EPISTEMOLOGICAL EXPLANATION OF LEAN CONSTRUCTION

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Abstract: The Toyota Production System, on which lean production is based, emerged as unplanned result of unrelated improvements and innovations. Although the related practices and principles are now widely reported, theories and philosophical premises underlying lean production are not commonly known. This applies also to lean construction, which, although originated as a set of countermeasures to the 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 model 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 played a major role also in the formation of 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 found benefits of lean construction is related to its Aristotelian epistemology.

INTRODUCTION

Although lean production has now become the mainstream model of manufacturing, and the related practices and principles have been widely reported (Womack & Jones 1996, Liker 2004), the theories and philosophical premises underlying lean production are not commonly known. This is not entirely surprising, as the Toyota Production System (TPS), on which lean production is based, emerged as unplanned result of unrelated improvements and innovations (Fujimoto & 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 (for example Morris & Lancaster 2006), vanishing soon, similarly to other fads. This lack of explanation is also problematic in teaching and training – at least in the West, the situation where only practical methods and rules can be taught but not their underlying rationale and explanation is seen 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 & al. 2016, Liu & al. 2010, Nieto-Morote and Ruz-Vila 2011, Alsehaimi & al. 2014, Castillo & al. 2014, Priven & Sacks 2015) have considerably added to the evidence base on the efficiency and effectiveness of lean construction in comparison to mainstream management methods.

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

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 has interestingly been addressed by Fujimoto (1999). According to him, it is learning and improvement that ensures the high performance of the Toyota Production System. Also, the centrality of waste as a starting point of improvement in the TPS is well-known (Hino 2005). Instead, in the conventional Western management model, it is rather 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 to differences between the traditional and the lean managerial model at the level of epistemology (a discipline addressing how knowledge can be acquired). Accordingly, for extending 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 approach to construction.

The paper is structured as follows. First, the methodology followed is briefly commented. The intellectual origins of engineering and management are then examined. The findings made allude to the influence of the time-honoured epistemological contrast between Plato and Aristotle; this is discussed next, 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.

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 other hand, of scientific engineering, and on the other hand, of quality engineering. Firstly, these two epistemological positions are related to the long-standing discussion of epistemology in science, and in fact identified to be more or less the same as the two alternative epistemological views, originated by Plato and Aristotle. Secondly, 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 Scot 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 – earlier these two fields had 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 behaviour of a structure or machine, and this in turn made it possible to pinpoint the best possible, 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 contrasts 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 exist still today in teaching and research of engineering: basing engineering on physical laws, definition of engineering predominantly as design, emphasis on optimal solutions, and use of deduction as the primary form of reasoning.

Thus, Rankine provides an example of the traditional vision on engineering as applied science, relying dominantly on deductive methods for producing engineering solutions based on theoretical knowledge. Although this viewpoint is contested nowadays in philosophy of engineering, it still goes very strong among engineering research and education.

Shewhart – the father of quality

The American Walter Shewhart is considered as 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 consistent quality of products through control over production.

Shewhart (1931) was not much 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 method of science (Shewhart 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 practices of quality and lean production: basing industrial engineering on the scientific method, focusing industrial engineering on production, emphasis on improvement and use of induction (from empirical experimentation) as the primary form of reasoning.

In a larger context, Shewhart subscribes to another vision on 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 & Maimon 1997) and design science research (March & Smith 1995). It is centred around the complementarity of theoretical knowledge and empirical observations as sources of engineering/design knowledge, requiring thus interaction between induction and deduction.

Comparison between Rankine and Shewhart

There are definite differences between Rankine's and Shewhart's ideas. Rankine's main interest is in design in contrast to Shewhart's focus on production. In engineering, Rankine wants to use the results of scientific research. In turn, Shewhart suggests the use of the scientific method – however, the hypothesis to be tested is not flowing from science but from the practical production context. In so doing, Shewhart (and his followers) popularizes the scientific method: it should be used in practical affairs, outside science. Rankine focuses on what is intended, the ideal or optimal solution. Shewhart's interest is more in reducing the gap between intended and achieved. In Rankine's scheme, reasoning proceeds forward, from ideas to the material world through deduction. Although Shewhart hardly treats matters related to reasoning, it is fair to conclude that reasoning backwards is also needed.

