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Epistemological Explanation of Lean Construction

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Abstract: The Toyota production system, on which lean production is based, emerged as the unplanned result of unrelated improvements and innovations. Although the related practices and principles are now widely reported, the theories and philosophical premises underlying lean production are not commonly known. This also applies to lean construction, which, although it originated as a set of countermeasures to specific problems in construction, has more recently evolved in alignment with lean production. For example, there is a stark but unexplained contradiction between lean and traditional construction management models regarding the importance of learning and improvement. In view of this, the aim here is to determine the epistemological orientation in these two models. It is found that two different starting points for epistemology, Platonism and Aristotelianism, have also played a major role in the formation of the fundamental ideas of engineering and management generally and in construction. An overly Platonic influence on engineering and management has created a number of problems. It is contended that one major explanation for the evident benefits of lean construction is related to its Aristotelian epistemology. **DOI: 10.1061/(ASCE)CO.1943-7862.0001597.**

Introduction

Although lean production has now become the mainstream model of manufacturing, and the related practices and principles have been widely reported (Womack and Jones 1996; Liker 2004), the theories and philosophical premises underlying lean production are not commonly known. This is not entirely surprising, because the Toyota production system (TPS), on which lean production is based, emerged as the unplanned result of unrelated improvements and innovations (Fujimoto and Miller 2007). However, the lack of underlying theories and philosophies means that there is no good and comprehensive explanation of lean production. Without explanation, it is tempting to think about lean as a management fad (e.g., Morris and Lancaster 2006) that will soon vanish, like other fads. This lack of explanation is also problematic in teaching and training—at least in the West, a situation in which only practical methods and rules are taught, without their underlying rationale and explanation, is seen as unsatisfactory.

This analysis applies also to lean construction, which in recent years has matured and is diffusing rapidly. At the same time, comparative and single case studies on projects (for example: Cheng et al. 2016; Liu et al. 2011; Nieto-Morote and Ruz-Vila 2012; Alsehaimi et al. 2014; Castillo et al. 2014; Priven and Sacks 2015) have considerably added to the evidence base regarding the efficiency and effectiveness of lean construction in comparison to mainstream management methods.

Lean construction originated as a set of countermeasures to specific problems in construction, but has more recently evolved through the adoption and adaptation of methods and principles of lean production. As suggested by Abdelhamid (2004), lean construction enthusiasts have thus looked both inside and outside their own field.

However, it is fair to state that there has been academic research looking at the conceptual, theoretical, and philosophical foundations of lean, both at the general level and at the level of construction. For example, the importance of learning in the Toyota production system was addressed in an interesting manner by Fujimoto (1999). According to Fujimoto, it is learning and improvement that ensure the high performance of the Toyota production system. Also, the centrality of waste as a starting point for improvement in the TPS is well known (Hino 2005). Instead, in the conventional Western management model, it is technology that is expected to produce higher performance (Imai 1986), and reluctance to disclose and acknowledge failure for the sake of learning can be observed (Brady 2014). This contradiction pinpoints the differences between the traditional and the lean managerial models at the level of epistemology (a discipline addressing how knowledge can be acquired). Accordingly, in order to extend the theoretical and philosophical explanation of lean construction, this presentation aims at the determination of the epistemological orientation in both the lean and the traditional approaches to construction.

The paper is structured as follows. First, the methodology followed is briefly commented on. The intellectual origins of engineering and management are then examined. The findings made allude to the influence of the time-honored epistemological contrast between Plato and Aristotle; this contrast is discussed, along with the historical diffusion of their views into engineering and management. An analysis of the problems caused by inappropriate epistemological views in conventional engineering and management follows. Then, the epistemological foundation of lean is discussed. A brief discussion on conclusions completes the paper.

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Methodology

By its nature, this paper is an integrative literature review. This is a form of research that reviews, critiques, and synthesizes representative literature on a topic in an integrated way such that new frameworks and perspectives on the topic are generated (Torraco 2005). Integrative literature reviews can be structured using a set of competing models; this approach has been used. Namely, the paper is based on the discovery of starkly differing epistemological positions at the origin, on the one hand, of scientific engineering, and on the other hand, of quality engineering. First, these two epistemological positions are related to the long-standing discussion of epistemology in science, and are, in fact, identified to be more or less the same as the two alternative epistemological views originated by Plato and Aristotle. Second, the historical diffusion of these two epistemological views into engineering and management is followed, and their consequences are discussed. The order of the argument closely follows the sequence in which the underlying process of discovery occurred.

Two Visions on Engineering

Rankine: The Father of Scientific Engineering

The Scotsman William Rankine consolidated the engineering field of structural mechanics in his books published in the 1850s and 1860s. The book *A Manual of Applied Mechanics* (Rankine 1872) contains his inaugural lecture to the class of civil engineering and mechanics at the University of Glasgow in 1858, titled "Preliminary dissertation on the harmony of theory and practice in mechanics." In many ways, this lecture is his programmatic declaration for a science of engineering.

