2006) note that the ALB problem generally deals only with single-sided lines; i.e. where a work station consists of just one set of tasks undertaken on one "side" of a line. In Özcan, et al.'s (2010) two-sided formulation, work stations 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, 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) hypothesized 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 re-designed 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. Over-time might be used to run a line an additional hour to increase nominal output by 2.5% (assuming a standard 40 hour 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 5 day work-week (40 hours nominal output) up to three shifts run continuously 7 days (168 hours nominal output).

Scheduling can allow a flexibility that the design cannot; but it has to be recognized 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 utilization 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 the lines all be the same. One possibility would be to design a line to satisfy a minimum specified or base-line demand at the lowest cost when run "normally"; and to have supplementary lines used for those periods when demand is greater than may be effectively accommodated through more intensive, over-time use. Line balancing could then optimize both the "base" level of production and consider various capacity increments and the most effective designs for overall performance. Gökçen, et al. (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 labor 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 emphasize narrowly defined variants or relatively slightly improved solution procedure (Mitroff and Silver, 2006). 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 optimized, and then suitable additions to that; or additional lines, up to the maximum, designed so that the overall costs are minimized 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.

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Table 1

Correlations

0.9816	Correlation of Production with Sales Jan., 1910- March, 1914
0.8857	Correlation of Production with Staff Jan., 1910- March, 1914
0.8756	Correlation of Production with Total Hours Jan., 1910- March, 1914
0.8900	Correlation of Sales with Staff Jan., 1910- March, 1914
0.8786	Correlation of Sales with Total Hours Jan., 1910- March, 1914
0.8132	Correlation of Production with Direct Hours Jan., 1910- March, 1914
0.9899	Correlation of Staff with Total Hours Jan., 1910- March, 1914
0.7977	Correlation of Production with Inventory Jan., 1910- March, 1914
0.8294	Correlation of Sales with Inventory Jan., 1910- March, 1914

Figure 1

Monthly Car Sales

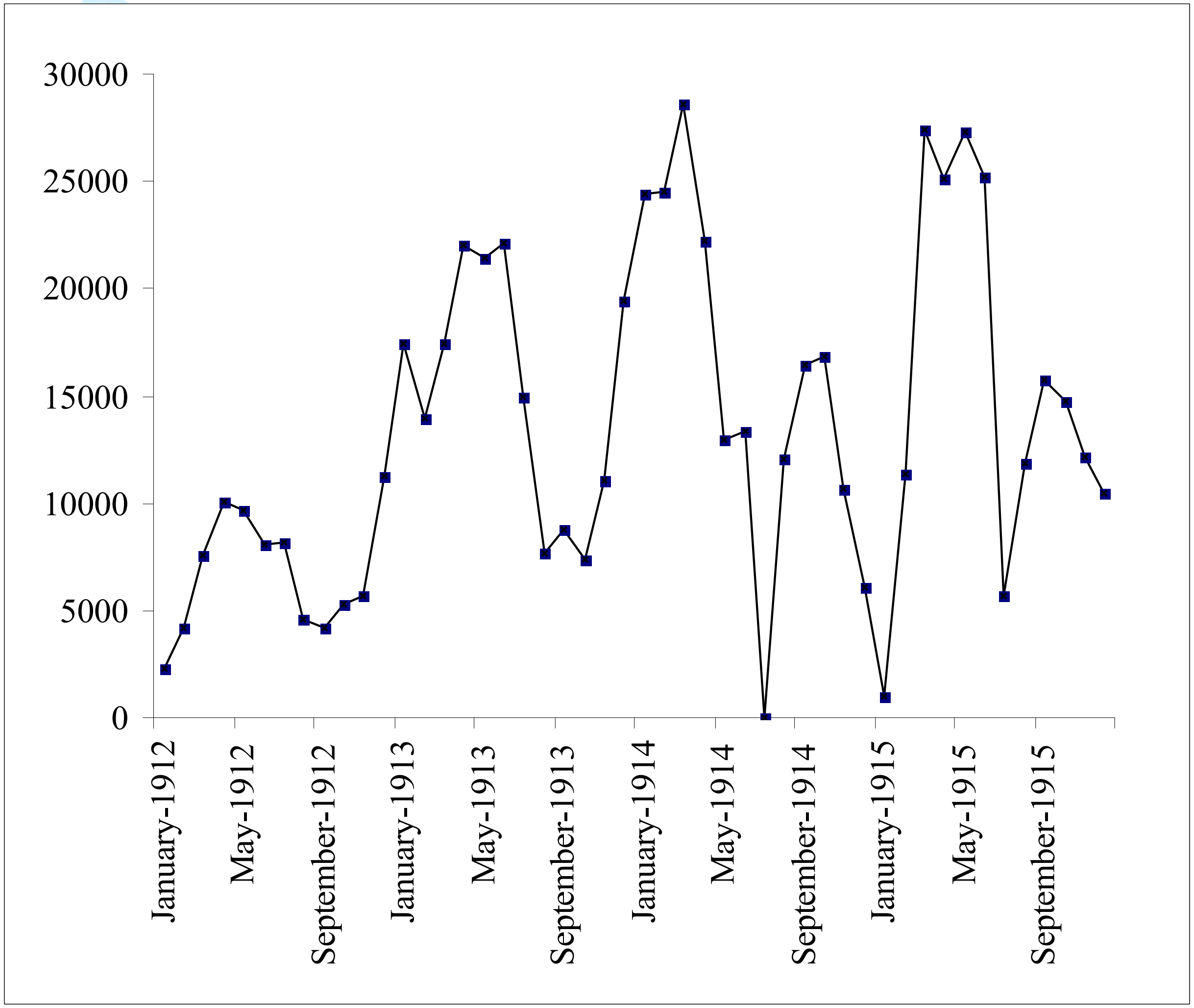

Figure 2

Production, Sales & Inventories