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Lean and Industry 4.0—Twins, Partners, or Contenders? A Due Clarification Regarding the Supposed Clash of Two Production Systems

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Abstract

Although Lean manufacturing techniques are not yet in place in every shop floor production, the so-called Smart Factory with the very promising German-coined label "Industry 4.0" is already making its tour. While the Toyota Production System (TPS) has shown to be the most performant manufacturing system, the Industry 4.0 initiative is still in the scoping phase with the demanding goal to become a highly integrated cyber production system. The partial and often limited knowledge about Lean production leads to distorted ideas that the two approaches are incompatible. In order to eradicate wrong statements, this paper tries to explain what Lean really is and how it has to be considered in the context of the Industry 4.0 initiative. Further, it discusses the existing contradiction within the Industry 4.0 goals regarding manufacturing performance and break-even point.

Keywords

Toyota, Production System, Lean, Industry 4.0, Smart Factory, Performance

1. Preface

This paper bases on the well received presentation "From Lean to Industry 4.0: An Evolution?—From a Visionary Idea to Realistic Understanding" held at Fertigungstechnisches Kolloquium (Industrie 4.0—Industrie 2025) organized by the Institute for Machine Tools and Manufacturing (IWF) of ETH Zürich, November 26, 2015 [1]. The high interest for the presentation and the discussion documented that "Industry 4.0" is a fuzzy term and that the topic is poorly understood by the audience. But what is usually understood by the catchword "Industry 4.0?" The following are usually cited (without commenting the correctness):

-new products and new services

-new business models

-internet of things (IOT)

-big data

-self-scheduled maintenance

-virtual reality/augmented reality

-fully automated production

This paper does not pretend to be a comprehensive scientific essay about Lean or Industry 4.0; it rather gives some ideas and concepts about Lean and the place Industry 4.0 might take within Lean. It is neither a position paper defending Lean manufacturing nor an essay promoting the Industry 4.0 initiative. It is just an essay having the intention to clarify basic concepts to eliminate wrong ideas about what Lean is in order to facilitate the correct relationship between the Industry 4.0 initiative right from the beginning. In the following, we will focus on the manufacturing performance dimension of the Industry 4.0 initiative.

2. Introduction

The term Industry 4.0 has been coined at the 2011 Hannover Fair, a concept better known as the "Smart Factory". The 4.0 makes reference to be a forth industrial revolution to come. The first industrial revolution is generally considered to be the steam machine which made the steam power exploitable opening the industry age. The second industrial revolution is generally seen as the discovery, or better the application, of electricity and how to use it, namely allowing automotive mass production. The third industrial revolution is generally linked to the computer and the possibility of data processing for computer integrated manufacturing (CIM), leading to the present era of information technology. These commonly used definitions of industrial revolutions were made retrospectively, *i.e.* are ex-post rationalizations. All these revolutions were linked to inventions based on break-through scientific discoveries (Watt, Tesla, von Neuman) with their first application opening new industries. Note that even real revolutionary inventions, such as Marconi's wireless telecommunication (Nobel prize in 1909) standing at the base of today's global communication, as well as derived possibilities of modern manufacturing supply chain control are not considered as revolutions for industry. Hence, the Industry 4.0 concept is not a technical revolution linked to a scientific break-through discovery, worse, it does even not exist yet.

However, it represents a politically established target for the producing industry—or vision if you will, intending to create an omnipotent cyber system, integrating different socio-techno-economic functions to allow fully automated production, integrated with the internet of things (IOT). Let us also clarify, already from the type of scientific discovery and technological application, *i.e.* from semantics of the word "revolution", that calling Industry 4.0 a revolution represents an inconsistency with the first three revolutions as it is a natural evolution of CIM, and it will rather materialize in small steps what could eventually be called V.3.1, V.3.2, etc. as additional features are implemented.

Apart from this misleading and inconsistent naming, which might be of negligible importance at the end of the day, as it is not influencing the aim of the project (but which nevertheless is of revolutionary importance for business), let us have a closer look at what Industry 4.0 consists of. In this paper we will consider the Japanese "e-factory", the Anglo-Saxon term "Smart Factory", as well as the Swiss terminology "Industry 2025", which sounds more appropriate, as synonyms for Industry 4.0.

The first position papers regarding Industry 4.0 are the result of German mixed industry-academics working groups posted on www.plattform-i40.de (e.g. [2] [3]) which give implementation guidelines and recommendations. Before starting with the Industry 4.0 adventure, however, let us step back to the industrial manufacturing requirements in order to get the whole picture. Indeed, in the next chapter, the paper outlines what the basic customer requirements are and, accordingly, how manufacturing systems have and may evolve. The third chapter describes the basic manufacturing performance parameters. The fourth and fifth chapter, respectively, explain what Lean and Industry 4.0 are all about. The sixth chapter, finally, deals with the comparative performance of different manufacturing systems, the domain of application and the analysis of break-even operation point. The paper intends to show that industry 4.0 will not make Lean obsolete, but that both manufacturing systems will generate a mutual dependency and have their specific domain of application regarding product variability and production volume.