The novelty he propagated was to utilize natural science, especially physics, for practical purposes in engineering—these two fields had previously been considered separate. Essentially, the question was about engineering design—"to plan a structure or a machine for a given purpose." The use of physical laws as axiomatic starting points for engineering design made it possible to accurately predict, through deduction, the behavior of a structure or machine, and this in turn made it possible to pinpoint the best possible, or optimal, solution. Thus, he defined the new style of engineering as a "scientifically practical skill which produces the greatest effect with the least possible expenditure of material and work."

According to Rankine, this new engineering contrasted with purely practical knowledge, providing only approximate solutions, based on prompt and sound judgment or an established practical rule. This practical knowledge dominated, especially in the realm of making and constructing—"to judge the quality of materials and workmanship, to direct the operations of workmen." Rankine did not hide his value judgment regarding the relative worth of scientific engineering and practical knowledge: "… the engineer or mechanic, who plans and works with understanding of the natural laws that regulate the results of the operations, rises to the dignity of a Sage."

Interestingly, all these hallmarks of scientific engineering still exist today in the teaching and research of engineering: the basing of engineering on physical laws, the definition of engineering predominantly as design, the emphasis on optimal solutions, and the use of deduction as the primary form of reasoning.

Thus, Rankine provides an example of the traditional vision of engineering as applied science, relying predominantly on deductive methods in order to produce engineering solutions based on theoretical knowledge. Although this viewpoint is contested nowadays in the philosophy of engineering, it continues to be emphasized in engineering research and education.

Shewhart: The Father of Quality

The American Walter Shewhart is considered the seminal contributor to statistical quality control, which later evolved into total quality control. His work was stimulated in the 1920s by the rapidly evolving mass production, which needed methods for ensuring the consistent quality of products through control over production.

Shewhart (1931) was not particularly interested in engineering design, but he needed it as his starting point (he discusses human wants as the starting point of mass production):

> The first step of the engineer in trying to satisfy these wants is therefore that of translating as nearly as possible these wants into the physical characteristics of the thing manufactured to satisfy these wants. In taking this step intuition and judgment play an important role as well as the broad knowledge of the human element involved in the wants of individuals.

Here, Shewhart fails to mention the use of physical laws in engineering. Indeed, he is more interested in production:

> The second step of the engineer is to set up ways and means of obtaining a product which will differ from the arbitrarily set standards for these quality characteristics by no more than may be left to chance.

Shewhart's concern was to reduce the gap between the intended and the achieved. How is this gap reduced? Through the methods of science (Shewhart and Deming 1939):

> Let us recall the three steps of control: specification, production, and judgement of quality. … In fact these three steps must go in a circle instead of in a straight line …. It may be helpful to think of the three steps in the mass production process as steps in the scientific method. In this sense, specification, production, and inspection correspond respectively to making a hypothesis, carrying out an experiment, and testing the hypothesis. These three steps constitute a dynamic scientific process of acquiring knowledge.

These ideas were later transformed into the plan-do-check-act cycle (PDCA), now widely known and applied in quality work and lean production.

Again, the basic ideas of Shewhart are today widely used in industrial engineering, especially in the practices of quality and lean production: the basing of industrial engineering on the scientific method, the focus of industrial engineering on production, the emphasis on improvement, and the use of induction (from empirical experimentation) as the primary form of reasoning.

In a larger context, Shewhart subscribes to another vision of engineering, namely, engineering falling into the tradition of design science, focusing on the creation of useful and beautiful objects, or more generally, solutions to problems. This tradition spans from Aristotle's science of production (Parry 2014) to Simon's (1969) science of the artificial, and it is currently represented in a variety of approaches, such the analysis-synthesis-evaluation model of design (Braha and Maimon 1997) and design science research (March and Smith 1995). It is centered around the complementarity of theoretical knowledge and empirical observations as sources of engineering/design knowledge, requiring interaction between induction and deduction.

Comparison of Rankine and Shewhart

There are definite differences in Rankine's and Shewhart's ideas. Rankine's main interest was in design, in contrast to Shewhart's focus on production. In engineering, Rankine wanted to use the results of scientific research. In turn, Shewhart suggested the use of the scientific method—however, the hypothesis to be tested did not flow from science but from the practical production context. In so doing, Shewhart (and his followers) popularized the scientific method—it should be used in practical affairs, outside science. Rankine focused on what is intended, the ideal or optimal solution. Shewhart's interest was more in reducing the gap between the intended and the achieved. In Rankine's scheme, reasoning proceeds forward from ideas to the material world through deduction. In Shewhart's scheme, specification represents deduction while production and inspection are related to induction; thus, reasoning proceeds both forward and backward.

The differences between Rankine and Shewhart have interesting initial similarities to a much older opposition, that is, the views of Plato and Aristotle on science.

Epistemologies of Plato and Aristotle

The Greek Plato (ca. 428–348 BCE), one of the most widely studied thinkers of all times, believed that full understanding of the world cannot rely merely on perception, which provides only a limited and naive view of nature. Fundamentally, perception is based on constant change.