Now, the difference between Rankine and Shewhart has interesting initial similarities to a much older opposition, namely views on science by Plato and Aristotle.

EPISTEMOLOGIES OF PLATO AND ARISTOTLE

The Greek Plato (ca. 428 BC-348 BC), 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 one side, and the so-called "Forms" on the other; the latter are the only reliable sources of knowledge. Proper scientific reasoning thus occurs only via deduction from Forms (or specifically, axioms) to something that can be compared to observations (Ross 1951), as depicted in Fig. 1a. 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 BC-322 BC) is 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 explanation through induction. This is 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 sensorial 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 does the opposite (top-down). The whole process therefore starts from empirical data, then generates new universal truths to explain new observations as shown in Fig. 1b.

---Fig. 1 here ---

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, whilst data science, for example, is Aristotelian in its extreme empiric fashion.

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, where knowledge is written by sensorial experience (Locke 1689), the Rationalists held that sensorial experience is illusory, whilst the source of knowledge resides instead in the mind (Leibniz 1704).

Such 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).

Each and 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 observationally-based. Only after Newton established his theory of gravitation, Kepler's law could be derived from prime principles via deduction. Besides, Newton's static cosmology, based on the law of attraction, generated interesting ramifications also to fields not directly connected to physics, such as economics (this will be discussed in the next section).

The above 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 to a long time span and to different contributions.

Regardless, the Empiricism vs Rationalism debate has marked the epistemological and scientific history for a long time, and is still very vivid nowadays. 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, similarly to what occurred about 300 years before (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 2015). Nevertheless, contemporary rationalism is far from being extinguished, though 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 been joining more or less constantly either the inductivist or the deductivist faction during the whole history of scientific methodology. It seems that in general there is no accepted resolution to this debate, whose features got increasingly sophisticated by 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 to science. Nevertheless, the epistemological questions require to be answered if progress is to be made: from where can we have knowledge to base our design and planning activities, or any productive action? Those leaning to Platonism argue that reason or theoretical knowledge – broadly, the world of ideas – should provide the basis. In turn, those subscribing to Aristotle contend that it is the empirical observation that should be taken as a starting point.

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

In one extreme, it has been typical to reduce engineering simply to an application of scientific knowledge, or to regard engineering sciences as an application of 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 for a series of both scientific discoveries and engineering inventions. In terms of the former, Galileo replaced the qualitative statements at the basis of Aristotelian physics with quantitative statements to describe the strength of materials and kinematics. He accordingly established a mechanical tradition that is still central to modern scientific practice, searching for the mathematical description of the nature of matter (Biener 2004, Machamer 2017). On the other hand, Galileo’s engineering inventions resulted from attempts to solve the problems of engineering practice by using mathematical and physical knowledge (Dijksterhuis 1950, Drake 1999). Thus, he invented a geometric and military compass, used in the balancing of cannons and in the construction of any polygons, together with the calculation of their area; a water thermometer; a compound microscope; a refracting telescope; a method for determining longitude through the orbits of Jupiter’s satellites; 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 “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 on 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 into the vision of engineering as design science.

According to the discussion on the relation between technology, engineering and science, engineering knowledge has been shown to differ from scientific knowledge to which the standard epistemological definition 'justified true belief' applies, whereas notions '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 of 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 relations 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 domain addressed?

We contend that the sphere of engineering and management in general, and specifically regarding construction, has been epistemologically influenced especially from three sources: (1) scientific engineering, (2) economics, and (3) quantitative methods. As exemplified through Rankine, the very idea of scientific engineering is to start from theoretical knowledge; also other hallmarks of Platonism are plain. Although more experientially and empirically based approaches have also existed, especially in the US, the Platonic view of engineering gained a dominating position after the Second World War (Seely 1999). As many engineers end up in managerial positions, this mindset has been influential beyond engineering, narrowly understood.