3. Today's and Tomorrow's Production Requirements

The manufacturing performance of a production system, of course, has to meet customer requirements. Customer requirements are usually a set of different needs. Apart from product quality requirements to be mandatorily observed, there are also service performance requirements in terms of e.g. speedy as well as punctual deliveries to be observed. Along with the ordered quantity, the produced and supplied batch, as well as the variable manufacturing cost and the fixed cost structure, all these factors determine the profitability of the production system. The simplified representation and intrinsic dynamic behavior of the basic target system can be modeled with the SPQR-model [4], to which we refer in **Figure 1**, which is also discussed in [1] [5]. This simple model explains the systemic interactions between the main customer-perceivable performance variables Speed, Punctuality, Quality, and Return, *i.e.* price, with the systemic stakeholder variables customer, employee, and shareholder. It shows with the customer the most important element and with the employee the most vulnerable element, as well as the systemic effects on the other system variables [4]. These basic requirements can be considered to be time-invariant and constitute a sort of a minimal axiomatic system which has to be observed in any case to be successful in business (**Figure 1**).

On the other hand, the manufacturing techniques have evolved over time from artisanal production of the nineteenth century, to mass production of the twentieth century, to the present tendency of mass customization characterized by high variability and small quantity per product. In parallel, the production system itself has evolved

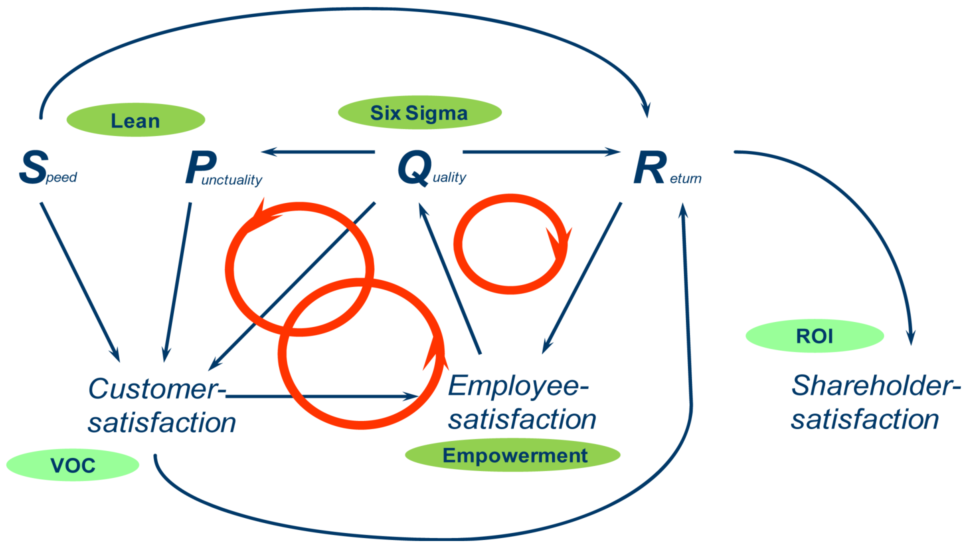


Figure 1. The SPQR model [4].

from "batch & queue" to "single piece" transfer-line manufacturing, to full automated manufacturing cells, complemented with lean manufacturing techniques following the Toyota Prodution System (TPS) [1] [5]. The supply chain integration extends lean concepts to the outbound logistics. Industry 4.0 on the other hand adds the Internet of Things (IOT) possibilities to an existing production system, in order to create an integrating cyber-physical dimension, to install a supply chain integrated and IOT-controlled manufacturing system.

The question is: where will the aggregated customer needs evolve to and which manufacturing system may ideally satisfy all axiomatic requirements in the future? The surging mass customization tendency reflects the base of a post-capitalistic society, where not the possession of an object as a status symbol stands in the foreground any more, but where the individual differentiation of products comes first. In a future, modern society, probably not the concept of possession will be in the focus anymore, but the utility of its use will stand in the foreground [1]; we refer e.g. to shared use of cars. Figure 2 shows that both requirements may be satisfied at the same time in the future, *i.e.* high-mix low-volume (individual manufacturing) as well as low-mix high-volume (mass manufacturing).

High customization, *i.e.* individual manufacturing, could mean, as described in the German "guidelines" [2] saying e.g. "…may give the possibility to assemble individual elements (Porsche seat) without problems…" (Figure 3(a)), not have priority any more in a sharing society, necessitating mass manufacturing according to Figure 2. Further it describes, "…such a high flexible production shall result in dynamic manufacturing lines, the car to be assembled going as a smart product through the manufacturing process".

However, we will see afterwards what such flexible options entail. The change of individual and social values may influence the future products and therefore most likely also the appropriate manufacturing system.

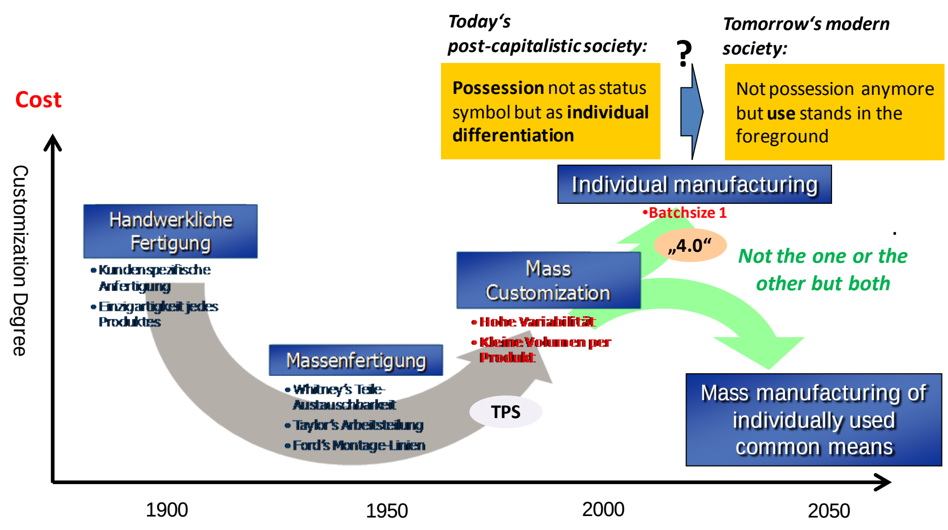


Figure 2. Evolving requirements and manufacturing systems [1].