Plato therefore discerns between perceptible things (which are unstable and thus unreliable) on the one hand, and the so-called "Forms" on the other hand; the latter are the only reliable sources of knowledge. Proper scientific reasoning occurs only via deduction from Forms (or specifically, axioms) to something that can be compared to observations (Ross 1951), as depicted in Fig. 1(a). Therefore, according to Plato, the most fundamental essence of reality does not belong to the material world, but to the realm of abstract concepts, the world of ideas.

In contrast, Plato's pupil Aristotle (384–322 BCE) was convinced that proper scientific knowledge is grounded on perception. Aristotelian science is about explanation, namely, discovering causes behind observed phenomena. His scientific method always begins with specific cases, via observations, and seeks for explanations through induction. These explanations are then applied to other particular cases by a deductive method, which starts from axiomatic assumptions to formulate new universal truths to be applied to the sensory world.

In other words, one starts with induction, moving from particular to universal, with a bottom-up approach; once the universal principle is formulated, deduction works in the opposite direction (a top-down approach). The whole process starts from empirical data and then generates new universal truths to explain new observations, as shown in Fig. 1(b).

Platonism, also called Rationalism, and Aristotelianism (often reduced to pure inductivism or Empiricism), have survived to the present time as two competing epistemological alternatives in science (Fig. 1). Certain branches of physics, especially string theory, strongly subscribe to Platonism, while data science, for example, is Aristotelian in its extreme empirical emphasis.

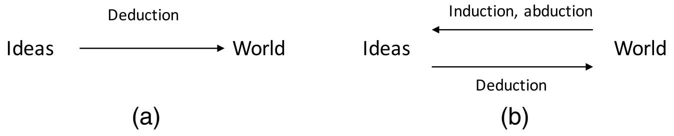

Fig. 1. (a) Platonic; and (b) Aristotelian epistemology.

Historically, Platonism and Aristotelianism were at the basis of intellectual investigations during the Hellenistic period, the Islamic Golden Age, the Middle Ages and the Renaissance. Some examples of personalities that were influenced by the two philosophers are Johannes Kepler (1571–1630), Galileo Galilei (1564–1642), and Gottfried Wilhelm Leibniz (1646–1716) for Plato, and Robert Grosseteste (1175–1253), John Locke (1632–1704), David Hume (1711–1776), and Isaac Newton (1643–1727) for Aristotle.

In particular, a significantly harsh dispute originated during the Enlightenment between the British Empiricists (John Locke, George Berkeley, and David Hume) influenced by Aristotle, and the Rationalists (René Descartes, Baruch Spinoza, and Gottfried Wilhelm Leibniz) influenced by Plato (Turner 1903). While the former believed that the human mind at birth is a blank slate on which knowledge is written by sensory experience (Locke 1689), the Rationalists held that sensory experience is illusory and the source of knowledge resides instead in the mind (Leibniz 1976).

Such a contrast continues to the present day with no apparent resolution, even though the alternation of both methodologies has shaped many contemporary scientific theories. As an example, the case of cosmology is remarkably interesting (Longair 2004).

Every contribution to the field of cosmology until Newton, from the Ptolemaic to the heliocentric model to Galileo's observations with the telescope and Kepler's laws, were, as a matter of fact, only empirical, or based on observation. Only after Newton established his theory of gravitation could Kepler's law be derived from prime principles via deduction. Newton's static cosmology, based on the law of attraction, resulted in interesting ramifications in fields not directly connected to physics, such as economics (this will be discussed in the next section).

The aforementioned example therefore shows how the interplay of inductive and deductive reasoning has been fundamental in shaping our scientific theories. One could even view this as a manifestation of a full Aristotelian methodology, extended over a long time span and to different contributions.

Regardless, the Empiricism versus Rationalism debate has marked epistemological and scientific history for a long time, and it remains very vivid even today. For instance, after Albert Einstein (1879–1955) formulated his theory of general relativity in 1915 and Edwin Hubble (1889–1953) observed in 1923 that the universe is expanding, a harsh methodological discussion followed in the 1930s and 1940s, splitting the community of cosmologists into two factions, namely rationalists versus empiricists, similar to what had occurred about 300 years earlier (Bondi 1957; Kragh 1996; Gale 2015). After some time, this dispute found a sort of resolution, as it became evident that the physics community mostly believes in empirical scientific knowledge (Ellis and Silk 2014). Nevertheless, contemporary rationalism is far from being extinguished, although many are now questioning the applicability and epistemological meaning of some well-established physical theories, such as string theory (Steinhardt 2014).

To summarize, philosophers and scientists have either joined the inductivist or the deductivist faction throughout the whole history of scientific methodology. It seems that, in general, there is no accepted resolution to this debate, whose features have become increasingly sophisticated because of the growing complexity of mathematical and physical models.