In economics, the current neoclassical paradigm gained foothold after 1870, with a tipping point 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 the cosmological stability, as treated by Newton. The idea of equilibrium in the economic system is a direct analogy from cosmology. Optimal decision on allocation of scarce resources came to be the leading economic concept. This new understanding of economics diffused rapidly from the 1950s onwards 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 already in the first half of the 20th century, while for management, the famous 1959 reports on business education (Gordon & Howell 1959, Pierson 1959) played a decisive role for positioning economics centrally in business school curricula.

Besides economics, quantitative methods were another of the three root stems for business research and education proposed by the above mentioned reports on the future management education in the US (Koskela 2017). This term refers especially to operations research, a field that used mathematical modelling 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: where earlier the starting point had been in the concrete problems to be solved, now the academics started to create mathematical descriptions, increasingly on assumed problems – a switch from an Aristotelian to a Platonic approach. One of the most successful inventions by 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 & al. 2014). Remarkably, the whole field of project management evolved around CPM and its underlying thinking (Morris 2011). One of the consequences has been that the body of knowledge on project management has largely focused on planning and has little to say on execution (Koskela & Howell 2002). All in all, it can be said that in the realm of productive activities, engineering, production and management, Platonic approaches have provided the dominant worldview in the latter half of the 20th century, and still in the beginning of this century. The upshot is that the overwhelming emphasis is on what is happening in the world of ideas – deduction towards a design based on theoretical knowledge, towards an optimal decision or towards an optimal plan. What will happen afterwards in the material world is of lesser or even no interest.

Certainly, at the same time, there have been counter-currents. 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 into completion as the Toyota Production System, is similarly Aristotelian. These will be commented below. Furthermore, there have been many correctives, Aristotelian methods triggered by the problems caused by overly Platonic approaches. A number of these will be discussed below.

EPISTEMOLOGICAL PROBLEMS IN CONSTRUCTION ENGINEERING AND MANAGEMENT

The general intellectual trends described above have trickled down to construction through education (especially at the university level), 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 the overly Platonic orientation, have also been transmitted.

Construction Engineering

The genesis of scientific engineering, as a Platonic endeavour, has directly contributed to several problems or shortcomings, which have accentuated in the second half of the 20th century, and then triggered various correctives towards the end of that century.

Preoccupation with design at the cost of other stages

As defined by Rankine, engineering is involved in design of machines and structures; the realization of these is left to men having practical knowledge (although not explicitly stated, it is obvious that the operation and maintenance is thought of in the same way by Rankine). 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 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 pre-occupation with the design stage in engineering has triggered various correctives in terms of concurrent engineering (Eastman 2012) and various life cycle approaches (Koskela, Rooke & Siriwardena 2016).

Preoccupation with optimality at the cost of gap between optimal solution and what is achieved

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

The other 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 – waste. It has been revealed that in civil engineering, in particular, failures account for even 10% of the production value (Aagaard and Pedersen 2013).

This 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 low 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 ideal and material world, it is a fault of your own or of somebody else. Indeed, so incompatible are the concepts of optimum and waste that along with the diffusion of the idea of 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, Sacks & Rooke 2012).

Preoccupation with pre-existing knowledge at the cost of contextually captured knowledge

For Rankine, engineering was 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 task context, say through experimentation or through failure analysis. Indeed, Brady (2014) has 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 recognizing, recording and reporting.

In correspondence with this situation, there have been many recent calls to add the capture of contextual knowledge into the core of engineering. Downey (2005) has suggested problem analysis to be added into the engineering curriculum. 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 the shift of focus from physical models to computer models. The advance of Building Information Modelling has been instrumental in this respect.

