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Elements of Advanced Manufacturing Theory

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Es gibt nichts Praktischeres als eine gute Theorie
(There is nothing more practical than a good theory)

Immanuel Kant

Foreword

This book on advanced manufacturing theory can be seen as addition and extension to the previous book of the authors with the title "Lean Compendium—Introduction to Modern Manufacturing Theory." It still is devoted to the slogan "Fabricare necesse est—but how?" All envisaged changes with respect to environmentally friendlier societies require novel infrastructure and new devices. A rapid change as it is required to fight climate change is still mainly hindered by production capacities. Not individual pieces are requested, but square kilometers of PV panels and of bipolar plates, etc., need to be manufactured, requiring highly efficient production sites with clear knowledge where the limiting bottlenecks are and how to maximize the throughput.

In this context, it must be mentioned that each manufacturing that stays within high wage countries is an active contribution to environmental protection in double respect, as transportation is reduced and production takes place under environmentally friendlier conditions. Also the crisis of raw materials hitting the industrial world in 2021 hopefully triggers a rethinking on global sourcing, i.e., insourcing instead of outsourcing, rising up the question how can production be realized under the severe cost pressures in the global competition. Manufacturing is the most challenging task in industry, because a large number of influences need to be taken into account. It is the complexity of production, lack of strict scientific approaches, number of influencing variables, restrictions, interrelations, knowledge, and experience including aspects of finances, resources, people, and technologies which makes seeking for optimal solutions in production so difficult. The supply crisis clearly teaches that optimization toward a single business environment leads to a high degree of vulnerability of the company and must be seconded by a strategy for enhancing the robustness. This introduces as an additional requirement the long-term survivability of manufacturing organizations in cases of fast-changing environments.

New technologies like the digitization, digital twins, and cyberphysical production systems (CPPS), the convergence of different data sources for increasing information value and role specific for everyone enables faster and more precise interaction and also unprecedented far-reaching possibilities to increase automation. On the other hand, beneficial new technologies introduce additional challenges, because due to global competition it becomes indispensable to rapidly adopt and exploit them. Therefore, manufacturing systems range among the most complex man-made systems, and the complexity seems to persist. It is this complexity that makes manufacturing susceptible to fashions, and there are quite some companies that have been restructured forth and back several times. Also it has been observed that due to the outsourcing fashion, some companies have reduced or closed their manufacturing without any real need.

Now, the value of this book is to set up a scientifically based theory of manufacturing named "Cartesian approach," removing manufacturing away from opinions and fashions. This approach also enables to really understand the behavior of manufacturing systems. While simulations are valuable tools for describing manufacturing systems, they only provide the behavior of the simulated system within the boundary conditions used for the simulation. An understanding and even more an optimization on this basis is possible only with organized multiple simulations. But because it is difficult to model complex dynamic systems with simple equations, applied system behavior-exploring discrete event simulation prevails today over manufacturing theory development.

The theorem- and law-based approach of the first book on lean manufacturing is herewith continued and applied to production systems governed by push control, which from the point of view of planning and mastering to optimality is much more challenging than a pull approach.

To dive into the topic of manufacturing, especially also for students of the topic, it is much easier if a framework theory exists acting as guideline according to the famous slogan of Georg Christoph Lichtenberg (1742–1799) "Man muß Hypothesen und Theorien haben, um Kenntnisse zu organisieren, sonst bleibt alles blosser Schutt.", translated "One must have hypotheses and theories in order to organize knowledge, otherwise everything remains mere rubble."

As the Lean Compendium, also this book on advanced manufacturing theory is a must for all stakeholders of manufacturing, students of engineering, practitioners in the daily organization of manufacturing sites, and company leaders.

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Prologue

Digitization will not change the way how industry will manufacture products in the future, but it will change how to operate manufacturing systems. The declared main goal of "Industry 4.0" is not only the digital integration of production systems within the supply chain, but also the implementation of a fully flexible shop floor and it goes beyond mass customization considering even one-offs. Internet of things (IOT) and increased artificial intelligence should support this evolution leading finally to cyber-physical production systems (CPPS). Increased computational performance of plant simulation has already conquered production science allowing to model complex manufacturing systems. And this is not only positive, because it has impeded the development of an advanced manufacturing theory—and this to the expense of a meaningful and adequate student's learning. In fact, didactics of manufacturing science remained stuck to elementary trivial laws (such as Little's law and Kingman's approximation) not having progressed accordingly. Since manufacturing theory didactics has not evolved at the same pace, it is absolutely necessary to develop a deeper understanding how alternative manufacturing systems are conceived, i.e., how different "hardware" (equipment configuration) can be operated best by which "software"(manufacturing principles). Indeed, different implementation concepts lead to different performances in terms of throughput speed. This knowledge requires to master the theory how manufacturing orders advance along the value-added downstream and how products logically flow on the shop floor. We have to build up an understanding of systems behavior in presence of different implementation possibilities, i.e., different manufacturing modes. Why has it not yet been possible to model complex manufacturing systems with simple manufacturing laws? We will here not put the stress on the "why," but on "how" to model the performance.

