Chapter 2
Modeling of Production Systems

In the following sections we will introduce the reader to the complexity of production systems. We will revisit the emblematic "two-pillar" temple model of the TPS giving to the systemic characteristics of the TPS also a suitable systemic representation by introducing an integrated "mono-pillar" model. This new Lean-systemic TPS model will be "le fil rouge" across this compendium to describe production theory of Lean. Furthermore, based on physical analogies we will enter into the basic concept of flow and define a thermodynamics-derived system of Lean Governing Principles.

2.1 Optimization of a Complex System

Different from exact natural sciences such as physics, chemistry, or mathematics, production theory is rarely developed in a purely analytical way, despite laws are governing the production logic. This might originate from the fact that production, i.e. the transformation of inputs into outputs, apparently is not the same such as physics described by mathematical transfer functions $y = f(x)$ with a deterministic solution. However, production is a multidimensional science of

- application of production-related math
- use and allocation of various limited resources
- respect of economic requirements
- within a non-deterministic environment, allowing different possible but also non-optimal solutions.

The final aim of production is to create value for society complying with a long-term sustainable company mission. Within a specified timeframe with limited resources, the economic requirements are to transform input factors such as different raw materials into output objects such as intermediate components or usable

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products. The transformation has to be performed in an optimal way; economists use to say

- maximize output with a given input, or
- minimize inputs to obtain a specified output.

For a production system, usually the latter applies. Different than physics and chemistry, production is a complex interdisciplinary science. The complexity is given by the characteristics of the multiple subsystems involved as well as the multiple degrees of freedom to realize the transformation. The main subsystems are:

- available process resources x_p, such as machines, workforce, and time with limited capacity (in a given timeframe)
- balance on hand of various input resources x_i, such as raw materials and components
- manufacturing laws of the applied transformation process governing the transfer function f(x)
- two, initially distinct, multi-objective functions of demand (customer) z_1 and supply (producer) z_2 integrated finally by following the SPQR axioms.

Different from most of operations research techniques, which optimize not only but mainly static problems (see e.g. Sect. 3.3 Queuing theory and WIP formation), the complexity of the system is further augmented by the temporal dynamics of succeeding random customer orders showing also high product-mix variability. To manage the delivery requirements within an evolving not-static context, time horizon of planning is fractioned and often solved with weekly scheduled production campaigns. We will see that Lean is skipping this rigid campaign model; by the way, which also flexible Industry 4.0 systems will try to do, nevertheless following a different approach (see Sect. 8.3 Lean and the fourth industrial revolution). We will not enter here into theoretic, complex modeling of multi-level systems with operations research techniques; however, we will see how Lean solves the complexity problem of production. In the following, we will define and intend production as:

- the optimization of a constraint system
- with the objective to transform input factors into products (physical transformation)
- complying to customer requirements such as OTD (VOC)
- having limited process resources available (capacities)
- applying an appropriate allocation, i.e. scheduling of resources (optimal solution)
- by following the economic rational of minimizing waste of input and resources (ROI).

This definition shows how complex it is to manage a production system.

2.2 Reconsidering the TPS: The Systemic Lean Model[1]

After WW2, over more than three decades, Toyota implemented step by step a comprehensive proprietary manufacturing system which in the 1980s became known as the TPS. This TPS has been growing organically meaning that it has been conceived continuously based on common practical sense and integrating acquired experience, questioning present Western manufacturing systems based on B&Q principle. One of the first books describing the system was written by Taiichi Ohno, considered the father of the TPS [2]. According to Liker [3], the Toyota house is attributed to Taiichi Ohno's disciple Fujio Cho, who developed the model to teach the TPS to suppliers. The model is of cognitive type, structuring the components of the TPS. It shows the foundation on what it bases, the two reinterpreted novelties of flow and quality, which can considered to be the two sustaining pillars of the TPS, as well as the team-based Kaizen to reduce Muda (Fig. 2.1). For further description of this classical TPS model and the related Lean tools, we refer to the existing literature, e.g. [3, 4].