Preoccupation with the viewpoint of one discipline

Clausing (1994) sees 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 co-operation (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 taking needs of other disciplines or stages into account) and just send them to the other designers or next stages. The weakness of this approach is now widely recognized, and this has triggered the pursuit of concurrent engineering, mentioned already above, and collaborative engineering (Lu & al. 2007).

Preoccupation with deduction at the cost 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 behaviour.

Reasoning proceeding in the reverse order, backwards, is needed when we start from an observation on the material world and want to create knowledge into the world of ideas or when we start from user requirements and want to create a design fulfilling those. Reasoning backwards takes many forms, such as regressive reasoning (reverse of deduction), induction (generalization from a sample) and abduction (creative leap to something new). All these are needed in design and problem-solving, and also when analysing waste for the sake of improvement. The problem has been that systematic teaching and training on these types of backwards reasoning is in 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 less known reasoning approaches, rather than the familiar approach of deduction.

Construction Management

The Platonic influence to construction management has been channeled, besides 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 their epistemological interpretation: push is based on a plan, and pull on the state of the production system. The former is related to the world of ideas, the latter to the material world. The 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 Critical Path Method (CPM) in 1959 (Koskela & al. 2014). Thus, the question is about an optimal plan that pushes tasks into execution. In case of a deviation from the plan, the primary goal is to do adjustments for reaching back to the original plan. Beyond that, there is no place for learning from observations on execution. Interestingly, verification and validation have been absent in relation to the CPM as a method. Jaafari (1984), 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 in 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 1990’s, Ballard (2000) realized that typically only half of the tasks in a weekly plan, resulting from the application of the CPM, get realized as planned. This observation, which made the claim of an optimal plan to collapse, led then 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 started in the 1930’s. The wider implementation of quality ideas in construction is related to ISO 9000 series of related standards, first published in 1987 (ISO refers to International Organization for Standardization). However, these standards contained a prescriptive approach to quality: they stipulated which kind of documents for the quality system should be prepared. Due to demands from customers, a major share of different organizations in the construction industry have now an ISO certification for the quality systems. However, the impact of such systems, with Platonic flavour, is debated. A telling example is provided by a recent PhD work, where the author could not find even one case where identified quality problems would have led to improvement action in the related organizations (Taggart 2016). Cogently, the newest version of the standard, (ISO 9001:2015) takes a much less procedural approach and stresses the application of the PDCA cycle at all levels of an organization.

Construction economics

The mainstream economic doctrine includes the axiomatic assumption of optimal productive efficiency of firms (Samuelson & 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 the 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 on the deceptive power of an axiomatic starting point is provided by Public Private Partnerships (PPP). They 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 wide application of this model over decades in different countries (Koskela & al. 2016).

EPISTEMOLOGY OF LEAN

Tacit knowledge in Japanese and Western epistemology

In contrast to the Western preference to abstract theories, Japanese epistemology values embodiment of direct, personal experience; traces of Cartesian rationalism can hardly be found (Nonaka & Takeuchi 1995). Thus, in traditional Japanese thinking, there are no Platonist tendencies, but no complete Aristotelian tendencies either because observations were not expected to be transformed into explicit theories. Such “know how” that is 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 of speaking a language, riding a bicycle, tying a knot, beating a sword. Especially in craftsmanship, but not only, it is required to be familiar with sorts of knowledge which are not always known explicitly 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 exists 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). With 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 as what 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 e.g. (Heidegger, 1996). Heidegger’s epistemology is deeply related to the conviction that the formalized, deeply codified scientific knowledge is not fundamental, rather it relies on tacit knowledge (Heidegger, 1996). This is in strong contrast with the Rationalistic tradition we considered in previous sections, for which it is exactly the other way around. Tacit knowledge is therefore not a partial and faulty expression of the precise, formal and objective scientific knowledge; on the other hand, the necessary basis and foundation of formal knowledge is given by this 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 therefore 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 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. The 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.

The 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.

