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Defining "Production System" from an Operations Science and Project Production Management Perspective

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ABSTRACT

What is a Production System? Different disciplines, ranging from manufacturing to civil engineering and construction to project management and Lean, refer to the term, but few define it. One can only assume its meaning is generally taken to be self-evident from the constituent words. However, for purposes of Project Production Management, as with other scientific fields, a more precise definition, distinct from colloquial usage or usage in other subjects, is an essential part of a theoretical framework for making predictions about project execution performance and to identify how to control project execution. Starting from the etymology of terms and key requirements drawn from operations science [1 – 2], we provide a precise definition of Production System. We explain the contrast between our definition taken from operations science literature and terminology used elsewhere, such as by the Toyota Production System [3 – 4], Era 2 Project Scheduling [5] e.g., Critical Path Method and the Last Planner System© [6]. The most important distinction is that the precise definition of Production System provided here enables Project Production Management to be a *quantitative theoretical* framework, capable of modeling and predicting limits on project execution for a given Production System, and of identifying precisely where buffers can be allocated to optimize key parameters of a Production System: system throughput, system cycle time and system WIP.

Keywords: *Production System; System; Production; Process; Operation; Action; Stock; Inventory; Throughput; Cycle Time; Task; Queue; Routing; Line*

INTRODUCTION

Varying definitions of "Production System" have proliferated, and differ widely in their content and emphasis. Many definitions speak to origins in manufacturing – roughly paraphrased as "the process of creating goods and / or services through a combination of materials, work and capital" as cited, for example, in *Design and Operation of Production Systems* [5, Chap 2]. Other definitions have co-opted manufacturing origins and adapted them for different applications, most notably in computer science [6]. Some definitions emphasize cultural / philosophical, organizational and execution aspects of production systems, such as Toyota's definition of the Toyota Production System [7], which they themselves characterize as:

"A way of making things based on two concepts – the first is called "jidoka" (which can be loosely translated as 'automation with a human touch') which means that when a problem occurs, the equipment stops immediately, preventing defective products from being produced. The second is the concept of 'Just-in-Time,' in which each process produces only what is needed by the next process in a continuous flow."

Related definitions of Production System, notably Lean Production, take a given set of processes or operations, and focus on articulating principles for the reduction or elimination of different categories of "waste" [8]. Some have classified "Lean" as a set of tools applied to production [9].

From the perspective of Project Production Management, and its foundation in operations science, the concept of "Production System" must be defined precisely to capture those essential features of operations science and PPM that are distinctive from other disciplines and bodies of knowledge.

Qualitatively, a definition of Production System must be sufficiently precise, yet broad enough to highlight that:

- **At its most abstract level, it conveys the notion of "a process of transformation of inputs to outputs" – of materials, resources, information – into goods and services.** Implicit in this high-level statement is the idea of capacity: the physical limits of materials and available resources, and / or capacity for information handling.

- **It conveys and quantifies the notion of flow**. Defined as not only physical flows of materials (raw materials, work in process and finished goods) but also of information (work in process such as partially completed services, partially completed information, completed services and information accompanying finished goods). Implicit in this high-level statement is the idea of throughput, or the maximum rate at which a system can move inputs through to outputs. Also implicit is the role of work-in-process or inventory, which indirectly connects to the idea of queues waiting to be worked on.

- **It must make high-level ideas of transformation and flow sufficiently precise to be useful as a quantitative theory, rather than a qualitative philosophy or set of principles.** In order to be a scientific theory, one must be able to make predictions that are confirmed by experimental evidence. The definition of Production System must be sufficiently precise to be amenable to mathematical tools of operations research – queuing theory, networks and graph theory, dynamic and linear programming, stochastic processes and discrete event simulation – so that limits on Production System performance can be computed, future behavior can be predicted within the limits of variability, and actions to control performance can be identified and their consequences predicted. It has been well noted in peer-reviewed academic literature that disciplines such as Lean are more qualitative than quantitative [4 - 6] though seemingly less understood by industry practitioners.