Figure 3. Industry 4.0, the idea regarding manufacturing, excerpt from [2].

Moreover, the statement by a German politician (Figure 3(b)), that small and medium enterprises (SMEs) will benefit from Industry 4.0 is wishful thinking for two reasons: Firstly, due to the necessary high investment needed and the increase of the related operational break-even point (BEP) (see below), and secondly, the increased production flexibility will allow big companies to deal with smaller customized demands now usually met by SMEs. The interest of German industry for the Industry 4.0 initiative is huge due to the fact, that the government released 250 million funds to explore the potential; again, key partners of the 4.0 initiative are not SMEs but big multi-national enterprises (MNEs)!

4. Basic Manufacturing Parameters

In the following, we do not have the intention to explain manufacturing theory, but we will have a brief look at what the cardinal points are which influence manufacturing performance, because manufacturing performance is compulsory. According to the SPQR-model, performance indicators such as PLT (Process Lead Time), OTD (On-Time Delivery), Cpk with a certain, industry-specific sigma quality level are key. These KPIs are linked to two necessary conditions to respect OTD requirements.

The first necessary condition for OTD is that PLT has to be shorter than the expected delivery time (EDT) [6]. To shorten PLT, the work in progress (WIP) necessarily has to be reduced which leads naturally to a single piece flow (SPF) manufacturing organization and layout.

The second necessary condition for OTD is, that the process capacity is large enough to manufacture the order entry quantity; *i.e.* the exit rate of the manufacturing process, determined by the longest cycle time within the process (*i.e.* the so-called bottleneck), has to be greater than the aggregated sum of incoming order takt rate [6].

Other KPIs linked to a manufacturing system are e.g. OEE (Overall Equipment Effectiveness), MTBF (Mean Time Between Failure), MTTR (Mean Time To Repair), die set-up time (also called change-over time), and of course operation cycle time (CT), *i.e.* value-add and non value-add time (Muda). Further, balanced characteristics of the operations in a transfer line or manufacturing cell, as well as reduced CT variability influence the exit rate (ER) of the whole process. Each manufacturing system, manual or automated, has to be tested against these performance parameters. These are pure technical manufacturing parameters. The economic parameters related to the physical capacity and financial aspects will be dealt with later.

Moreover, many manufacturing systems are still based on the traditional B&Q (Batch and Queue) manufacturing instead of a SPF (Single Piece Flow). SPF, where applicable, has a considerable shorter PLT compared to manufacturing systems based on B&Q scheduling. The transformation from an MRP-scheduled B&Q to a customer-pull triggered SPF is therefore one of the reasons to apply Lean techniques, which optimize the whole production system; ideally said: to achieve OTD, lean self-controlled pull-scheduling has replaced computer-based central ERP-type push-scheduling.

5. What Lean Is All about

Lean Manufacturing (LM) is the American interpretation of the Toyota Production System (TPS) [7] given by Womack and Jones from the MIT [8] [9]. The TPS has been built up during several decades and was brought to perfection in the 1980ies [7] [10]. In the Western world, Lean is regrettably often reduced to the concept of Kaizen (the Japanese word for continuous improvement) and the elimination of Muda (the Japanese word for waste), which is by far too simplistic [11]. This trivialization may be, among others, one of the reasons why Lean usually is considered not to cope with the highly automated Industry 4.0 initiative.

Lean, however, is much more than Muda elimination, because Lean is in reality a comprehensive manufacturing theory which can even be modeled mathematically [6]. Furthermore, the TPS, modeled according to the iconic two-pillar "Temple" representation, often leads people to understand Lean as a toolbox from which to choose the appropriate "tools" needed. Pay attention, Lean is not a toolbox, Lean is a synergic tool system [11]! To overcome this deficiency and to emphasize that Lean is a theory composed of synergic elements with several Lean techniques to model and implement a comprehensive manufacturing system, a new systemic representation of Lean has been conceived with a systemic mono-pillar model (Figure 4).