Which kind of systems? The following statement from early 1960s is attributed to Eiji Toyoda, the influential director in 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 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, kaizen, based on the PDCA cycle, and supported by different kind 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 since 1950, as stated by 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 is – inadvertently – witnessed by Spear and Bowen (1999), who suggest, drawing on sustained participant observation, that the 'Toyota DNA' consists of the use of scientific method as a way to learning and improvement. Especially, this involves a clearly specified hypothesis, 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 into the company culture to such an extent that it had converted into tacit knowledge.

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

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 on production processes, available machinery and skillsets of workforce, relies on experimentation, prototypes and simulation studies (Liker 2004). In construction, first run studies have settled as a corresponding method (Howell & Ballard 1999).

- Production control is using both push and pull based techniques for managing production (Liker 2004).
- In improvement, the focus is on problems found in practice, waste. In the absence of waste, problems are artificially created say by lowering the inventory levels (Liker 2004).

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

The 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-side use of Platonic ideas in engineering are solved in lean production:

- From early on, concurrent engineering has been applied for giving a voice in design to the subsequent stages, especially production and operation. Also, later stages, like maintenance, have been given a stronger 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; especially regressive reasoning and abduction are supported through a systematic problem solving approach, including the method of 5 Why's.

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

CONCLUSION

An overview on the analyses presented is given in Table 1. They 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. 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 found benefits of lean production is thus arguably related to its epistemological foundation. This has not been explicitly discussed in prior literature.

--- Table 1 here ---

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

However, it is opportune to remind that Platonism has its lasting value as an approach starting from concepts and ideas; it is thus a better balance between the Platonic and Aristotelian tendencies in engineering and management that is needed. For realizing that, a wide discussion in the relevant disciplines and professions is requisite. For enabling future generations of engineers to avoid related problems, it is also suggested that the foundations of epistemology and philosophy of science should be introduced into university teaching.

DATA AVAILABILITY STATEMENT

No data were generated or analyzed during the study.

REFERENCES

Aagaard, N.-J., Pedersen, E. S. (2013). Failure and Documentation of Building Structures, *Proceedings of the 19th CIB World Building Congress, Brisbane 2013: Construction and Society*. ed. / Stephen Kajewski; Karen Manley; Keith Hampson. Queensland University of Technology, 2013. 399 (CIB Proceedings).

Abdelhamid T.S. (2004). "The Self-Destruction and Renewal of LEAN CONSTRUCTION Theory: A Prediction from Boyd's Theory". *Proceedings of the 12th Annual Conference of the International Group for Lean Construction*, 3-6 August 2004, Helsingør, Denmark.

AlSehaimi, A., Tzortzopoulos Fazenda, P. and Koskela, L., (2014). Improving construction management practice with the Last Planner System: a case study. *Engineering, Construction and Architectural Management*, 21(1), pp.51-64.

Ballard, H. G. (2000). *The last planner system of production control.* Doctoral dissertation, The University of Birmingham.

Biener, Z. (2004). Galileo’s First New Science: The Science of Matter. *Perspectives on Science*, 12(3): 262–287.

Bolt, B. (2004). Heidegger, handlability and praxical knowledge. In *Australian Council of University Art and Design Schools Conference*, Canberra (pp. 23-25).

Bondi, H. (1957). *Some Philosophical Problems in Cosmology*. London, George Allen and Unwin.

Brady, S. P. (2014). Learning from Structural Failure: The Challenges and Opportunities, *Proceedings of the Institution of Civil Engineers - Forensic Engineering*, Volume 167, Issue 1, February 2014, pp. 10-15.

Braha, D., & Maimon, O. (1997). The design process: properties, paradigms, and structure. *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans*, 27(2), 146-166.

Brown, T. (2008). Design thinking. *Harvard Business Review* 86(6): 84.

Castillo, G., Alarcón, L. F., & González, V. A. (2014). Implementing lean production in copper mining development projects: Case study. *Journal of Construction Engineering and Management*, 141(1), 05014013.