Of this classical two-pillar temple model, a large number of different interpretations, of more simple or more complex TPS representations exists. Nevertheless, they all feature the same lack, such as describing the TPS as a list of topics, which has been leading several Western companies to adopt just some of the indicated tools interpreting the TPS like a tool-box. This might have been the consequence of overstressing the ultimate mantra of waste reduction, losing the comprehensive

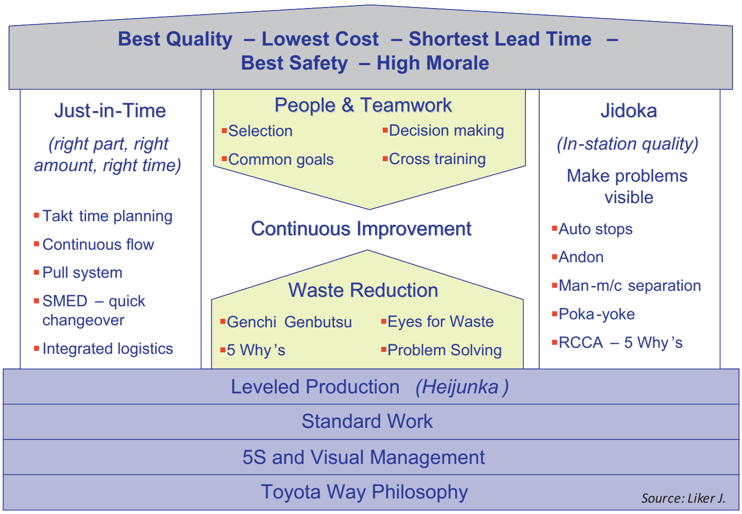

Fig. 2.1 The widespread representation of the TPS is the classical two-pillar temple house model, as depicted by e.g. [3]; note, TPM is missing

[1]The main part of this section has been taken as excerpt from [1].

concept which stands behind the TPS. Indeed, despite showing the TPS model a structure, it seems to be interpreted as an amorphic structure. This sounds to be a contradiction because amorph means to have no structure. What I mean is, the missing of logic interconnections and implications of each subsystem leading to a solid systemic structure.

The original Lean philosophy compared to the original TPS is simplified and usually "sold" as waste reduction. This is not wrong per se, but the aim of TPS is much higher, with waste reduction being quasi a natural by-product if the TPS is well applied. Indeed, Toyota developed exactly the necessary concepts and techniques to limit, or better to avoid, waste production having scarce availability of resources. A synergic system of techniques have been put together around SPF (which, nota bene, is not a Toyota invention, but based on Taylorism and applied first in Ford's T-model production) to allow a flawless quality-oriented operation of a SPF without waste, as well as Heijunka-box leveled pitch to limit WIP (work in process, which is also considered as waste and which delays PLT) and increasing flexibility. Such as the TPS acronym suggests, the emphasis is put on the production system. It is a new way how to produce, how to maximize the output of assembly process type of operations by speeding up PLT, integrated by in-station guaranteed product quality. The TPS has not been conceived by applying manufacturing theory (what we try to do with this book), but by attentive observation and evaluation how to best eliminate any waste and optimize process performance (learning by doing, i.e. observing and improving). Interesting is, that Toyota does not eliminate Muda per se, but via elimination of Mura, i.e. smoothening unevenness. Apart of the underlying tools (SMED single minute exchange of die or Heijunka-pitch) to create a smooth production scheduling, as well as the simple technique to control production triggering (Kanban), the TPS has also originated the continuous improvement approach (Deming's PDCA cycle translated into Kaizen). The striving for perfection by using the "hidden" knowledge of the operators at the shopfloor level, where production takes place (Gemba), has been copied already very early by Western companies, creating the suggestion box system. This was a first timid attempt to implement the continuous improvement process, however far away from how it has been intended by the Japanese Kaizen approach; by the way, in Switzerland it is still believed by 10% of "professionals" that the Kaizen approach corresponds to the suggestion-box [5]. The final goal of the TPS has been the wasteless JIT production. At the end, it took three decades to develop what is called TPS today, and the system is further improving by taking today's technological progress in automation into consideration.

On the other hand, we have the derived American Lean approach. Already the naming is symptomatic what stands at the top of the goals: Lean reflects speed, waste elimination and cost reduction, i.e. performance translated into dollars. This is the straight forward oriented approach of Western enterprises to catch-up. The usually most taught Lean concepts are mainly all about VSM (Value Stream Mapping) and Muda identification and elimination as well as Womack's Lean Transformation approach [4]. In addition, a strong tool-based belief is at the core, which often deviates from the real origin of the problem itself. This is a different approach than the original TPS. This is not surprising; indeed, the TPS is an organically grown production system, a production philosophy, whereas Womack's Lean Thinking [4] is the propagation of a "recipe" to catch-up fast in order to become again competitive. Although Lean is often superficially used as synonym to TPS, the rationale behind and the approach is clearly different but not the goal.