- **It must encompass the different types of Production System that have been identified in the literature [7 – 8]**. Figure 1 is a high-level illustration of the Production System in a generic construction project. Each step, from Fabrication to Delivery to Installation, can obviously be broken down into more detailed steps. Each step is preceded and succeeded by a stock / inventory / work-in-

process (WIP). Put simply, what makes Figure 1 a Production System is not just the idea of linking operations with inventory diagrams in a line or routing [9], as that would not be very distinctive from any generic process flow diagram. As clearly explained in *Factory Physics* [10, p. 202 and 11, p.46], any form of production has two primitives: (1) demand, and (2) transformation to satisfy that demand. Each operation that is a "transformation to satisfy demand" has a stock to supply, a non-zero cycle time (non-zero in the real world) and finite throughput.

What makes Figure 1 a Production System is that the operations are well-defined enough for each operation to have an individual cycle time and throughput, and the inventories satisfy the basic requirements for queuing theory to be applied i.e. waiting times are applicable. With that stipulation, it is possible to apply analytical tools like Little's Law or Kingman's Formula to draw conclusions on the overall cycle time and throughput of the system, the critical WIP level in the system and its response to variability. Production Systems are simply the networks formed by the sequence in series and parallel of operations with such rules, supplied by inventories and stocks, to which the mathematical techniques of queuing, graph theory and other operational science fields can be applied.

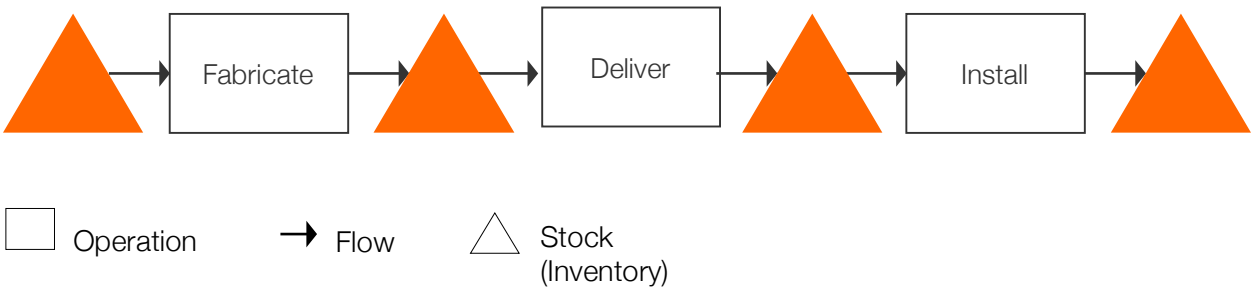


Figure 1: An example of a Production System

And so, to arrive at a useful definition, how do we proceed? We start with the basics, by looking at the etymology and definitions of the terms operation, process, system and production. Two words – process and system – have a variety of meanings reflecting their use across a broad range of fields. By picking the relevant meanings to align with the high-level requirements we articulated, we can arrive at a satisfactory definition of production system for our purposes.

ETYMOLOGY AND DEFINITIONS

Operation – the word operation is derived from the Latin *operari,* meaning to "to work, labor, toil or have effect." The associate Latin noun, *opus,* is a "work" or "action." And so, the word operation connotes task, action, performance or work. In the context of a Production System, we use the word operation to refer to a single discrete action performing some transformation, i.e. the most primitive element that has a definable throughput, cycle time and stock or inventory.

Process – the word process originates from the Latin *procedere,* meaning to "to advance or progress." The noun process at its most abstract level is "a series of actions or steps to achieve something." Over time, it has come to have a specialized set of sub-meanings, noted by dictionaries such as the Cambridge English Dictionary. Two recent modern specializations are the use of the word "process" in computing – an instance of a program being executed in a multitasking operating system environment, and in printing, as in a "four-color printing process." However, a long-standing use has been "a systematic series of mechanized or chemical operations that are performed to produce something."

Expanding from manufacturing or construction to incorporate the notion of services and knowledge work (such as design and engineering), we adopt "a series of actions or steps to achieve something." Implicit in this is how much time each action takes, and the sequence of operations achieved by linking them together.