Diffusion of Epistemological Commitments into Engineering and Management

The context considered here, namely engineering and (related) management, is of course different from science. Nevertheless, the epistemological questions need to be answered if progress is to be made: from where can we gain knowledge on which to base our design and planning activities or any productive action? Those leaning toward Platonism argue that reason or theoretical knowledge—broadly, the world of ideas—should provide the basis. In turn, those subscribing to Aristotle contend that empirical observations should be taken as a starting point.

At the outset, it is worthwhile to have a brief overview of the recent philosophical discussion on the nature and knowledge formation of engineering (and technology), as the confrontations between science and engineering (or technology), on the one hand, and theoretical and empirical knowledge, on the other hand, have been actively discussed (van Poel 2010).

On one extreme, it has been typical to reduce engineering simply to an application of scientific knowledge, or to regard the engineering sciences as an application of the natural sciences—this is the vision of engineering promoted by Rankine.

A remarkable, well-known example of such close interaction between science and engineering comes from Galileo, who distinguished himself with a series of scientific discoveries and engineering inventions. In terms of the former, Galileo replaced the qualitative statements at the basis of Aristotelian physics with quantitative statements describing the strength of materials and kinematics. He accordingly established a mechanical tradition that is still central to modern scientific practice, searching for mathematical descriptions of the nature of matter (Biener 2004; Machamer 2017). However, Galileo's engineering inventions resulted from attempts to solve problems of engineering practice using mathematical and physical knowledge (Dijksterhuis 1950; Drake 1999). He invented a geometric and military compass, used in the balancing of cannons and in the construction of polygons, together with the calculation of their area. He also invented a water thermometer, a compound microscope, a refracting telescope, a method for determining longitude through the orbits of Jupiter's satellites, and an escapement mechanism for a pendulum clock (Drake 1999).

More specific definitions of engineering have taken a closer look at engineering (Pitt 2010) and its practices (Vincenti 1990) and considered engineering as the "science of the artificial" (Simon 1969) or "science of particular" (de Vries 2010), similar in nature to medicine. In particular, the role and importance of engineering experience, based essentially on observations of preceding designs (Vincenti 1990), has been emphasized in the past discussion, whereas design, per se, has been considered as a distinctive character of engineering (Moses 2010). These treatments fall under the vision of engineering as design science.

According to the discussion of the relationship between technology, engineering, and science, engineering knowledge has been shown to differ from scientific knowledge, to which the standard epistemological definition of "justified true belief" applies; notions of "practical usefulness" (Houkes 2009) and "effectiveness" (de Vries 2005) have been shown to play crucial roles in qualifying engineering knowledge (de Vries 2003; Pitt 2001). Accordingly, knowledge formation in engineering, considered to happen primarily via design (Pitt 2001) and models (Pirtle 2010), has its own specific character as well.

All in all, although these discussions have usefully characterized and illuminated the relationship between engineering, science, and knowledge, the fundamentally distinct viewpoints of Plato and Aristotle have not been explicitly or broadly present in them. What is the role, then, that these two viewpoints have had, and currently have, in the domains addressed?

We contend that the sphere of engineering and management in general and the realm of construction in particular have been epistemologically influenced by three sources: (1) scientific engineering, (2) economics, and (3) quantitative methods.

As exemplified by Rankine, the very idea of scientific engineering is to begin from theoretical knowledge; other hallmarks of Platonism are also clearly evident. Although more experientially and empirically based approaches to engineering have also existed, the Platonic view of engineering gained a dominating position after the Second World War (Seely 1999). Because many engineers end up in managerial positions, the Platonic mindset has been influential beyond engineering, narrowly understood.

In economics, the current neoclassical paradigm gained a foothold after 1870, with a tipping point coming in the 1930s. It adopted Newtonian physics as its methodological model (Toulmin 2003), but misunderstood its Aristotelian character—only the axiomatic method, the Platonic part, was taken on board. Especially influential was the idea of cosmological stability, as treated by Newton. The idea of equilibrium in the economic system is a direct analogy from cosmology. Optimal decisions regarding the allocation of scarce resources came to be the leading economic concept. This new understanding of economics diffused rapidly from the 1950s onward into allied disciplines and practical decision-making. This was promoted by the inclusion of economics into engineering and management curricula. In engineering, the first textbooks of engineering economics (Fish 1915; Grant 1930) emerged in the first half of the 20th century; in management, the famous 1959 reports on business education (Gordon and Howell 1959; Pierson 1959) played a decisive role in positioning economics centrally in business school curricula.

Aside from economics, quantitative methods were another of the three stems of business research and education proposed by the aforementioned reports on the future of management education in the US (Koskela 2017). Quantitative methods refers especially to operations research, a field that uses mathematical modeling for problem-solving. Operations research was successfully used in the Second World War, and great expectations were attached to its civilian application in the 1950s. However, when the professional field transformed into an academic discipline, its character changed; previously, the starting point had been the concrete problems to be solved, but now the academics began to create mathematical descriptions, increasingly based on assumed problems—a switch from an Aristotelian to a Platonic approach. One of the most successful inventions of operations research has been the critical path method (CPM), which was enthusiastically hailed as a modern solution to the problems of construction and product development in the 1960s (Koskela et al. 2014). Remarkably, the whole field of project management evolved around CPM and its underlying thinking (Morris 2011). One of the consequences is that the body of knowledge in project management has largely focused on planning and has little to say regarding execution (Koskela and Howell 2002).