This model explains that in order to have a smooth functioning and reliable SPF, several prerequisites, such as Standard Work, TPM, Poka Yoke techniques have to be put in place. Please note, SPF in its original interpretation, was not invented by Toyota; indeed it exists since the production of the Ford T-model. SPF has many advantages and supports maximizing the output of a production system. This clearly shows that certain manufacturing principles are necessary to speed-up production output and are prerequisites for a highly efficient production system. However, having an SPF does not mean to have Lean implemented. Nevertheless, while SPF is meanwhile an established technique in automotive transfer line manufacturing industry, SPF has been or is now being introduced in several other industries, namely electronics (where it is already a

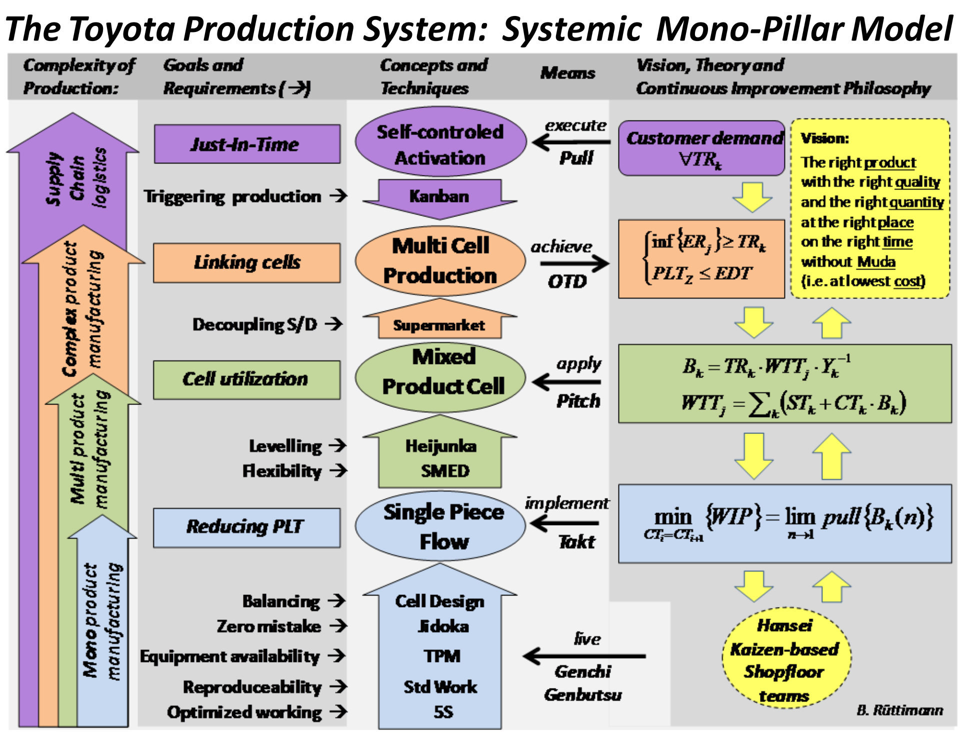


Figure 4. Systemic working mechanism of lean (adapted from [1] [11]).

reality), or other assembly-based industries as well as mechanical manufacturing. Indeed, SPF will boost performance, reducing WIP and shorten PLT, improving quality to meet JIT requirements and therefore increases competitiveness. Lean goes even further: it is meant to increase utilization of equipments within cell manufacturing and to allow flexible production of several products within the same cell, mixed product cells are established with Heijunka leveled production pitch to achieve JIT delivery (**Figure 4**).

For complex products to be manufactured in different cells, these cells are linked together via strategic buffers to form multi cell production systems (**Figure 4**). These strategic buffers called "supermarkets" serve only to decouple demand and supply, *i.e.* downstream from upstream, because of different cycle time characteristics, linking the manufacturing cells to form an integrated production line. These cells in certain realities are already linked via AGVs (Automated Guided Vehicles). The whole system is conceived to comply to a customer-pull triggered Kanban to achieve a JIT supply. As from **Figure 4** emerges, at the base of Lean stands a comprehensive manufacturing theory.

Apart from the theoretical manufacturing aspects of Lean, Lean is also a manufacturing philosophy of continuous improvement, called Kaizen. Kaizen is performed in self-directed teams, *i.e.* on the shop floor level, to strive to the learning organization.

While the TPS puts crucial importance to reduce IT dependence (think of the manually managed Kanban cards for self-controlled cell production decoupling non-synchronized manufacturing cells), Industry 4.0 tries to integrate every available shop floor information via IT already with the incoming orders in the supply chain management (SCM). The strong IT-focus might be one of the origins leading to the presumed inferiority of Lean compared to the Industry 4.0 initiative. But exactly this concern is unfounded. In many companies Kanban cards were substituted by RFI (Remote Frequency Identification) controlled withdrawal for certain applications in recent years, but the concept of Kanban remains. Furthermore, Lean has long ago reached outbound logistics (to assure JIT supplies) and the original concept of e-factory goes back to the year 2003 (Mitsubishi).

In short, we can state that Lean can be described with the following two characterizations:

-most performant manufacturing theory

-human-based continuous improvement approach.

Therefore, instead of associating Lean with trivial Kaizen and Muda, it is better to define Lean as the systemic view of "a Kaizen-based JIT-production" [11]. This definition covers the dichotomic aspect of the TPS: it relates to the underlying best performance manufacturing theory as well as the continuous improvement management philosophy of operational excellence striving for perfection.

6. In a Nutshell: What Does Industry 4.0 Represent

As already stated, Industry 4.0 is not the latest existing industry revolution, but an ambitious project strongly supported by the German government; we will therefore rather talk more appropriately about the Industry 4.0 initiative. First books about the Industry 4.0 topic are appearing (e.g. [12] [13]). Nevertheless, they have introductory character showing that the topic itself has to be explored at first. Until now, nothing more than partial implementations are existing, while the bulk of scientific publications are in the field of IOT. Figure 5 shows a derived simplified but necessary roadmap and structure in order to be successful with the Industry 4.0 initiative. It clearly shows the necessity to get clarity about the requirements and constraints of the system before developing the subsystems. N.B. we are already in the phase of developing the subsystems without having clarified the domain of application. Further, Industry 4.0 will not materialize such as "deus ex machina", it will rather develop from "version to version". Standardization and internet security will be one of the biggest challenges; however, in the following, we will touch the aspect of the routing and scheduling control, influencing the performance aspect of manufacturing systems and show that certain objectives may have to be revised.