It has also to be explicitly stated that the TPS has been developed to optimally match the assembly type of production, but this does not mean, that it is not applicable to other types of manufacturing systems, as the Japanese shipyards already showed in the eighties. Nevertheless, in non-assembly industries, the Toyota production theory and techniques are reluctantly implemented, because resulting sometimes difficult to interpret the concepts and therefore how the tool has to be adapted to the different process characteristics. The consequence is to use only a part of the Lean tool set limiting the exploitation of the real improvement potential. The limited use of the tools might also stem from the classic two-pillar temple house representation of the TPS (Fig. 2.1) which might mislead to pick a few suitable tools just as needed.

To highlight the synergic interaction of the systemic TPS elements, it is advisable to teach students the Lean approach with an integrated presentation of the JIT and Jidoka concepts within a mono-pillar model as shown in Fig. 2.2 [6]. Indeed, being the final aim to have "the right product with the right quality" the Jidoka based in-line or in-station quality should not be shown separate from the JIT flow

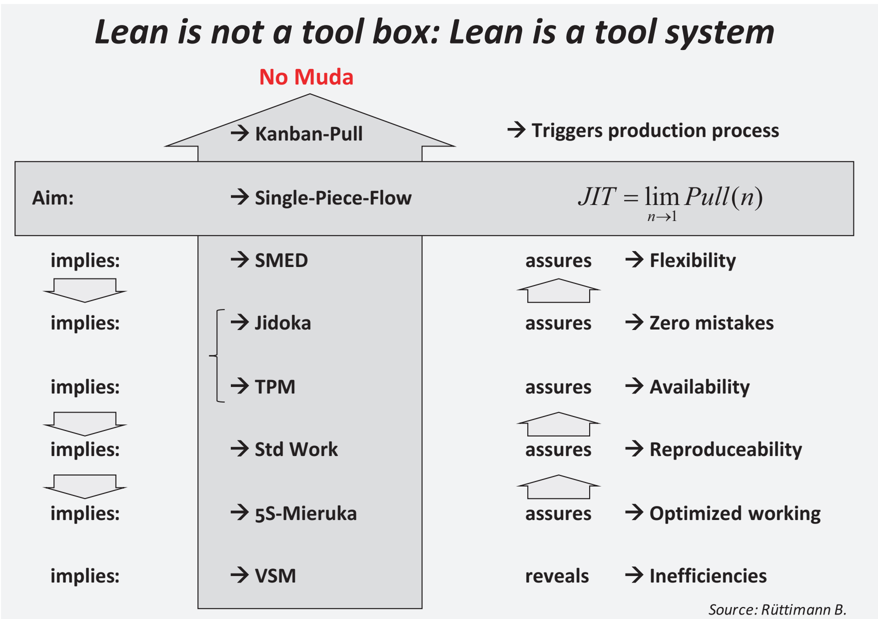

Fig. 2.2 The systemic mono-pillar Lean model [from 6] shows the basic ideas behind the synergic tool system

pillar, as displayed by the classic two-pillar TPS temple model of Fig. 2.1, built-in quality becoming one element among others to implement a flawless SPF. If ever a "multi-pillar" representation may be used, the parallel concept to Jidoka (manufacturing quality parts) should also embrace TPM (Total Productive Maintenance) assuring the correct functioning of the equipment, with TPM being as much important as quality to allow a flawless SPF. Such as the various techniques of Jidoka (Poka Yoke, Andon, stopping line culture, etc.) also TPM techniques (maintenance prevention, preventive maintenance, predictive maintenance, autonomous maintenance) have to be put into place to guarantee the full operability of the line at any time. Be aware, in the case of a breakdown of a machine you do not have a WIP decoupling buffer as operational reserve in between of the operations to continue production; you must guarantee the problem free functioning of the equipment—that is the reason to have the overall equipment effectiveness OEE indicator in place.