This textbook leads today's rather heuristics-based didactics of manufacturing theory toward a Cartesian, i.e., rational way of manufacturing theory didactics that is more suitable to academics lecturing. Such a predicate logic-founded theory of manufacturing, based on theorems, corollaries, and lemmas as well as on clearly defined implementation principles, elevates the manufacturing topic finally to science. The book develops a mathematical modeling of the behavior with "push" manufacturing principle-based production systems. The exposed theory will facilitate structured learning and will favor the training of knowledgeable manufacturing engineers who understand the performance behavior of generally robotics-supported lines, i.e., the underlying "physics" of production and not only the "engineering" of such production lines.

The present book develops further the introduced Cartesian approach of a predicate-derived manufacturing theory initiated with the "pull"-focused textbook "Lean Compendium—Introduction to Modern Manufacturing Theory." That book introduced a new, innovative, and groundbreaking way to explain and teach manufacturing theory with clear and unambiguous definitions as well as basic, but fundamental laws valid for all, pull or push, batch or flow, manufacturing systems. Based on that, it developed a theorem-based description of the Toyota JIT manufacturing system. It explains the JIT-pull under a manufacturing theoretic instead of an implementation and tools-based point of view. Following this work, in the present book we describe the modeling mathematics of "push"-implemented production systems, which still constitute the lion's part of Western manufacturing systems. It continues to develop the concise logics of already enounced theorems with new ones, favoring a rational understanding of manufacturing theory.

This present book logically groups several recently published papers written by the authors since the publication of the previous book leading to this additional compendium "Elements of Advanced Manufacturing Theory," which you hold in your hands. The content is structured as follows:

Chapter 1 introduces to the issues linked to the lack of a law-based manufacturing theory and explains the benefit of a Cartesian-derived approach didactics. It shows exemplarily the consequences of the present ambiguous manufacturing language with vague naming of present production concepts, far away from an exact science-based theory. It exemplifies the derived benefit of a physics-paradigmatic, predicate-based concept also applied to manufacturing theory.

Chapter 2 tries to classify the different main manufacturing systems using the implementation principles introduced in the textbook "Lean Compendium—Introduction to Modern Manufacturing Theory." It compares their performances in terms of elasticity and flexibility.

Chapter 3 focuses on the significance of the most important machine or workstation of a production system, which is the bottleneck. Indeed, the bottleneck workstation determines the performance of a production system. It compares the interpretation of bottleneck with two different approaches, the operations research view, and the theory of constraints view.

Chapter 4 enlarges the solution space for on-time delivery (OTD) compliance by introducing the virtual elasticity. Here, the importance of process speed in terms of lead time comes into play. It gives also the conditions for a weak or strong solution for OTD.

Chapter 5 enlarges the requirements of OTD compliance to a deterministic product-mix manufacturing. This is the domain of Toyota-derived JIT Kanban-pull systems, which in fact would not need this treatise, because OTD is implicitly guaranteed by JIT. The important OTD topic, however, is examined for the push manufacturing principle, because it is still dominant in Western industrial world. Unfortunately, due to lack of knowledge, production managers hesitate to shift to superior JIT-pull systems for such type of product-manufacturing environments. To analyze the performance, a norm on the exit rate (ER) is defined, leading to a space of normed nominal capacities.

Chapter 6 deals with non-deterministic product-mix characterized manufacturing systems. Such systems are best represented by CPPS of "Industry 4.0 Revolution," i.e., having the maximum non-ergodicity of commercial orders, comprising according to the German *i4.0 action group's* envisaged one-off customization. Instead of applying discrete event simulation to analyze the optimized scheduling of production planning, a mathematical modeling of such full variable manufacturing systems is introduced. It tries to give a first structured understanding of the related issues.

Chapter 7 presents a frequently cited paper demystifying the aim of omnipotent modern CPPS with an extensive assessment of the realistic possibilities of such futuristic systems. The main problem lies in the operational cost of cyberphysical systems and also in the necessary investment in overcapacities to guarantee strict OTD observance. In addition, the difficulty of implementing one-off product producible CPPS is also inherent to the matching, or better incompatibility, of the high flexibility market requirements and economic breakeven considerations.

The book is the collection of seven topic-related papers and has not been re-edited as a textbook. Its content, however, is didactically well structured and relevant for advanced studies of manufacturing theory, as the papers were conceived for this purpose. The content and exposure of the papers have not only a scientific relevance, but also a suitable didactics connotation. In fact, they give a consistent and law-based view of the behavior of manufacturing systems engineered with various selected implementation principles. Moreover, due to the circumstance that the single papers are self-contained, the chapters do not have to be read in sequence of this book, but can be selected and read according to the interest or according to a related production challenge. The introduction of each paper gives a summary regarding introduced concepts of former papers representing a recapitulation of the learnings.