One of the main aims of the Industry 4.0 initiative is to integrate the IOT into the manufacturing system, *i.e.* the next generation of supply chain management SCM with physical shop floor scheduling forming a sort of Cyber Physical Production System (CPPS) as depicted in Figure 6. Instead of basing on MRP/ERP scheduling of B&Q systems or customer-pull JIT SPF lines, the aim is to make the scheduling interacting with the IOT SCM to allow a smooth, app and internet-based production scheduling matching incoming material and arriving orders with the maximum flexibility [3]. This governance may also be transferred to the inbound logistics of available work stations and WIP ready to be processed. In this case the manufacturing system necessitates a dynamic programmable routing of products and orders via fully AGV connecting different addressable autonomous equipment and workstations to become a fully flexible manufacturing area. These workstations need to be interlinked by an optimized network-like modeled structure representable with CPM, PERT, or Petri net dynamics as well as some suitable Operations Research approach of graph optimization. How the governing of the whole system will be implemented, either by decentralized neuronal algorithms or completely centralized is still open; in any case a centralized control of all optimization algorithms has to be implemented in order to assure at least Pareto efficiency of the system.[1]

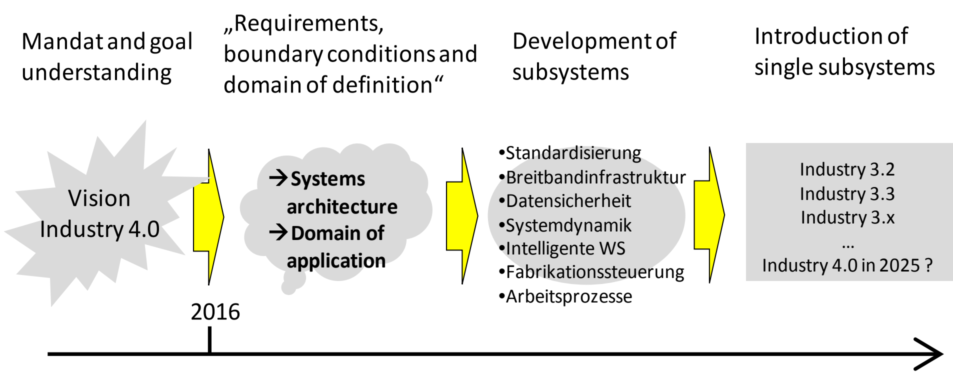


Figure 5. The industry 4.0 journey [1].

[1]Pareto efficiency, also called Pareto optimality, is a state of dominant solutions within a domain of possible solutions in which it is not possible to improve a characteristic or objective function without worsen another characteristic or objective function at the same time.

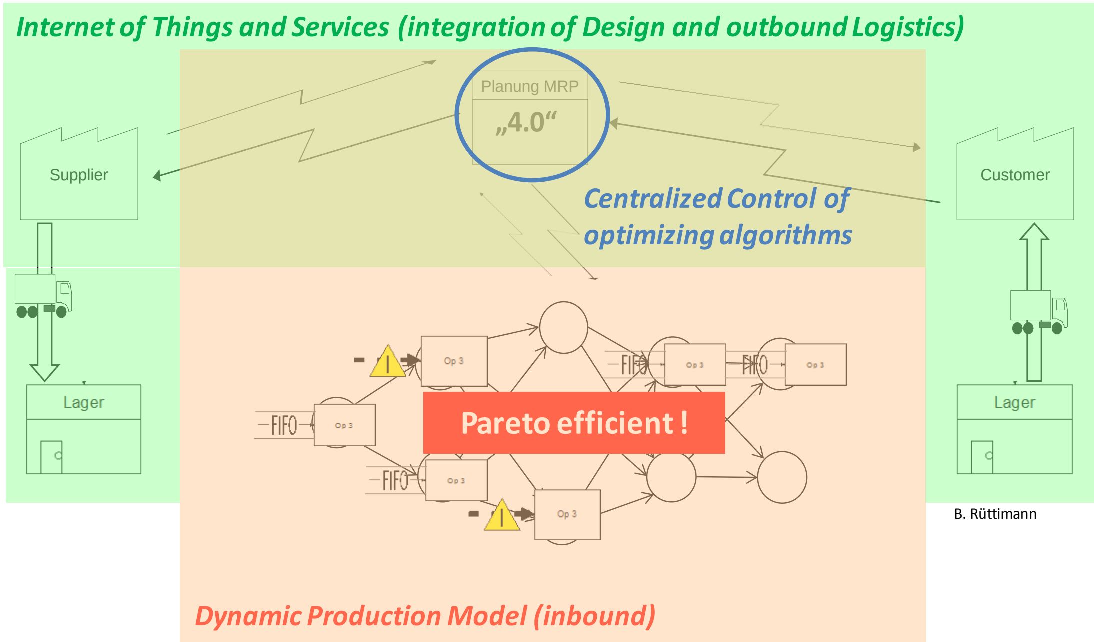


Figure 6. Two interacting main systems forming the CPPS [1].