This mono-pillar representation shows the cascaded requirements to implement a flawless SPF. This model is a first attempt to show the system's interactions in a simplified way between the main Lean tools. It points at the intrinsic aim to have a SPF in order to gain speed for reducing process lead time and to increase productivity. It shows also that Kanban stocks are not the aim, despite it is sometimes understood so. The model of Fig. 2.2 reveals a quite different aspect of the TPS than the two-pillar temple model of Fig. 2.1; namely the real intrinsic nature of the theory of Lean regarding the Lean tools (neglecting for simplicity the Kaizen aspect of Lean, i.e. continuous improvement). It shows clearly that Lean is not a toolbox, but a tool system. It explains that standardized work is needed to assure reproduceability of different operators, being part of a takted line. It shows also that TPM is required to assure availability, i.e. uptime, of the equipment to implement a flawless SPF without interruption which would immediately limit productivity. Indeed, in Western companies TPM is still implemented with the intention to have less downtime and to supposedly increase output. But in the TPS, the TPM is necessary to assure no breakdowns, because the breakdown of a machine would stop the whole line within a SPF production, reducing immediately the output of the whole line. However, in the B&Q mode the downstream equipment can continue to produce due to the WIP in front of the operations, with WIP being a sort of operational buffer. It has to be stressed that it is an illusion to think that TPM increases the output; indeed, the output is given by the bottleneck, as we will see. All the attention should be drawn to the bottleneck of the operation, reflected by the "shadow price" of Linear Programming optimization models [7], impacting directly profitability. Furthermore, the model shows that Jidoka and Poka Yoke are necessary to implement in-line quality control and to avoid transferring a defective product to the next production station to assure, among others, the production of the right scheduled quantity. SMED is a technique to reduce change-over times. In Western companies change-over time usually is reduced to have supposedly higher production capacity available, whereas in the TPS change-over time is reduced to allow mixed-product cellular manufacturing for a Heijunka box pitch-leveled scheduling with reduced batch size. All this is focused to implement a safe disruption-free SPF triggered by customer demand pull. It clearly shows that Lean is not a toolbox from which to select just a nice tool, Lean is a production system consisting of a tool system, or better techniques, of which every tool has to be put in place to assure a flawless production. Implementing this tool system eliminates automatically and implicitly most of Muda. However, even this model is not apt to show the interoperability of tools for a complex product manufacturing system which certainly will need to go more into detail.

The required main techniques to implement a flawless SPF of a transfer line or a manufacturing cell have been shown in Fig. 2.2. A real manufacturing environment, however, is made of several products needing several machining operations performed in different cells. These cells C_j or better shopfloor ateliers comprise usual processing-technologies such as sawing, machining, grinding, welding, heat treatment (often batch operated), surface treatment, assembly and painting. The simplest production case is the *mono*-product manufacturing, ideal for the introduction of a SPF to reduce PLT. This is done by minimizing WIP with a paced production line. To guarantee the correct takt of the line, the already mentioned techniques such as 5S, standard work, TPM, Jidoka, balancing operations have to be put in place. When *multiple* products are manufactured within the same cell (mixed-product cellular manufacturing), still maintaining a SPF, a further complication has to be mastered. Indeed, the batches B_k of a product k have to be sized to the takt rate TR_k and the workstation turnover time WTT_j of the cell C_j if a JIT delivery of several products is required. The applied techniques for this purpose are SMED and Heijunka box scheduling as well as cell design for the correct staffing. The production situation is often a complex-product manufacturing environment comprising different processing-technologies in different cells. In this further extended complexity, several manufacturing cells are linked together via strategic buffers, called supermarkets. Such buffers decouple the non-synchronized demand (D) of the downstream cell to the supply (S) of the upstream cell due to different cycle times (CT) of operations between the cells. The conveying of raw material to the cells, i.e. the internal logistics, can be implemented via optimized milk-runs as we will see. The replenishment of the supermarkets is self-controlled via Kanban, triggering the production when a stockout approaches. And finally, the requirements to be observed for a customer on-time-delivery (OTD), is that the smallest exit rate ER_j of all cells C_j has to be greater than the required customer imposed TR, and that the process lead time PLT_Z of the last, i.e. of the customer “visible” processing step Z—corresponding to the manufacturing order entry point—have to be shorter than the expected delivery time (EDT) of the customer. These are the necessary and sufficient conditions for an OTD. This means finally fulfilling a customer JIT supply. Such an extended model is shown in Fig. 2.3 as well as in [1, 8] which reflects the mathematical full induction or backward-chaining logic (i.e. from the individual to the general view), going from the mono-product manufacturing, via the multi-product manufacturing to the complex-product manufacturing. It represents the increased complexity related to in-house logistics.