All in all, it can be said that in the realm of productive activities, engineering, production, and management, Platonic approaches provided the dominant worldview in the latter half of the 20th century, and have continued to do so in the beginning of this century. The upshot is that the overwhelming emphasis is on what is happening in the world of ideas—deduction toward a design based on theoretical knowledge, toward an optimal decision, or toward an optimal plan. What happens afterward in the material world is of lesser or even no interest.

Certainly, at the same time, there have been countercurrents. The quality movement that emerged from Shewhart's seminal efforts can be seen as an example of the Aristotelian approach. The related lean movement, foreshadowed by scientific management and essentially brought to completion as the Toyota production system, is similarly Aristotelian. These will be discussed subsequently. Furthermore, there have been many correctives, Aristotelian methods triggered by the problems caused by overly Platonic approaches. A number of these will be discussed subsequently as well.

Epistemological Problems in Construction Engineering and Management

The general intellectual trends described previously have trickled down to construction through education (especially at the university level) and professional institutions and methods. They have been offered as modern and superior alternatives to craft-based, experiential methods in construction, but of course they have not completely substituted for them. Unfortunately, a number of problems, related especially to an overly Platonic orientation, have also been transmitted.

Construction Engineering

The genesis of scientific engineering as a Platonic endeavor has directly contributed to several problems or shortcomings that were accentuated in the second half of the 20th century and subsequently triggered various corrective measures toward the end of the century.

Preoccupation with Design at the Cost of Other Stages

As defined by Rankine, engineering is involved in the design of machines and structures; the realization of these is left to men that have practical knowledge (although he did not explicitly say so, it is obvious that Rankine also thought of operations and maintenance in the same way). This preoccupation is visible in the still widely known definition of engineering by the American Engineers' Council for Professional Development (ECPD):

> The creative application of scientific principles to design or develop structures, machines, apparatus, or manufacturing processes, or works utilizing them singly or in combination; or to construct or operate the same with full cognizance of their design; or to forecast their behavior under specific operating conditions; all as respects an intended function, economics of operation or safety to life and property.

Thus, although construction and operation are now recognized as valid areas for engineering, they should be looked at through the lens of design. However, construction and operation remain underdeveloped areas of engineering. In addition, the Platonic attitude implies that in design, subsequent stages are hardly taken into account. The following anecdote from an ethnographic study of an engineering office is revealing (Demian and Fruchter 2006):

> Bart is very much old school in that a building is just an assembly of details, and that there's nothing wrong with drawing one detail and completely ignoring the fact that there is another detail that must interface with it. He just draws all of these details independently and expects the contractor to figure out how they all fit together.

This original preoccupation with the design stage in engineering has triggered various correctives such as concurrent engineering (Eastman 2012) and various life cycle approaches (Koskela et al. 2016).

Preoccupation with Optimality at the Cost of a Gap between the Optimal Solution and What Is Achieved

For Rankine, the optimality of the solution was one hallmark of scientific engineering. The idea of optimality has been further strengthened by the rise of modern economics from the 1930s onward as well as the evolution of quantitative methods somewhat later, leading to the approach of optimal design from 1960 onward. However, there are two problems confronting this idea. As Shewhart identified, the use environment of products varies wildly, making the determination of one single optimum difficult, if not impossible. The methods of robust design (Taguchi and Clausing 1990) have been developed to counter such (and other similar) problems.

Another difficulty is that an optimum exists only in the world of ideas; when it is implemented in the material world, the achievement will more or less deviate from the optimum. These deviations, when large enough, lead to various problems and failures causing avoidable costs—that is, waste. It has been revealed that in civil engineering, in particular, failures may account for up to 10% of the production value (Aagaard and Pedersen 2013).

The phenomenon of waste is troublesome for those subscribing to the Platonic view, and it is turned down in different ways. An argument flowing from the Platonic approach itself is that waste belongs to the natural, varying imperfections of the material world and is of little interest in comparison to the pursuit of eternal truths in the ideal world.

Another argument is that optimum as such eliminates waste (OECD 1972): "It is also clear that optimum production, which by definition means no wastage and the best use of available resources ...." A third popular argument is that if there is a gap between the ideal and material worlds, it is your own fault or someone else's fault. Indeed, so incompatible are the concepts of optimum and waste that along with the diffusion of the idea of the optimal allocation of resources from the (then new) economics after the Second World War, a stark reduction in the use of the term *waste* occurred (Koskela et al. 2012).

Preoccupation with Preexisting Knowledge at the Cost of Contextually Captured Knowledge

For Rankine, engineering was the utilization of physical laws for the design of machines and structures. This view of engineering has persisted. Unfortunately, this overshadows the possibility and need for acquiring knowledge related to the context of a task, perhaps through experimentation or through failure analysis. Indeed, Brady (2014) found, from a set of results from different engineering fields, that, in general, individuals and organizations are reluctant to disclose and acknowledge failure—denying and suppressing dominates over recognizing, recording, and reporting.