In fact, engineers have to pay attention not to forget manufacturing performance requirements (e.g. ER, PLT, OTD) related objectives in the overall "equation system" as well as financial restrictions (investment amount). Apart of the technological challenge, this will become one of the biggest field of research. Indeed, the Pareto efficiency objective, which by the way could also be modeled as conditional requirement within a multi-objective system, is mandatory in a Muda-free approach and arises especially in programmable stochastic environments. In a deterministic environment the tautology of production laws assures implicitly Pareto efficiency.

Envisioning a CPPS seems to be a reasonable target, leading to a promising competitive advantage compared to present existing production systems. The potential advantage might be:

-higher flexibility (which is the aim of such systems), *i.e.* on the spot manufacturing to customer specifications

-potentially no waiting times for start of production

further

-"pull" potentially remains possible and is not compromised, although the scheduling will be "push" governed

-"flow" remains potentially possible although restricted by the smart product on AGVs with variable operation cycle times

-higher reaction speed (JIT may not mean on the hour anymore, but on the minute)

-full information on whereabouts of parts and machine breakdowns increases flexibility.

However, the performance concerns of such a CPPS, allowing stochastic mix variability, compared to present pure Lean JIT TFL according to the TPS at comparable capacity costs will most probably be:

-longer PLT (Process Lead Time)

-lower PCE (Process Cycle Efficiency)

-variable and therefore generally lower ER (Exit Rate), *i.e.* loss of capacity

-lower OEE' (corrected Overall Equipment Effectiveness, including the utilization rate)

-lower OTD (On Time Delivery).

The consequence of increased flexibility given by such an automated system will therefore be a decrease of the overall performance of the system measured in aggregated throughput and order-specific OTD. Performance issues, however, are the most challenging topics in today's global competitive environment and have to be considered when planning a manufacturing system. In fact, the dreams of engineers have to face up to economic restrictions of competitiveness performance as we will see.

Now, whether the technological progress eliminates the Kaizen-based approach depends also on the circumstances that blue collar workers are ideally no more needed in the remote future (final aim: "robots making robots"). For the time being the man-machine interaction is necessary and is pushed with touch-sensitive robots to limit injuries of operators integrated in a robotics dominated manufacturing cell (intermediate aim: "robots assisting man assembling robots").

Generally, or at least in the past, Toyota has been valuing people more than machines. Indeed, workers are learning day by day treasuring the experience contributing to the accumulated know-how to improve the system, whereas machines, becoming obsolete, have to be amortized and then replaced. This shows clearly the different value system of Japanese compared to Western management. Whether or not a highly motivated blue collar worker will maintain the dominance over a highly sophisticated cyber system is questionable—time will show. Indeed, we can also continue bringing Lean thinking to exaggeration and state: workers are not paid to assemble, workers are paid to improve the system and handle out-of-control situations. This statement might be considered to be heretic, but sharply thinking manufacturing professionals will understand.

Indeed, in the meantime certain complex assembly operations can also be performed by robots much better (if they have attained operational reliability, e.g. with Total Productive Maintenance approach, TPM). But until a cyber system is able to solve autonomously different problems by having the flexibility of trained and motivated workers and technicians, production will continue to be based on blue collars. Until self-learning systems will be reality and become reliable, with the present technology of "wired logic" and the need to forecast all potential out-of-control situations, it will be hard to have an omnipotent manufacturing system in some years; indeed, the system will most probably become unflexible. But exactly flexibility (of course restricted flexibility within the planned "wired" variability of products), actually, is the strong point of the customer-pull driven TPS manufacturing that addresses quick changes of demand (SMED setup technique).

7. Systems Performance and How Does Industry 4.0 Fit in

Of what does the performance of a manufacturing system consist? Among of the above mentioned KPI, the ER (the capacity of the manufacturing system), as well as PLT (the velocity to transit the manufacturing system) are key for OTD. Let us compare the performance of the main traditional manufacturing systems B&Q and SPF as well as the Industry 4.0-CPPS (**Figure 7**).

Through its powerful JIT organization of manufacturing cells, the SPF of Lean manufacturing systems allows to assure best OTD and short PLT for all product orders – one of the reasons for which it has been conceived. For a given product mix, through appropriate cell organization and staffing, ER can even become variable (volume elasticity) in order to face changing workload and to maintain PLT. This allows to reach the paramount objective of OTD for all products of the mix.

Traditional B&Q has a long PLT due to batching and the ER is given by the bottleneck equipment. Depending on the size of the batches WIP is generated, which prolongs PLT. Thanks to ERP planning systems, OTD may be reached, but the customer expected delivery time (EDT) may become an issue of negotiations.