All these interactions are shown in the cognitive model of Fig. 2.3, a comprehensive, at the same time schematically simplified view of the modular construction

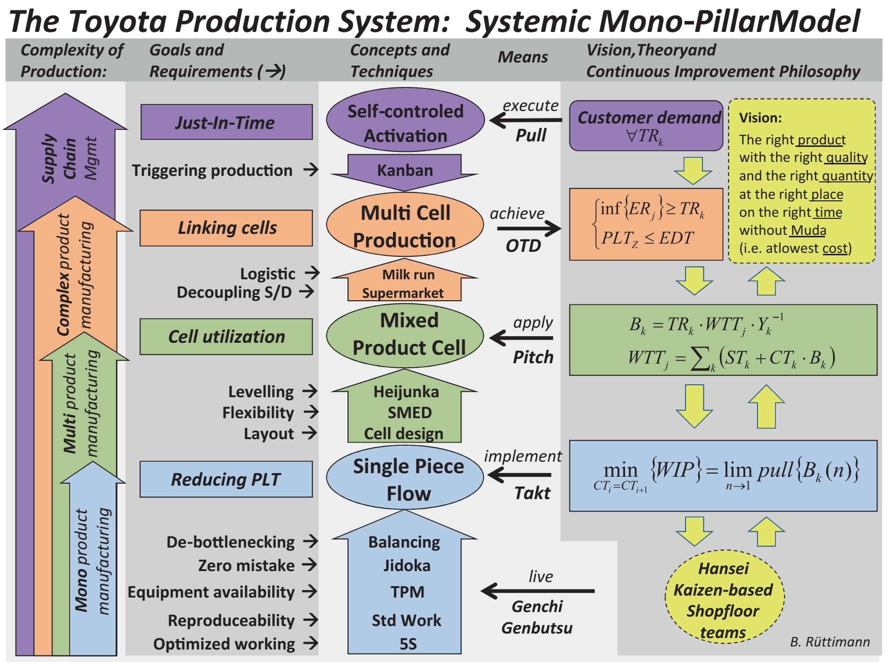

Fig. 2.3 The comprehensive mono-pillar Lean model showing the synergic mechanism of the TPS [adapted from 1, 8]

of the TPS-Lean model, showing also the rationale for each logical manufacturing complexity. It clearly states the goal of the concepts and which technique needs to be applied in order to satisfy the requirements to achieve the overall goal. In addition, the shopfloor continuous improvement is shown too (Kaizen teams), which represents the daily small improvements on all stages. Indeed, the final vision of "the right product, with the right quality, and the right quantity, at the right place, on the right time, without Muda" needs the implementation of all TPS techniques which transform the underlying theory into action, will implicitly lead to eliminate Muda. Western companies probably have the impulse to add "at the lowest cost" to this final vision, what, however, is not necessary, since achieving this vision implicitly leads to lowest cost. The new TPS model of Fig. 2.3 stands at the base of the next chapters.

Figure 2.3 exemplarily shows in a simplified manner the multiple tasks of producing within a lean-optimized, complex manufacturing environment. It shows synergic concepts and techniques and how they work together (also simplified, but explicitly modeled). In Fig. 2.3 the word tool has by purpose been replaced by technique to emphasize the aspect of necessary requirement to be used; indeed, a tool may be used or not, a technique has more relevance with regard to the "how" the theory is applied. Implementing all these concepts with the available techniques will automatically reduce the major part of waste in form of transport, inventories and WIP, waiting time which is mainly queuing time, overproduction, and quality issues. The TPS is therefore an implicit way to reduce much of Muda simply by implementing the TPS techniques and elevating manufacturing performance to the highest score. On the contrary, the Lean approach, as the reduced Western approach of VSM (VSM which is not a TPS tool, but was perfected by the Americans [9]) is an explicit way to show and to eliminate Muda in some way, this is especially the case in service companies. It is now evident, that the often applied Lean approach is not completely identically with the TPS, despite Lean and TPS are considered to be synonyms.