System – the word system is derived from the ancient Greek *sustema* and thence the Latin *systema*. Thus, it has two distinct sets of meanings, from which numerous specializations exist:

1. A set of interconnected things or parts working together to form a complex whole e.g. a manufacturing assembly line consists of a series of manufacturing stations working together in an interconnected network

2. A set of principles or procedures according to which something is done; an organized scheme or method e.g. the metric system, a set of rules in measurement or classification

Definitions (1) and (2) for a system can lead to profound differences in overall meaning, as we show when explaining the difference between Production System and the Last Planner System© for instance.

A review of literature, even peer-reviewed academic literature, shows considerable variation in the usage of the word *system*, with specific definitions rarely cited. Even more confusing is that different sets of literature vary in their treatment of *system* versus *process*, with some using the two words interchangeably, and some treating one as subordinate to the other. Our purpose is to arrive at a definition that is operationally useful in terms of making theoretical predictions.

For this reason, we adopt definition (1) for the definition of Production System – a set of processes working together in an interconnected network. Essential features are the notions of individual operations concatenated together in a routing or line, or more complex connections where you may have several parallel lines or routings connected. This feature essentially makes the concept amenable to applying mathematical tools of operations research, such as graph theory and queuing theory [18].

Production – the word production is derived from the Latin *produco*, meaning "to bring forth" or the modern "to produce." Manufacturing texts have specialized this to mean a "step-by-step conversion of one form of material to another form through chemical or mechanical process to create or enhance the utility of the product to the user" [5, Ch. 2]. It is generally emphasized that production is a value-adding

process, meaning that each step is intended to add value to the work-in-process until it is of maximum utility to the end consumer. As alluded to earlier, we expand the notion of production to mean step-by-step transformation of inputs or resources (which might include materials and information) into outputs, to create or enhance the utility of a product or service.

Putting this all together, we can define a production system as an interconnected network of processes, with each process being a sequence of operations, that transform inputs into outputs. At the input and output of each operation, work-in-process accumulates, such as queues waiting for the successor operation. Each operation has a cycle time and throughput (rate per unit time at which units of production are completed). A unit of work-in-process waiting in an inventory or stock has a wait time as it queues for the next process to accept it. With this set of stipulations, production systems allow the full power of operations science analysis to be brought to bear.

THE CONTRAST WITH USAGE IN OTHER DISCIPLINES

The preceding discussion defined a Production System as a network of connected processes. Each process is a sequence of discrete operations. Each operation provides a transformation action to satisfy demand, with demand and transformation being the two primary elements that all Production Systems have. This is clearly a more specialized definition than usage in other disciplines. For instance, a process flow drawing of a Production System adhering to our definitions is more specific and constrained than more general process flow maps that are referenced in literature. One might ask: *so what*? What benefits result from the more precise definition of Production System given here? One is able to draw some significant conclusions from even the modest discussion on definition provided here:

Our more precise definition of Production System supports a technical framework for a predictive *theory* of Project Execution and Delivery.

A strongly held position of the Institute is that operations science and its associated mathematical apparatus forms the theoretical basis of Project Production Management. It leads to a technical framework that allows for a predictive *theory* of project execution and delivery – theory in the sense that it enables quantitative prediction on the limits of what is theoretically achievable, and for design of how to achieve those theoretical limits. The precise definition of Production System given in this article is essential for that theoretical framework to be operationally useful. Some powerful and insightful results from the applications of operations sciences have been reported in peer-reviewed academic literature.

The most relevant examples provide a critical analysis of the lack of precision in the definition of terms, and analyzes push and pull systems [13]. The authors define what a “pull” system is, mathematically proving that the increased controllability of pull systems is a result of pull putting a bound on the WIP in the system, and derives the hybrid CONWIP control protocol that under some general conditions has superior properties to either push or pull. A second seminal work is reproduced in this edition of the Journal [14], and is a tour de force that surveys the historical evolution of “push,” “pull,” and “Lean,” and highlights the consequences of loosely defining terms. This article puts all three terms on a sound theoretical basis from an operations science foundation. Among the most profound results is the elegant

statement that the qualitative principles of Lean can be reduced to a statement about Lean minimizing the cost of the buffers in the Production System. The sound theoretical basis of Lean and Six Sigma principles explained from an operations science foundation is explored in further detail in *Factory Physics* [10].