Cheng, R., Allison, M., Sturts-Dossick, C., Monson, C., Staub-French, S. and Poirier, E., (2016). *Motivation and Means: How and Why IPD and Lean Lead to Success*. Lean Construction Institute (www. leanconstruction. org).

Clausing, D. (1994). *Total quality development: a step-by-step guide to world class concurrent engineering*. ASME Press, New York.

Demian, P. & Fruchter, R. (2006). An ethnographic study of design knowledge reuse in the architecture, engineering, and construction industry. *Research in Engineering Design*, 16(4), 184-195.

Dijksterhuis, E.J. (1950). *The Mechanization of the World Picture*, translated by C. Dikshoorn, Oxford: Oxford University Press

de Vries, M. J. (2003). The Nature of Technological Knowledge: Extending Empirically Informed Studies into What Engineers Know. *Techné: Research in Philosophy and Technology* 6:1-21.

de Vries, M. J. (2005). The Nature of Technological Knowledge: Philosophical Reflections and Educational Consequences. *International Journal of Technology and Design Education* 15 (2): 149–154.

de Vries, M. J. (2010). Engineering science as a "discipline of the particular"? Types of generalization in engineering sciences, In van de Poel, I. and Goldberg, D. E. (eds.) *Philosophy of Engineering, An Emerging Agenda*. Springer.

Downey, G. (2005). Are engineers losing control of technology?: From 'problem solving' to 'problem definition and solution in engineering education. *Chemical Engineering Research and Design* 83(6): 583-595.

Drake, S. (1999). *Essays on Galileo and the history and philosophy of science*, N.M. Swerdlow and T.H. Levere, eds., 3 volumes, Toronto: University of Toronto Press.

Eastman, C. M. (Ed.). (2012). *Design for X: concurrent engineering imperatives*. Springer Science & Business Media.

Ellis, G. a. S., J. (2015). Scientific method: Defend the integrity of physics. *Nature* 516: p. 321–323.

Fish, J. C. L. (1915). *Engineering economics: first principles*. McGraw-Hill Book Company, Incorporated.

Fujimoto, T. (1999). *The evolution of a manufacturing system at Toyota*. Oxford University Press.

Fujimoto, T., & Miller, B. (2007). *Competing to Be Really, Really Good: the behind-the-scenes drama of capability-building competition in the automobile industry* (Vol. 22). International House of Japan.

Gale, G. (2015). Cosmology: Methodological Debates in the 1930s and 1940s. *The Stanford Encyclopedia of Philosophy* (Summer 2015 Edition). E. E. N. Zalta.

Gordon, R.A. and Howell, J.E., (1959). *Higher education for business*. New York, NY: Columbia University Press.

Grant, E. L. (1930). *Principles of Engineering Economy*. New York: Ronald Press Co..

Heidegger, M. (1993). "What Is Metaphysics?" In Martin Heidegger, *Basic Writings: From Being and Time to The Task of Thinking*. 2d ed. Ed. David Farrell Krell. San Francisco: Harper San Francisco.

Heidegger, M. (1996). *Being and time*. A translation of Sein und Zeit. (Joan Stambough, Trans.). Albany: State University of New York Press.

Hino, S. (2005). *Inside the mind of Toyota: Management principles for enduring growth.* CRC Press.

Houkes, W. (2009). The Nature of Technological Knowledge. *Philosophy of Technology and Engineering Sciences*, A volume in Handbook of the Philosophy of Science, 309–350.

Howell, G., & Ballard, G. (1999). *Design of construction operations*. Lean Construction Institute. White Paper, 4.

Husserl, E. (1965). "Philosophy as Rigorous Science", translated in Quentin Lauer, S.J., editor, 1965 [1910] *Phenomenology and the Crisis of Philosophy*. New York: Harper & Row.

Imai, M. (1986). *Kaizen*. New York: Random House Business Division.

ISO 9001: 2015 *Quality management systems*. Requirements (ISO 9001: 2015).