Indeed, TPS is an organically grown system having nearly attained perfection with Toyota whereas Lean thinking—being an emulation of the TPS—comprises the explicit transformation from B&Q to SPF as well as the explicit focus on waste reduction in order to improve the manufacturing system. Although, performing a VSM exercise, showing Muda and recursive loops “to lean it up”, is only a limited view of Lean, but often applied, nevertheless, it is for sure the ideal approach for starting the Lean journey to achieve OPEX (operational excellence). Indeed, VSM is one of the most powerful tools of Lean to visualize and therefore to understand basic manufacturing principles, how the manufacturing system works and to begin the Lean transformation of Western companies not only in industries, but also in services.

The evidence is appearing that from “thinking lean” chasing Muda and by the effective communication to reduce Muda, is a target-hitting powerful marketing slogan, finally to “lean-up” everything. On the contrary, the TPS bears a “hidden” but solid and perfect production theory which contrasts the western B&Q approach going beyond explicit Muda reduction. Therefore, to explain Lean with trivial “Muda reduction” by so-called Lean consultants is indeed far too limited and should be avoided; the comprehensive sense of Lean including the systemic theory aspects should be divulged too. Further, in order not to banalize the proven TPS with saying that Lean equals Muda eradication, it is preferable to describe or better to **define Lean as a “Kaizen-based JIT production”**. This definition covers the dichotomic nature of Lean referring to the implicit Muda reduction by saying how it is implemented (by JIT production) as well as the strive for perfection by saying how it is managed (by Kaizen).

2.3 Physical Analogies to Model Production Systems

Mathematics is a divine science. Many phenomena in nature find their mirror image in mathematical equations. Moreover, many physical phenomena have a similar mathematical structure as if being mathematics itself a natural phenomenon; indeed, e.g. the discharge of a capacitor or the emptying of a level-controlled water reservoir are represented both with differential equations of the same structure. Let us take the widely used modeling of hydraulic engineering to transform the conceptual cause-effect modeling of system dynamics theory.

Figure 2.4 shows a simple cause-effect model of the filling and emptying of a water reservoir. The negative feedback loop shows the stabilizing character of the system controlling the level of the reservoir; the higher the level y, the higher the outflow, i.e. stabilizing the system and not blowing-up. This cause-effect relation of system dynamics can be translated into a hydraulic model of a reservoir with time-variant or time-invariant inflow q_{in} and variable outflow q_{out} as shown in the picture by the level-controlled valve. Indeed, $\lambda = 1/T$ is the "pace" of control regulating the effluent, where T, such as RC in an electronic circuit, represents the average time of adaptation. Based on the description of hydraulic systems, the dynamic of water level y is modeled by the following simple differential equation, which describes the temporal evolution of the level of water with adaptive emptying λy, i.e. controlled by the level itself and the not further specified inflow function $q_{in} = q(t)$ of the reservoir of system's exogenous nature.

$$\frac{dy}{dt} = q(t) - \lambda y$$

$$\dot{y} \cdot e^{\frac{t}{T}} = q(t) \cdot e^{\frac{t}{T}} - \frac{y}{T} \cdot e^{\frac{t}{T}}$$

$$\dot{y} \cdot e^{\frac{t}{T}} + \frac{y}{T} \cdot e^{\frac{t}{T}} = q(t) \cdot e^{\frac{t}{T}}$$

$$\frac{d}{dt}\left(y \cdot e^{\frac{t}{T}}\right) = q(t) \cdot e^{\frac{t}{T}}$$

$$y \cdot e^{\frac{t}{T}} - y_0 = \int_0^t q(\tau) \cdot e^{\frac{\tau}{T}} \cdot d\tau$$

$$y = y_0 \cdot e^{-\frac{t}{T}} + e^{-\frac{t}{T}} \cdot \int_0^t q(\tau) \cdot e^{\frac{\tau}{T}} \cdot d\tau$$

If we assume a constant inflow rate $q(\tau) = q_0$ then we have an asymptotic behavior of y approaching the equilibrium $y = q_0 T$ as we can see in the following calculations where T represents the average adaptation time