The Last Planner System© is a form of Production Control. The "Pull-Planning for Production System Design" element of the Last Planner System is not a Production System as defined here.

The Last Planner System© [4, p. 147, 15] is a system for controlling production as the cited references state. But what type of system is it, and more specifically, is it a Production System in the sense that we have defined here? To clarify, it is not a Production System in the sense defined by PPI, for a few important reasons.

One very basic reason is that System, used in the sense of Last Planner System©, uses the following definition (2): a set of principles or procedures according to which something is done; an organized scheme or method e.g. the metric system, a set of rules in measurement or classification. This is self-evident from looking at the definition of Last Planner System© given by the Lean Construction Institute [15, 1.4] – "LPS is planning, monitoring and control system that follows lean construction principles such as Just-In-Time (JIT) delivery, value stream mapping (VSM), and Pull Planning."

In contrast, System used in the sense of Production System uses the definition (1): a set of interconnected things or parts working together to form a complex whole, e.g., a manufacturing assembly line consists of a series of manufacturing stations working together in an interconnected network.

The difference in the two uses of System might be superficial, but has some profound consequences once the technical precision of Production System as defined here is taken into account. None of the quantitative predictive power we described available from the mathematical apparatus of operations science is available to the Last Planner System© and its constituent elements, because the terminology and usage is broader and necessarily shallower.

In particular, a "Pull Plan," as derived from following the Last Planner System© is *not a Production System.* As defined in the Last Planner System©, [15, 5.1.2], Pull Planning is "strategically planning segments of work in order to produce progressively elaborate Weekly Work Plans (*What Should Occur*)." Key elements described in the business standard include the Phase Schedule and the Collaboratively Built Plan, each with a focus on handoffs. These are all important elements of assuring control of work execution. But as stated, they do not form a Production System as described here. The critical observation here is that the Pull Planning activities of the Last Planner System© are about forming a plan or schedule, but not about elements we consider critical in a Production System. It is silent on limits on throughput and capacity, the quantification of variability and the placement of buffers. It is also silent on the limits of the Production System – are supply flows included? Are policies related to batch size, capacity utilization and WIP levels a design consideration? These remarks are not intended to disparage the Last Planner System©, but rather to clarify that under certain circumstances, it can be a very effective form of

Production Control. It is not, however, the only means of Production Control. A more fundamental analysis of Production Systems [15 – 16], indicates that different forms of production control are appropriate for different classes of Production Systems, another positive consequence for putting the notion of Production System on a more rigorous theoretical foundation.

While Era 2 Project Schedules, Pull Plans, etc., may show inputs and outputs, they are not Production Systems.

In the previous edition of this Journal, we argued that the evolution of project management execution and practice can be viewed in roughly 3 Eras: Era 1 focuses on Productivity, Era 2 focuses on Predictability and the new Era 3 focuses on Profitability [3]. We also argued that Project Production Management was helping usher in Era 3, and contrasted some of the differences of Era 3 practices with those of Era 2, with one difference being the Era 2 preoccupation with scheduling and forecasting using measures largely derived from financial accounting practices. The master project schedule is a major artifact of Era 2, utilizing a variety of techniques, such as the Critical Path Method used to derive "optimum" schedules with planned dates, resources, etc., for project execution. Hard data abounds, showing that such tools have not been effective in producing desirable project execution outcomes and have, in many cases, driven even poorer execution [3].

As with the earlier discussion on the Last Planner System©, an Era 2 master schedule shows inputs and outputs, and while it may nominally look like a process flow map with inputs and outputs, is not a Production System as defined here. The reasons are the same: the focus on schedules and plans and the focus on planned completion times, resources etc., generally omit the theoretical considerations of WIP levels, capacity utilization, throughput and buffers, not to mention the theoretical limits on work execution.

The Toyota Production System is not a Production System as described in this article.