Corresponding with this situation, there have been many recent calls to add the capture of contextual knowledge into the core of engineering. Downey (2005) suggested that problem analysis be added into engineering curricula. The benefits of acquiring knowledge through experimentation, trials, and tests in engineering (and product development) has, in the last decades, been emphasized by many authors (Thomke 1998) and in approaches such as design thinking (Brown 2008). In construction, these developments have, for their part, been reflected in a shift of focus from physical models to computer models. The advance of building information modeling has been instrumental in this respect.

Preoccupation with the Viewpoint of One Discipline

Clausing (1994) considered that the traditional design process has not moved far enough beyond partial design, i.e., design from the point of view of one engineering discipline. Thus, according to Clausing, the traditional approach suffers from failure of cooperation (missing unity within the team) and failure of process (missing clarity with regard to the activities). This situation has often been called silo mentality; designers prepare designs from the point of view of their own discipline (without much regard for the needs of other disciplines or stages) and send them on to the other designers or next stages. The weakness of this approach is now widely recognized, and this recognition has triggered the pursuit of concurrent engineering (mentioned previously) and collaborative engineering (Lu et al. 2007).

Preoccupation with Deduction at the Expense of Other Types of Reasoning

According to Rankine, the type of reasoning associated with engineering is reasoning forward (from ideas to the world), deduction. Deduction is especially evident in the task often called analysis—given a structure, determine its behavior.

Reasoning that proceeds in the opposite order—that is, backward—is needed when we start from an observation on the material world and want to create knowledge in the world of ideas or when we start from user requirements and want to create a design fulfilling them. Reasoning backward takes many forms, such as regressive reasoning (the reverse of deduction), induction (generalization from a sample), and abduction (a creative leap to something new). All these are needed in design and problem-solving and also when analyzing waste for the sake of improvement. The problem has been that systematic teaching and training in these types of backward reasoning plays only a minor role in the curricula of engineering schools. In this way, education reinforces the Platonic tendencies of engineering. Indeed, one of the difficulties related to the concept of waste is that investigation of waste requires lesser-known reasoning approaches rather than the familiar approach of deduction.

Construction Management

The Platonic influence on construction management has been channeled, aside from the general mindset of scientific engineering, through quantitative methods and economics. Again, problems and shortcomings have resulted.

Production Planning and Management

The two well-known approaches to production management, push and pull, have an epistemological interpretation: push is based on a plan, and pull is based on the state of the production system. The former is related to the world of ideas and the latter to the material world. Wide experience shows that using (Aristotelian) pushing and pulling is widely superior to (Platonic) pushing only.

In construction, push-based production management emerged with the invention of the critical path method in 1959 (Koskela et al. 2014). The CPM is assumed to provide an optimal plan that pushes tasks into execution. In case of a deviation from the plan, the primary goal is to make adjustments in order to return to the original plan. Beyond that, there is no place for learning from observations of execution. Interestingly, evaluation and validation of the CPM as a method has been more or less absent. One notable exception is provided by Jaafari (1984), who, after reviewing six themes of critique against the CPM, states: " . . . there is nothing inherently wrong in either CPM concept or the subsequent schedules resulted from its analysis, the fault lies in the way it is applied in practice." Of course, this attitude is part and parcel of the Platonic tradition—the starting point in the world of ideas must be correct; it is the execution in the messy material world that is the cause of any problems.

In the beginning of the 1990s, Ballard (2000) realized that typically only half of the tasks in a weekly plan resulting from the application of the CPM are realized as planned. This observation, which made the claim in regard of the CPM providing an optimal plan to collapse, led to the development of the last planner method (Ballard 2000), which uses both the push and pull principles and is thus an Aristotelian counterpart to the CPM.

Quality

As discussed above, empiricism was at the heart of the quality movement when it began in the 1930s. The wider implementation of quality ideas in construction is related to the International Organization for Standardization (ISO) 9000 series of related standards, first published in 1987. However, these standards contained a prescriptive approach to quality; they stipulated which kinds of documents should be prepared for the quality system. Due to demands from customers, a major share of the different organizations in the construction industry now have an ISO certification for quality systems. However, the impact of such systems, with their Platonic flavor, is debated. A telling example was provided in a recent PhD work, in which the author could not find even one case in which identified quality problems would have led to improvement actions in the related organizations (Taggart 2016). Cogently, the newest version of the standard [ISO 9001:2015 (ISO 2015)] takes a much less procedural approach and stresses the application of the PDCA cycle at all levels of an organization.

Construction Economics

Mainstream economic doctrine includes the axiomatic assumption of the optimal productive efficiency of firms (Samuelson and Nordhaus 2005). This is accepted in the discipline of construction economics. For example, in his book on construction economics, Myers (2016) states, in stark contradiction to wide evidence on waste in construction:

> In any free market economy businesses will never waste inputs. A business will not use 10 units of capital, 10 units of labour, and 10 units of land when it could produce the same amount of output with only 8 units of capital, 7 units of labour, and 9 units of land.