As shown in **Figure 6**, the CPPS of Industry 4.0 tries to optimize production scheduling with the "announcing" of incoming orders and the availability of the pre-material and semi-finished goods to achieve high flexibility and to optimize work load by maintaining a push scheduling. On the other hand, high product flexibility automatically entails high variability of CT at different machines and therefore a variable bottleneck which opens an additional complexity grade. High performance of short PLT will be possible for some single orders, but will be difficult to be realized for the whole order backlog. And exactly that is the issue of Industry 4.0 according to the simplified concept represented in the Industry 4.0 future state of **Figure 3(a)**. Even if we hypothesize a central takted line (as the reality may look like) with automatic activated side-cells, the ER will diminish. Optimization algorithms may maximize load or shorten PLT, or both by trying to attain Pareto efficiency, but they cannot change physical constraints. High unused costly capacity may be the price for achieving high flexibility

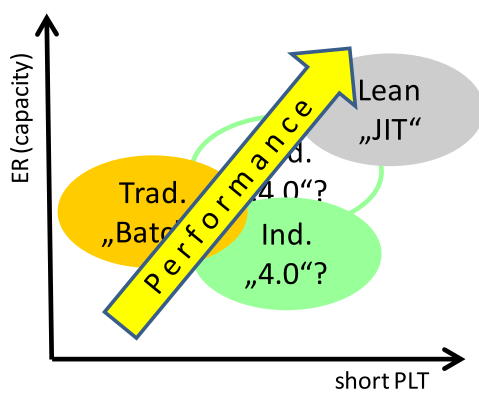


Figure 7. Comparison of manufacturing systems and performance (adapted from [1]).

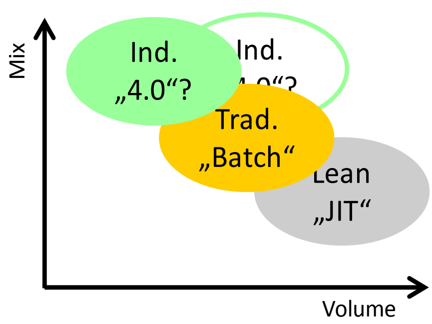
what makes it difficult to have an acceptable ROI whereas the WIP will be maintained at acceptable level via sophisticated scheduling algorithms. Performance defined along these lines will leave the first place to Lean JIT manufacturing systems.

These performance insights lead to consider the field of applications of the different manufacturing systems. For simplification, if we take the two main axes for manufacturing systems classification, *i.e.* mix and volume (Figure 8(a)), it shows that the various manufacturing systems show different field of applications to exploit their advantages; Industry 4.0 flexible production rather in the high-mix low-volume quadrant, and Lean JIT transfer lines rather in the low-mix high-volume quadrant. Of course the potential domain of application of the CPPS, not existing yet, is subject to estimation. However, it shows that every system has its domain of existence. Figure 8(b) shows the relative positioning of manufacturing systems regarding to mix flexibility and volume elasticity. Certainly, the positioning may vary, but the performance of the respective system would change too. Through its job-shop characteristic, B&Q shop floor organization might show the highest flexibility, eventually equalized by the 4.0 CPPS, but this needs still to be proven.

To the pure technical engineering categorization of different manufacturing systems we have to add the economic dimension into the "check and balance" view in order to be also practically viable. Today's high automated transfer lines are high performance lines, but show only limited possibility for volume elasticity and mix variation, and the mix has to be known in advance to be manufactured (deterministic mix). Exactly this "wired logic" of mix in lean high performance lines with limited flexibility at low production costs is intended to be substituted by a "programmable logic" of the Industry 4.0 initiative with high flexibility (stochastic mix) and consequent high production cost.

Automated technology is costly and the envisaged CPPS shows even more technology, fuelling investments. Contrary to the promotion stated by a German politician targeting SME in Figure 3(b), SMEs will hardly be able to make such high investments, it will mainly be the MNEs that will introduce CPPS and potentially, as it is represented by the envisaged flexibility in Figure 3(b), invade SME niches.

Capital intensity usually goes along with high productivity and therefore a break-even point (BEP) analysis is needed (Figure 9). Figure 9 shows that the CPPS of



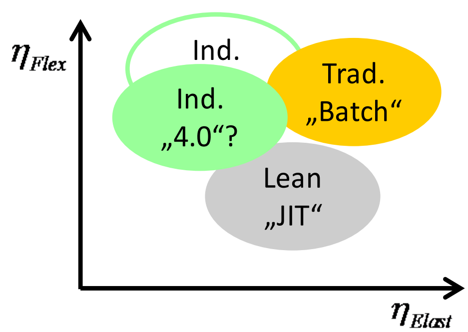


Figure 8. (a) (b) Manufacturing systems and field of applications (adapted from [1]).

Industry 4.0 plays in the high-volume region, which stands in contrast to the low-volume classification of Figure 8 as well as for elasticity consideration of such highly variable systems. This is a contradiction compromising the final aim of Industry 4.0 to have highest flexibility at lowest cost! Economic thinking has to be integrated into pure technical aspects to let Industry 4.0 materialize as an improvement of the current systems. First critical reflections are beginning to make their tour (e.g. [14]).

At the end, this leads to the question: are CPPS and Lean incompatible? No—they are not. What is important is to think about the Lean theory intended as the manufacturing system's performance as depicted in Figure 4 to be integrated into CPPS control algorithms, being Lean JIT the highest performance system, at least today. The CPPS should be an extension to Lean outbound logistics, integrating upstream and downstream logistics exploiting the web potentiality as well as reconsider Lean flow.

Toyota sparked an industry revolution by demonstrating how to manufacture efficiently with respect to performance and cost. CPPS rather than being a revolution, it will be a natural evolution. Whether it does work according to the expected performance, depends also how Lean mathematical theory will be incorporated!