Jaafari, A. (1984). Criticism of CPM for project planning analysis. *Journal of Construction Engineering and Management* 110(2): 222-233.

Knights, D. &Willmott, H. (2017) *Introducing organizational behaviour and management*. 3rd edition. Cengage Learning.

Koskela, L. (2000) *An exploration towards a production theory and its application to construction*. Technical Research Centre of Finland, VTT Publications 408.

Koskela, L. (2017) Why is management research irrelevant? *Construction Management and Economics*, 35 (1-2), 4-23.

Koskela, L. J., & Howell, G. (2002). The underlying theory of project management is obsolete. In *Proceedings of the PMI Research Conference* (pp. 293-302). PMI.

Koskela, L., Howell, G., Pikas E. and Dave, B. (2014). If CPM is so bad, why have we been using it so long? *22nd Annual Conference of the International Group for Lean Construction*, Oslo, Norway, 25 - 27 July 2014, Akademika forlag. Pp. 27 - 37.

Koskela, L., Rooke, J., Siriwardena, M. (2016) Evaluation of the Promotion of Through-Life Management in Public Private Partnerships for Infrastructure. *Sustainability*, 8, 552.

Koskela, L., Sacks, R. and Rooke, J. (2012). A brief history of the concept of waste in production. *IGCL 20*, 18 - 20 July 2012, San Diego, California, USA.

Kragh, H. (1996). *Cosmology and controversy: the historical development of two theories of the universe*. New Jersey, Princeton University Press.

Leibniz, G. W. (1976). *Philosophical Papers and Letters: a selection*. Springer Netherlands.

Lejeune, M. (2011). Tacit Knowledge: Revisiting the epistemology of knowledge. *McGill Journal of Education*, 46(1), 91–105. doi:10.7202/1005671ar

Liker, J. (2004) *The Toyota Way*. McGraw Hill.

Liu, M., Ballard, G. and Ibbs, W., 2010. Work flow variation and labor productivity: Case study. *Journal of management in engineering*, 27(4), pp.236-242.

Locke, J. (1689). *An Essay Concerning Human Understanding*.

Longair, M. S. (2004). *A brief history of cosmology*. Carnegie Observatories Astrophysics Series, Vol. 2: Measuring and Modeling the Universe, 2004 ed. W. L. Freedman (Cambridge: Cambridge Univ. Press).

Losee, J. (2001). *A Historical Introduction to the Philosophy of Science*. Oxford University Press, New York.

Lu, S. Y., ElMaraghy, W., Schuh, G., & Wilhelm, R. (2007). A scientific foundation of collaborative engineering. *CIRP Annals*, 56(2), 605-634.

Machamer, P. (2017). Galileo Galilei, *The Stanford Encyclopedia of Philosophy* (Summer 2017 Edition), Edward N. Zalta (ed.).

March, S. T., & Smith, G. F. (1995). Design and natural science research on information technology. *Decision support systems*, 15(4), 251-266.

Morris, P. W. (2011). *A brief history of project management*. Oxford University Press.

Morris, T., & Lancaster, Z. (2006). Translating management ideas. *Organization Studies*, 27(2), 207-233.

Moses, J. (2010). Architecting Engineering Systems. In van de Poel, I. and Goldberg, D. E. (eds.) *Philosophy of Engineering, An Emerging Agenda*. Springer.

Myers, D. (2016). *Construction economics: A new approach*. 4th ed. Spon Press, London.

Nieto-Morote, A. and Ruz-Vila, F., 2011. Last planner control system applied to a chemical plant construction. *Journal of Construction Engineering and Management*, 138(2), pp.287-293.

Nonaka, I., & Takeuchi, H. (1995). *The knowledge-creating company: How Japanese companies create the dynamics of innovation*. Oxford University Press.

OECD. (1972). *Eighteenth Annual Report and Resolutions of the Council of Ministers, European Conference of Ministers of Transport*. OECD Publishing, 289 p.