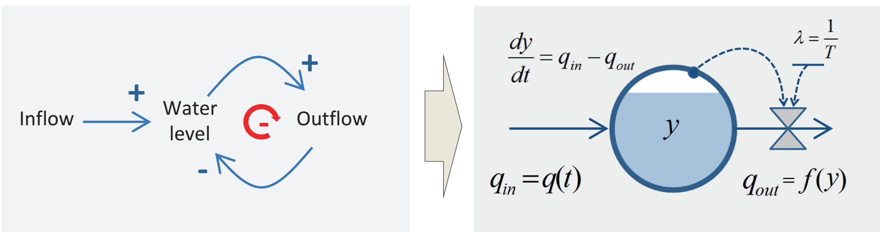

Fig. 2.4 Cause-effect diagram modeling the dynamics of a water reservoir with stabilizing, negative feedback loop translated into a hydraulic model serving later as analogy for manufacturing systems to derive paradigmatically the laws of WIP formation

$$y(t) - y_0 \cdot e^{-\frac{t}{T}} = e^{-\frac{t}{T}} \cdot q_0 \cdot \left[T \cdot e^{\frac{\tau}{T}}\right]_o^t = e^{-\frac{t}{T}} \cdot q_0 \cdot T \cdot \left(e^{\frac{t}{T}} - 1\right) = q_0 T\left(1 - e^{-\frac{t}{T}}\right)$$

$$\lim_{t\to\infty} y(t) = \lim_{t\to\infty} \left\{y_0 \cdot e^{-\frac{t}{T}} + q_0 T\left(1 - e^{-\frac{t}{T}}\right)\right\} = q_0 \cdot T$$

Figuratively, the differential equation explains the variation of the level by the net balance of inflow and outflow within an infinitesimal time interval. Although in manufacturing systems the exit rate ER is usually not controlled directly by the WIP, WIP-based ER is still the domain of management decision taken for staffing a manufacturing unit to increase ER. For our purpose, we will use a similar analogy to enounce and formalize later the dynamic of WIP formation, corresponding to the water level y of the hydraulic model. However, we will not have to deal with differential equations but for our purpose algebraic equations will be sufficient.

We can go further by entering the topic of vector spaces for modeling, becoming even more abstract. Let us define a vector space $\underline{q}$ in RxRxR, e.g. an electrical field

$$\vec{q} = \begin{pmatrix} u(x,y,z) \\ v(x,y,z) \\ w(x,y,z) \end{pmatrix}$$

and take the concept of divergence, concept which might have been forgotten if you have grey hairs. The divergence is defined for vector fields. Written with the Nabla operator notation applied to $\underline{q}$ it is

$$div\vec{q} = \nabla\vec{q} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}$$

which returns a scalar value regarding the balance of the flow of an infinitesimal volume Q(x,y,z) in a vector field. If $div\underline{q} = 0$ the point Q is neither a source ($div\underline{q} > 0$) nor a sink ($div\underline{q} < 0$). If a divergence-free vector field is also stationary, then, with a little bit of imagination, we could allegorically define a fast takted SPF (i.e. a continuous flow) with the notation

$$\left\{\lim_{CT_i\to 0} SPF(CT_i) : |\nabla\vec{q} = 0\right\}$$

Indeed allegorically, because a production system does not show the characteristics of a vector field. Nevertheless, to continue, $div\underline{q} < 0$ would represent a time trap, building up WIP and introducing a delay. You have not to fear, we will maintain our promise to limit math and not become too abstract. However, this example of divergence just shows intuitively the concept of flow and how certain concepts such as equal arrival and departure rate, i.e. WIP variation is equal to zero, can be explained by physical analogy.

Usually, the goals of Lean are written in the “roof” of the two-pillar TPS model such as in Fig. 2.1. When we are talking about the goals of the TPS we intend here the governing goals and not the Hoshin Kanri policy deployment cascade. The goals stated in the roof of the two-pillar TPS model are multiple. In mathematics, this equals to optimize a multi-objective function. In operations research and economics it leads to the concept of Pareto optimality. Pareto optimality applies in the context of concurrent multi-objective maximization (or minimization) of functions. A solution is called Pareto optimal, or Pareto efficient, when any increase of one objective function is made to the detriment of another. The optimum is achieved when this condition is attained. Although the goals and mindset of Lean have already largely been divulged and are commonly known, I prefer to add a further model of the Lean objective system leading to Pareto stability calling it the Lean Governing Principles. Indeed, we could apply a further paradigmatic physical analogy, the one of the thermodynamic postulates, to explain the regal-like Lean reigning goals; they show that also a production system is subjected to follow a logic of "divine" rational (Fig. 2.5). This framework of Lean Governing Principles shown in Fig. 2.5 is topologically closed, i.e. it is comprehensive according to the definition of mathematical topology. Indeed, the properties of compactness and connectivity are given in an extended interpretation. Such as the thermodynamic postulates govern the evolution of thermodynamic processes, in Lean we talk about