Indeed, the complexity of the Industry 4.0 initiative does not lie in the technical multidimensionality alone, but also in the logic restrictions given by production theory of high performance systems. Currently, Industry 4.0 emerges in this respect as the temptation of the quadrature of the circle, *i.e.* to combine high flexibility with high performance: the lean theory of Toyota tried to reduce variability in its scheduling (Heijunka pitch) to maximize output while Industry 4.0 increases exactly the variability. More than the search for an omnipotent solution, reality will rather materialize with parallel existing manufacturing systems with more or less CPPS components (Figure 10).

"Industry 4.0" per se will materialize anyway, with or without this initiative, in fact, digitalisation in the industry has long begun and is still in progress. Certainly, it is the connection, the availability, and the processing of the data that makes the difference in the future. Critical minds might therefore even say that Industry 4.0 is a self-fulfilling prophecy to a certain degree and will not come up to the great expectations it raises.

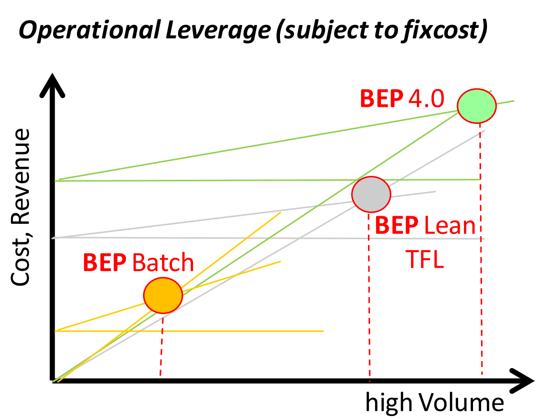


Figure 9. Manufacturing systems and break-even point (adapted from [1]).

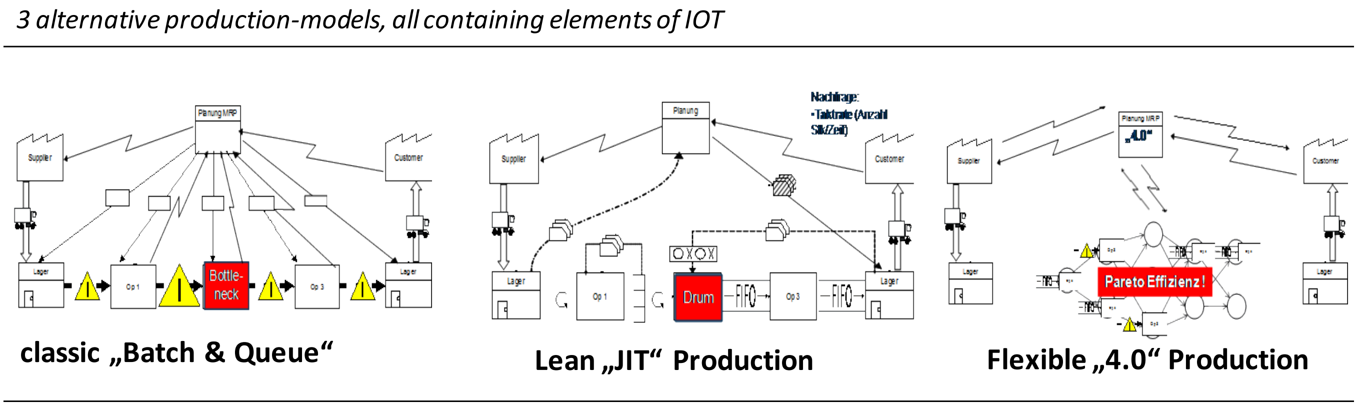


Figure 10. The three main coexisting alternative manufacturing models [1].

8. Conclusions

Industry 4.0 is an initiative which technological development and how it affects present manufacturing systems needs to be understood first. Industry 4.0 will not materialize as a revolution, but in pieces which have to be integrated into the comprehensive Lean theory framework. The presently experienced non-focused activism is likely to fail to meet the high expectations set into Industry 4.0 also due to a lack of a clear definition and unclear understanding of manufacturing performance laws and therefore it represents an unrealistic goal at this point in time. With all its potential, although artificial intelligence algorithms, object oriented programming languages, computational power, sensors and actuators, virtual and augmented reality in 2D and 3D, etc. which have tremendously increased in performance, but none of these components can go against theoretic manufacturing restrictions.

Therefore, the Industry 4.0 initiative as a whole has a high probability to fail, such as cybernetics in the sixties trying to automate socio-economic systems, if it is not put into the right context by considering fundamental manufacturing laws. The latter describe how performance changes with increased variability of products manufacturing content and related variability regarding cycle time of work stations; Industry 4.0 manufacturing therefore has to find the right domain of application. Indeed, as per 2016, omnipotent Cyber Physical Production System CPPS have the flavor of “dreams of engineers” supported by “governmental benevolence”, due to the lacking of basic knowledge about manufacturing requirements of performance and investment restrictions. The right applicability is key and how to integrate the CPPS in the Lean theory. Industry 4.0 is the topping on that cake. It makes Lean Production more flexible; whether it makes it faster, smoother, and more stable and more accurate has to be proven. Further studies need to analyze the influence on performance variables by increased mix variability and the necessary capital investment to implement an industry 4.0 shop floor.

Our message in a nutshell: “Industry should learn to walk first before it may dream of flying. Indeed, in 2016, in many real existing cases, industrial manufacturing systems are still stumbling”.

Whether or not enterprises will survive depends at the end heavily on manufacturing cost and performance. Production managers are well advised to implement the Lean transformation to their companies now instead of waiting for the promised land of Industry 4.0.

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