This may appear surprising, but is self-evident from the definition cited earlier. It assumes a definition of System (2) – a set of principles or procedures according to which something is done, an organized scheme or method e.g. the metric system, a set of rules in measurement or classification. As a result, the Toyota Production System is best viewed as a qualitatively based and quite effective set of principles to improve the execution of certain types of Production Systems, specifically those that are high volume line flow systems with well-quantified variability. But it does not really help one understand how to adjust to different types of Production Systems like those described in the literature [[13, p. 528, 15 – 16],

CONCLUSION

By adopting a definition of *Production System* that captures the ideas of transformation and flow that have been alluded to in other abstract treatments, but that is concrete enough so that each constituent step has a cycle time, throughput and a queue preceding and succeeding it, we are able to apply the mathematical apparatus of operations science. This includes graph theory, queuing theory, mathematical

programming and discrete event simulation to enable PPM to be a genuine theoretical framework. This is in contrast with other treatments that are, at best, qualitative and philosophical in nature but not quantitative and predictive.

The principle advantage of our more precise definition is that it underpins a full theoretical framework drawn from operations science, to assess theoretical limits on achievable work execution, and to design how to achieve those theoretical limits. We contrasted the implications of this more precise definition with usage in other fields, highlighting the advantages in certain cases. We claim this is a superior advantage of the Project Production Management framework for project execution and delivery, unmatched by other disciplines.

REFERENCES

1. S. Shingo, *A Study of the Toyota Production System: From an Industrial Engineering Viewpoint (Produce What Is Needed, When It Is Needed),* 5th Edition, Productivity Press, 1989.
2. T. Ohno *Toyota Production System: Beyond Large-Scale Production*, Productivity Press, 1988.
3. R. G. Shenoy and T.R. Zabelle, "New Era of Project Delivery – Project as Production System", *Journal of Project Production Management*, Vol 1., November 2016.
4. W.R. Seed, "Transforming Design and Construction: A Framework for Change", Lean Construction Institute, p. 147.
5. M. Belgran and E.K. Safstan, *Design and Operation of Production Systems*, Springer-Verlag, 2010, ISBN 978-1-84882-494-2.
6. Toyota Production System. http://www.toyota-global.com/company/vision_philosophy/toyota_production_system/
7. G. Bitran and L. Chang, "A Mathematical Programming Approach to a Deterministic Kanban System", *Management Science*, Vol. 33, pp. 427 – 441.
8. J. Womack and D. Jones "Lean Thinking: Banish Waste and Create Wealth in your Corporation", , Productivity Press, 2003.
9. J. Bicheno and M. Holweg, *The Lean Toolbox: A Handbook for Lean Transformation*, 5th Edition, Picsie Books, 2016.
10. W.J. Hopp and M.L. Spearman, *Factory Physics,* Waveland Press Inc., 2008.
11. E.S. Pound, J.H. Bell and M. L. Spearman, *Factory Physics for Managers*, McGraw-Hill, 2014.
12. W. Zangwill, "From EOQ Towards ZI", Management Science, Vol. 33, pp 1209 – 1223.
13. M. L. Spearman and M. A. Zazanis, "Push and Pull Production Systems: Issues and Comparisons", *Operations Research*, Vol. 40, No. 3, May – June 1992, pp. 521 – 532.
14. W. J. Hopp and M. L. Spearman, "To Pull or not to Pull: What is the question?", *Manufacturing & Service Operations Management*, Vol. 6., No. 2, 2004, pp. 133 – 148.
15. "Last Planner System: Business Process Standard and Guidelines", Lean Construction Institute, Rev. 6, 22 June 2015.
16. R. H. Hayes and S.C. Wheelwright "Link Manufacturing Process and Product Life Cycles", *Harvard Business Review*, January 1979, pp 133-140.
17. R. W. Schmenner, "Production/Operations Management: Concepts & Situations", *Science Research Associates*, July 1981, 4th Edition by Macmillan, April 1990.

18. F. Harary and M. F. Batell “What is a System”, *Social Networks*, Vol. 3, 1981, pp. 29 – 40.