– leveling demand to obtain a steady-state dynamic equilibrium represented by a flow;
– optimizing resource allocation which is equivalent to reduce cost or increase productivity;
– speeding-up processes which is equivalent to reduce WIP; and finally
– striving to attain zero defects, which has to be the governing rationale of each production department and plant.

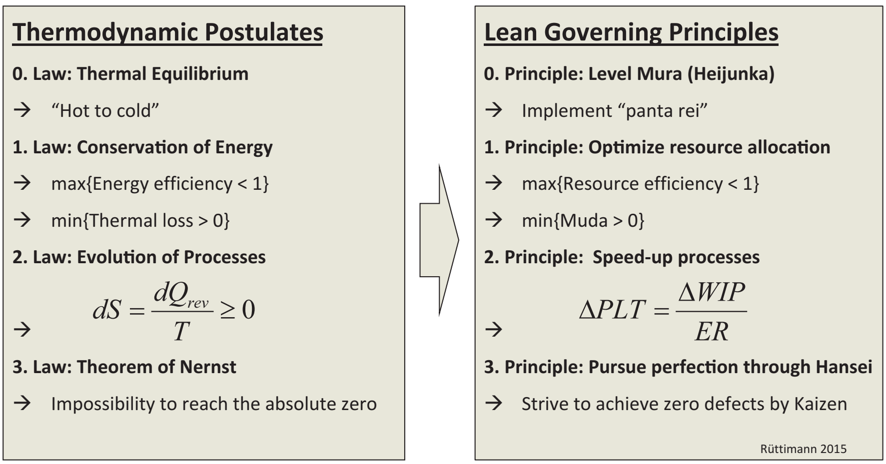

Fig. 2.5 Comparative analogy of the Lean Governing Principles to the thermodynamic laws [adapted from 6]

The Toyota Way puts a lot of emphasis on the cultural aspects how a company is managed, how it empowers people, how decisions are taken and implemented. These Toyota credo have been enunciated in 14 principles by Liker [3]. According to the more tangible-driven topics of this book, we will focus on the technical manufacturing aspects. In the following, we will consider our production system as being a physical system according to the Lean Governing Principles framework of Fig. 2.5, possible to be modeled mathematically by an appropriate analogy, discussing the systemic operability presented in the new Lean model of Fig. 2.3. Therefore, in this book we will deal especially with the principles 0 and 2 to confer them an additional attention. The first and third principles have been already widely discussed in other books e.g. [3], but also the 0 and 2nd one, although they are not specifically called governing principles. I want to clarify, despite the semblance of a Pareto-similar optimality criteria of the Lean Governing Principles might be given, it is noticeable to highlight that they bear a tautological nature, the principles not being in contrast with each another but leading to the confluence of a common synergic objective of perfection. Please also note, the analogies between thermodynamics and Lean are surprising but they have been constructed artificially to match figuratively, especially the phenotypic semblance of Clausius's entropy equation by adapting Little's original law to discrete incremental variation. Indeed, whereas the entropy equation of the second thermodynamic postulate is based on the property of the extensive heat variable Q linked to its intensive variable temperature T, the variables WIP and ER in the second Lean principle, explaining PLT of a production system, present an indirect connection and their intrinsic "physics" properties are independent.

Just for clarification, the term production system is the most generalized concept of modeling input-output relations in an economic system of resource transformation. Whereas on the one hand a manufacturing system has more the connotation of a shopfloor operational system of physical transformation, best represented by an assembly operation, on the other hand, a processing system is best represented by a chemical process. The distinction between manufacturing operations and processing operations may become fuzzy in certain production systems, also because of mixed systems (production of a tissue substrate becoming paper at a first step and cutting of paper rolls into paper sheets in a second step). In the following, for simplicity reasons, we will deal primarily with operations of manufacturing type.

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