This predicate-based Cartesian description of manufacturing theory with theorems, corollaries, and lemmas finally elevates the often generally and superficially taught production topic to a near "exact science." The discrepancy between the usual descriptive theory didactics and this rational approach becomes now evident.

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Contents

Chapter 1
The Need for Manufacturing Theory

Today's universities' manufacturing courses on production system design and analysis of performance dynamics are heuristics than rational-based, far away from a physics or mathematics theorem constructed science. This is also due to increasing computational power, which allowed the proliferation of simulation-based modeling for complex manufacturing systems to analyze their behavior and optimize their performance. Indeed, manufacturing theory remained stuck to generic practice-based production concepts. The lack of a well-structured scientific production specific theory is increasingly problematic. Engineering students lacking the foundation of a solid theory will base manufacturing systems design rather on believing that the optimization software will solve the scheduling issue instead of comparing alternative modern design principles to conceive high performance manufacturing systems. This attitude is far away from a scientific rational approach to design demand characteristic and product appropriate manufacturing systems by knowing "the theory". A scientifically formulated manufacturing theory should cover two aspects: Firstly, a proper Cartesian-based understanding and law-based modeling of manufacturing systems to describe rationally their behavior; and secondly, a library with a comprehensive set of elementary production systems' design principles. The design principles define the functioning of the manufacturing system and the theory models the resulting dynamics of the manufacturing system. This chapter exemplarily shows the increased didactic and professional benefit of such an appropriate, solid, theorem and law based manufacturing science. In addition, it also discusses the impact of presently applied manufacturing simulation in today's context of emerging Industry 4.0 type cyber-physical production systems (CPPS).

This chapter is mainly based on the paper: Considerations on Present Production Science Theory and Didactics: The Evident Lack of a Rational Manufacturing Theory, JSSM, 2021, 14, 482–501.

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1.1 Introduction

«Hic locus est ubi mors gaudet succurrere vitae» is an often seen inscription at anatomic institutes of European universities. This inscription documents that what today is called 'heuristic approach' has already been used in the dawn of scientific thinking coming close to the approach of empiric learning gaining experience by doing. Heuristics starts usually from empirically acquired knowledge in absence of science-founded laws by applying a deductive rational logic to gain insights and drawing correct, or sometimes, false conclusions. It is interesting that heuristic approaches are widely used to the present days. This is not negative, however, if systems become too complex, e.g. such as manufacturing systems usually are, heuristic approaches find their limits. Indeed, the lack of a scientific manufacturing theory stresses the divulgation of common isolated practice-derived manufacturing beliefs forcing, without systematic solid foundations, the explorative simulation approach. In such cases, a cognitive model-based theory would allow to put the discussion on the level of a rational science-based understanding. Today, simulation techniques are applied to model, or to exploring, the dynamic behaviour of a manufacturing system. There is an evident twofold reason for that: not only the lack of a manufacturing theory but also the complexity of manufacturing systems. Generally, the modeling of a system might be solid law-based or rather exploration focussed, simulating or emulating the behaviour, finding deterministic solution, or optimizing and decision-oriented. It is not the intention of this chapter to provide an anthology of simulation techniques and modeling types, but to show that both topics, theory and simulation, are complementarily linked. Nevertheless, to the contrary of manufacturing "science", some natural exact sciences, such as physics or chemistry, have developed their own governing laws mainly supported by the help of mathematic formalism. Mathematics at its own has developed an own exact and structured logic, based on axioms, theorems, and corollaries to be consistent.

This has not been the case for production sciences where theory and the knowledge transfer is still stuck divulging simple empirics-deduced and heuristic-induced approximations or even false manufacturing "theory" concepts, such as the widespread believe "the whole attention should be directed to the most expensive equipment". This often heard statement is correct from a theoretic economic asset point of view, but not from a manufacturing one. In manufacturing, the attention has to be oriented towards the bottleneck, which directly limits productivity. While in the dawn of modern physics rational laws have been formulated directly derived from simple empiric experience, think only at Galilei and Newton, Ampère and Ohm, the definition of manufacturing theory curriculum missed to translate empiric gained knowledge into universally valid "production laws". Therefore, graduated engineering students lack the rationality of a science-based theory not only to design but also to discuss the behavioural dynamics of manufacturing systems, which should distinguish them from old school practicioners. To find the reason for that we have to discover the intrinsic difference between manufacturing and physics or chemistry, which is inherent to the topic itself. Indeed, manufacturing is not a natural science, but is a manmade artificial construct of applied concepts. Therefore, it has not primarily the understanding of the logic transformation process as topic, but how the morpho-physical transformation of the object is technically implemented on the shopfloor. This means that manufacturing, and we say expressly not manufacturing science, is rather implementation and solution-oriented and not understanding-oriented, i.e. practical engineering and not theoretical physics based. The pity is that Lean-based manufacturing solutions often are neglected in the knowledge transfer in favour of generic simulation-based optimization approaches instead of trying to understand "modern" alternative production systems such as the Toyota Production System (TPS). However, what makes manufacturing so different and difficult to be formalized? How is it defined? If you consult Wikipedia about manufacturing you will be disappointed, a misleading definition which we purposely do not cite here, and shows the existing nebulous delirium about the topic. A clearer and more comprehensive definition of a manufacturing system has been given in [1]:

"[Manufacturing is] the optimization of a constraint system within a non-deterministic environment

- with the objective to transform raw materials into products (applied technology)
- complying to customer requirements such as on-time delivery (OTD, respecting the voice of the customer)
- having limited process resources available (restricted capacities)
- applying an appropriate allocation, i.e. scheduling of resources (optimal solution)
- showing different throughput and lead-time characteristics (process performance)
- by following the economic rationale of minimizing waste of inputs and resources (ROI)".

Note that product quality is not even mentioned here, because it is presumed to be engineered and delivered at 'six sigma' level to the customer. The same applies for machine downtime, which should be limited to maintenance and set-up. The above definition shows how complex it is to manage a production system, but also why a theory model is not easy to be developed and why it has not yet been configured until today. Indeed, common laws are usually simple, however, man-made manufacturing systems are complex. Such a configuration is difficult to be reconciled. To model the complexity of manufacturing, operations research techniques such as linear programming have been deployed to find appropriate production scheduling covering at least a part of the above reported definition. Already the naming of *linear programming* is a testimonial of the very first applications of linear optimization techniques to solving manufacturing-related planning problems. The predominant applied batch & queue (B&Q) manufacturing in Western industries production forcedly called for the application of queuing theory. From queuing theory some elementary calculations such as Little's law, Kingman's and Kuehn's approximations have been derived. To master the complexity of production planning systems, sophisticated production planning software packages have been developed (called MRP, MRP2, ERP) with increased scope, controlling the advancement of planned scheduled production orders to supply customer orders on time. Furthermore, the manufacturing "theory" is often divulged academically by integrating cognitive heuristics based thinking with empirically gained knowledge and applied simulation. Indeed, the development of a proprietary, specific "physics" of manufacturing has been rarely the topic of research. Nonetheless, the scientific community is conscious about the lack of a systematic manufacturing system design approach [e.g. 2], but it seems not bother about the lack of a law-based manufacturing theory as long as there is enough computing power. And exactly this shows the prevailing of practical-focussed implementation approach compared to the understanding-focussed theory approach. However, exactly this theory topic once has already been raised by Little in one of his papers 30 years ago [3]. Since then hardly any relevant initiatives have been undertaken. The reason why this topic has not yet been systematically researched, is not only linked to the complex multi-disciplinarity of the topic itself, but also intrinsic to the increased computational performance, enabling and facilitating easy solution finding by simulation and therefore helping to make optimized implementation decisions.

Nevertheless, we have to pay attention not to be controlled by artificial intelligence (AI) logic-based automation without understanding the governing laws. On the contrary, we have imperatively to understand the basic laws governing the outcome. It is inacceptable that students know how to program and use expensive software of manufacturing systems, but they do not know the basics regarding how different production systems work, e.g. sometimes even believing that Lean is summarily defined by 5S, Kanban, and Kaizen. The intelligent task consists in conceiving performant manufacturing systems knowing upfront the approximate resulting behavior of the selected implementation solution. Indeed, physicians perfectly know the celestial laws, nevertheless it is the computer which calculates the planetary trajectories. Manufacturing simulation, however, is not law-based, but often uses discrete event simulation (DES) to explore the solution space. Manufacturing simulation has to be supportive and is not for compensating the lack of knowledge. It should even less be a surrogate to knowledge, as it is the case today. It is not only recommended, but necessary that production engineers have understood the functioning of a law-based production theory and the consequence of applied production-related principles. Such a new approach is equal to a paradigm shift in production theory didactics and consequent education of modern engineers conferring them a profound knowledge.

In the following, we will show some excerpts of such a law-based production theory and the most recent production-proprietary findings summarized in new, recently published production theory corollaries. The intention of this chapter is to promote a rational science-derived didactics based on theorems of manufacturing theory but also to develop further production related theory initiated with the manufacturing text book *Lean Compendium—Introduction to Modern Manufacturing Theory* [1]. The superiority of such a law-based theory compared to the present teaching approach will finally become evident.