Parry, R. (2014). Episteme and Techne [Online]. *Stanford Encyclopedia of Philosophy*. Stanford, US: Stanford Center for the Study of Language and Information. Available: plato.stanford.edu/archives/fall2014/entries/episteme-techne

Pierson, F.C., (1959). *The education of American businessmen*. New York, NY: John Wiley.

Pirtle, Z. (2010). How the models of engineering tell the truth. In van de Poel, I. and Goldberg D. E. (eds.) *Philosophy of Engineering, An Emerging Agenda*. Springer.

Pitt, J. C. (2001). What engineers know. *Techné: Research in Philosophy and Technology* 5 (3):116-123.

Pitt, J. (2010). Philosophy, Engineering, and the Sciences. In van de Poel, I. and Goldberg, D. E. (eds.) *Philosophy of Engineering, An Emerging Agenda*. Springer.

Polanyi, M. (1966). The tacit dimension. Gloucester: Peter Smith.

Priven, V. and Sacks, R., 2015. Effects of the last planner system on social networks among construction trade crews. *Journal of Construction Engineering and Management*, 141(6), p.04015006.

Rankine, W. J. M. (1872). *A manual of applied mechanics*. Sixth ed., revised. Charles Griffin, London.

Ray, T. & Little, S. (2001). “Communication and Context: Collective Tacit Knowledge and Practice in Japan’s Workplace ba”. *Creativity and Innovation Management*, 10: 154–164. doi:10.1111/1467-8691.00217

Ross, S. D. (1951). *Plato's Theory of Ideas*. Oxford University Press, Oxford.

Samuelson, P., & Nordhaus, W. (2005). *Economics* (18e). McGraw-Hill.

Seely, B. E. (1999). The Other Re-engineering of Engineering Education, 1900–1965. *Journal of Engineering Education*, 88, 285-294.

Shewhart, W. A. (1931). *Economic control of quality of manufactured product*. D. Van Nostrand Company, New York.

Shewhart, W. and Deming, W. (1939). *Statistical Method from the Viewpoint of Quality Control*. The Graduate School, the Department of Agriculture, Washington.

Simon, H. A. (1969). *The sciences of the artificial*. Cambridge, MA.

Spear, S. & Bowen, H.K. (1999) Decoding the DNA of the Toyota production system. *Harvard Business Review*, Sept-Oct, pp. 96 - 106.

Stahl, G. (1993). *Interpretation in design: The problem of tacit and explicit understanding in computer support of cooperative design* (Doctoral dissertation, University of Colorado).

Steinbock, Anthony J. (1998). *Phenomenology in Japan*. Springer Netherlands, Dordrecht

Steinhardt, P. (2014). Big Bang blunder bursts the multiverse bubble. *Nature* 516.

Taggart, M. (2016) *The Role of The Supply Chain in Reduction and Elimination of Construction Defects and Rework: An Action Research Approach*. Doctoral Dissertation. The University of Huddersfield.

Taguchi, G. & Clausing, D. (1990). Robust quality. *Harvard Business Review*, 68(1), 65-75.

Thomke, S. H. (1998). Managing experimentation in the design of new products. *Management Science*, 44(6), 743-762.

Torraco, R. J. (2005). Writing integrative literature reviews: Guidelines and examples. *Human resource development review*, 4(3), 356-367.

Toulmin, S. E. (2003). *Return to reason*. Harvard University Press.

Turner, W. (1903). *History of Philosophy*. Boston, Ginn.

van Poel, I. (2010). Philosophy and Engineering: Setting the stage. In van de Poel, I. and Goldberg, D. E. (eds.) *Philosophy of Engineering, An Emerging Agenda*. Springer.

Vincenti, W. G. (1990). *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*. The Johns Hopkins University Press.

Walton, Mary. (1986) *The Deming Management Method.* Putnam, New York. 262 p.

Womack, James P. & Jones, Daniel T. (1996) *Lean Thinking*. Simon & Schuster, New York. 350 p.

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

	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 pre-existing 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