Another example of the deceptive power of an axiomatic starting point is provided by public–private partnerships (PPP). These are based on the idea that, in creating a single point of responsibility and a long temporal involvement, the PPP model provides an effective economic incentive to implement through-life management. However, a recent study could not find substantial evidence on through-life management benefits, in spite of the wide application of this model over decades in different countries (Koskela et al. 2016).

Epistemology of Lean

Tacit Knowledge in Japanese and Western Epistemology

In contrast to the Western preference for abstract theories, Japanese epistemology values the embodiment of direct, personal experience; traces of Cartesian rationalism can hardly be found (Nonaka and Takeuchi 1995). Thus, in traditional Japanese thinking, there are no Platonic tendencies—but no complete Aristotelian tendencies, either, because observations are not expected to be transformed into explicit theories. Such know-how, which was learned through practice, was difficult to discuss in the West before Polanyi (1966) gave it a specific name, "tacit knowledge". One might define this concept as all the knowledge that cannot be fully codified, like the ability to speak a language, ride a bicycle, tie a knot, beat the metal when making a sword. Particularly in craftsmanship (although not only in craftsmanship) it is necessary to be familiar with sorts of knowledge that are not always explicitly known and/or cannot be transferred to others. In Polanyi's words, experts always know more than they can tell (Polanyi 1966; Lejeune 2011).

However, there is a phenomenological implication of tacit knowledge that resonates with some Western approaches, not only with Aristotle but also, for instance, with the more recent work of Edmund Husserl (1859–1938). In his criticism of cognition, Husserl essentially negates the conviction that truth is reached when we access an object; we cannot know the truth itself, only the experience of confirmation (see e.g., Husserl 1965; Steinbock 1998). Accordingly, Husserl's system starts from, and extends remarkably, the methodological principle of intuition, the same type of intuition that is at the basis of tacit knowledge (Steinbock 1998).

Furthermore, Husserl's pupil, Martin Heidegger (1889–1976), developed original and influential ideas on ontology and epistemology, advocating the primacy of practice over theory [see, for example, Heidegger (1996)]. Heidegger's epistemology is deeply related to the conviction that formalized, codified scientific knowledge is not fundamental; rather, scientific knowledge relies on tacit knowledge (Heidegger 1996). This is in strong contrast with the Rationalistic tradition considered in previous sections, in which the relationship between scientific and tacit knowledge is exactly the other way around. Tacit knowledge is therefore not a partial and faulty expression of precise, formal, and objective scientific knowledge; on the contrary, the necessary basis and foundation of formal knowledge is given by such common sense, or tacit knowledge (Stahl 1993; Heidegger 1993).

In other words, Heidegger maintains that we gain access to the world only through *use*; we come to know the world theoretically only *after* we have understood it by direct experience, by handling (Bolt 2004). In this context, tacit knowledge is strictly related to our understanding of an artefact. For example, the "handiness" of a hammer is discovered through the act of hammering, not by looking at it "theoretically"; understanding is the care (*Sorge*) that follows from handling (Heidegger 1996).

Surely, tacit knowledge has existed and been relied on in Western cultures, but they have always privileged individual discoveries and the scientific method. Japanese society, on the contrary, adopts collectively held tacit knowledge as a foundation for practice (Ray and Little 2001). This arguably resonates with the Heideggerian views on tacit knowledge.

Japanese Epistemological Starting Points and Their Fusion with Shewhart's Ideas

How are these Japanese starting points visible in the Toyota production system? Cogently, the Japanese author Hino (2005) describes the knowledge used at Toyota as follows:

> Although formal knowledge—standards, procedures and documentation—may be important to improving business outcomes, in the end, it is tacit knowledge—human instincts—that is decisive. This is why organizations need systems and mechanisms to hone the instincts of individuals.

What kind of systems? The following statement from early 1960s is attributed to Eiji Toyoda, the influential director at the time when the Toyota production system originated (Hino 2005):

> In our company we tell people to take bold action because it's all right if they fail. If they do fail, we have them write a report on the failure. We have to do this because if they just remember it without writing it down, then the lesson doesn't get transmitted to the next generation.

Hino (2005) further explains the idea of a failure report; everybody is expected to write up the reasons for the failure and what steps can be taken to avoid it. It seems that these reports later morphed into systematic continuous improvement, or kaizen, based on the PDCA cycle, and supported by different kinds of standards, visual management, and the A3 method.

But how did the PDCA cycle end up at Toyota? Deming, a collaborator of Shewhart, taught this method widely in Japan from 1950, as he stated himself (Walton 1986):

> The Shewhart cycle was on the blackboard for top management for every conference beginning in 1950 in Japan. I taught it to engineers—hundreds of them—that first hot summer. More the next summer, six months later, and more six months after that. And the year after that, again and again.

The systematic adoption of the PDCA cycle at Toyota was—inadvertently—witnessed by Spear and Bowen (1999), who suggested, drawing on sustained participant observation, that the "Toyota DNA" consists of the use of scientific method as a way of learning and improvement. Particularly, this involves a clearly specified hypothesis that is to be tested in a rigorous manner. Although—to them—the system seemed well established and unambiguous in practice, Toyota workers were unable to explain what they were doing. This led Spear and Bowen, unaware of Deming's teaching activities in Japan, to assume that this system had grown naturally out of the workings of the company over five decades. What they describe is, of course, the PDCA cycle, which had become ingrained in the company culture to such an extent that it had become tacit knowledge.

The significant Aristotelian elements, coming both from Japanese culture and Shewhart's proposed approach, are plainly evident in the Toyota production system. However, this does not exclude a strong role given to deduction in the form of planning and the realization of plans, for example.

Epistemology of Lean Production and Lean Construction

Lean production, and specifically lean construction, have inherited their epistemological traits from the Toyota production system. The three major activities needed for production are design (of the production system), control (of production), and improvement. The Aristotelian elements are prominently present in each:

- Production system design, although based on existing knowledge of production processes, available machinery, and the skillsets of the workforce, relies on experimentation, prototypes, and simulation studies (Liker 2004). In construction, first run studies have developed as a corresponding method (Howell and Ballard 1999).
- Production control uses both push- and pull-based techniques for managing production (Liker 2004).
- In improvement, the focus is on problems found in practice, or waste. In the absence of waste, problems are artificially created, for instance, by lowering the inventory levels (Liker 2004).

Thus, at all levels of managing production, Platonic and Aristotelian tendencies blend, with emphasis on the latter.

Table 1. Comparison of features in traditional and lean construction engineering and management, as influenced by epistemology

Feature	Traditional construction, influenced by Platonic epistemology	Lean construction, influenced by Aristotelian epistemology
Construction engineering		
Preoccupation with	Design stage, through sequential engineering	All life cycle stages, through concurrent engineering
Focus on	Optimality; the general and abstract	Waste elimination; the particular and concrete
Privileged knowledge source	General preexisting knowledge	Contextually captured knowledge
Disciplinary scope	One engineering discipline; silo mentality	Collaborative engineering; holistic mentality
Primary types of reasoning	Deduction	All types of reasoning (induction, regression, abduction, and deduction)
Construction management		
Production planning and management	Push	Push and pull
Quality management	Procedural approach (quality system)	Plan-do-check-act (*kaizen*)
Construction economics	Axiomatic assumption of optimal efficiency	Acknowledgement of waste

Problems Caused by the One-Sided Use of Platonic Ideas Are Solved in Lean

It is remarkable that all the problems caused by the one-sided use of Platonic ideas in engineering are solved in lean production:

- From early on, concurrent engineering has been applied in design in order to give a voice to the subsequent stages, especially production and operation. Also, later stages, like maintenance, have been given a stronger position in engineering and a body of knowledge, total productive maintenance (TPM) has developed.
- The focus on optimal plans and design is complemented—in practice, overshadowed—by the consideration of deviations, problems, and, generally, waste.
- Contextually captured knowledge is actively promoted and utilized in the form of market research, experimentation, and, generally, in the framework of kaizen.
- The silo mentality is replaced with effective collaboration, supported by procedures and methods (like A3) and spatial solutions (*obeya*, big room).
- All types of reasoning are encouraged; regressive reasoning and abduction are especially supported through a systematic problem solving approach, including the 5 whys method.

Thus, lean production seems to offer a holistic solution for eliminating the problems caused by the one-sided use of Platonic ideas, from which traditional Western engineering and management have suffered.

Conclusion

An overview of the analyses presented is given in Table 1. The analyses provide two contributions to knowledge. First, they show that the Platonic epistemology has dominated in construction engineering and management, leading to various problems and triggering several correctives. However, a common cause for the problems and correctives, namely unbalanced epistemological choices in the form of preference for Platonism, has not been explicitly discussed and identified in previous literature. Second, the analyses show that lean production (including lean construction) subscribes to the Aristotelian epistemology, and effective methods and tools have been developed for realizing the extraction of knowledge from empirical reality. One major explanation for the evident benefits of lean production is, therefore, arguably related to its epistemological foundation. This has not been explicitly discussed in prior literature.

These two findings are significant not only for the sake of the diffusion of lean production and construction but also as further arguments for disciplinary rethinking in engineering, economics, quantitative methods, and management in general.

However, it is worthwhile to remember that Platonism has lasting value as an approach starting from concepts and ideas; thus, a better balance between the Platonic and Aristotelian tendencies in engineering and management is what is needed. In order to reach this balance, a wide discussion of the relevant disciplines and professions is requisite. In order to enable future generations of engineers to avoid related problems, it is also suggested that the foundations of epistemology and philosophy of science be introduced into university teaching.

Data Availability Statement

No data were generated or analyzed during the study. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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