Kwofie, S. and Pasquire, C. 2020. "Lean Thinking for Structural Engineers." In: Tommelein, I.D. and Daniel, E. (eds.). *Proc. 28th Annual Conference of the International Group for Lean Construction (IGLC28)*, Berkeley, California, USA, doi.org/10.24928/2020/0083, online at iglc.net.

LEAN THINKING FOR STRUCTURAL ENGINEERS

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ABSTRACT

The positive transformation realised from lean concept application in the manufacturing industry has inspired many researchers to investigate and propose its adoption in Architecture, Engineering and Construction industry (AEC). The lean application in construction sector has received significant attention. Building up on previous recommendations regarding lean design and construction, this study explored lean thinking for Structural Engineers (SE) to identify new, efficient and innovative ways for executing structural designs and engineering works. The research study was based on qualitative research method using Systematic Literature Review (SLR). An overview of research works on lean applied to designs demonstrated lean to be a multi-dimensional concept characterised by different levels and therefore defied a universal definition. This paper therefore focused on the first part of the study where an understanding of lean was gained with respect to structural designs and was characterised with lean principles, techniques, processes, practices and tools to deliver value for customers.

KEYWORDS

Lean thinking design, lean product development, lean design management, systematic literature review.

INTRODUCTION

The success of Toyota Production System (TPS) application in manufacturing has inspired many researchers to explore its application in construction (Koskela, 1992; Ballard and Howell, 2003; Alarcon et al. 2005). Unlike the manufacturing industry, which has consistent design process (Womack et al. 1990), the Architecture, Engineering and Construction industry (AEC) usually executes unique projects with several complexities and this makes direct application of lean production principles in the construction setting difficult (Jorgensen and Emmitt, 2009; Deshpande et al. 2012). Considering these challenges, several studies have been carried out to extract the key lean production system principles which have successfully been applied to both simple and complex projects in the AEC industry (Koskela, 2000; Deshpande et al. 2012) resulting in delivery of better value whilst stakeholders make real profits (Morgan and Liker, 2006). Successively, review of literature exposed several researches on lean concept implementation in design phase with emphasis on designers but little has been discussed with respect to structural design and engineering works. This research consequently posed a question as "What does lean design mean to Structural Engineers?" and sought to explore understanding of

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Lean Structural Designs (LSD) for Structural Engineers (SE) to identify new, efficient and innovative ways of working.

RESEARCH METHOD

The research study was based on qualitative research method using Systematic Literature Review (SLR) as it provides guidance for a systematic, comprehensive, explicit and reproducible literature review (Tranfield et al. 2003; Denyer and Tranfield, 2009).

In producing SLR, Denyer and Tranfield (2009) reviewed and proposed five (5) principal steps: (1) Question formulation; (2) Locating studies; (3) Study selection and evaluations; (4) Analysis and synthesis and (5) Reporting and using the results. The study was conducted using these steps in conjunction with appropriate methods, tools and procedures, which have been summarised in the research strategy (Fig 1). The quality appraisal was done on 227 publications consisting of journals, conference proceedings, thesis, book sections, technical reports, etc. The evaluation established a total of 42 articles related to the research study and satisfied all the criteria for review. The initial coded themes were then expanded in Nvivo by axial coding to generate sub-themes and other themes based on converged and diverged views of the researchers using thematic synthesis approach whilst refining the coding structure.

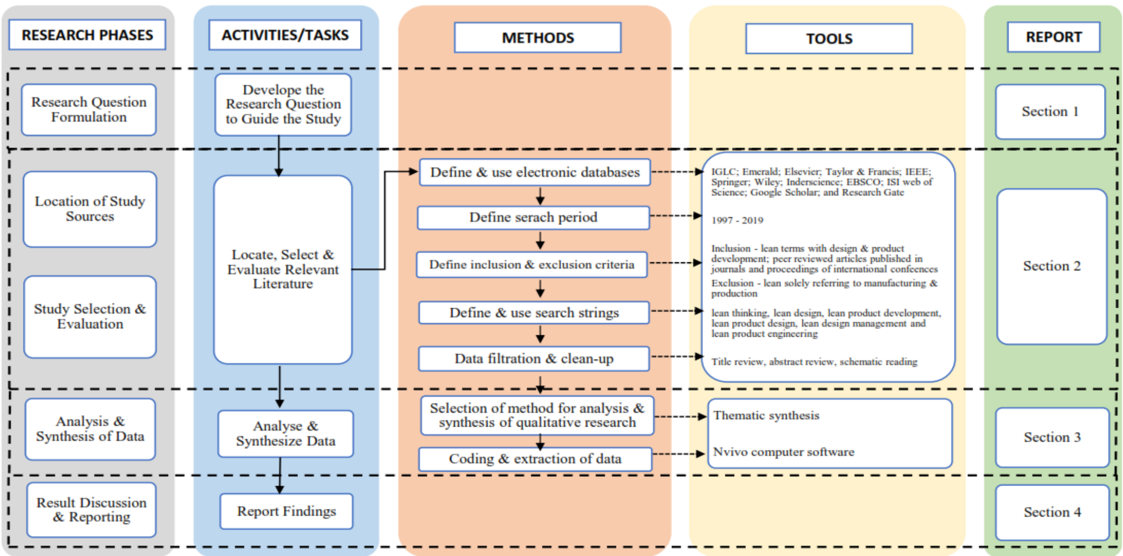

Figure 1: Overview of Research Strategy

DEFINITION OF LEAN STRUCTURAL DESIGN

Lean in the general world view has been perceived as *"lacking or deficient in flesh; lacking richness, sufficiency or productiveness; containing little or no fat; deficient in an essential quality"* (Merriam-Webster, n.d.). Nonetheless, lean applied to construction has been defined differently by several researchers. For instance lean production is defined as the philosophy that ensures elimination of waste from a product's value stream by optimising all resources needed for production (Womack et al. 1990; Bhasin and Burcher, 2006; Torres et al. 2018). Lean production was also defined by Shah and Ward (2007) as an integrated socio-technical systems aimed at reduction of waste through concurrently minimising supplies, customer and internal variability. Hopp and Spearman (2004) further addressed lean production as generation of goods or services where buffering costs due to excess lead times, inventories or capacity are minimised. The concept of value generation and waste reduction appear to be the spine connecting these diverse definitions of lean when applied to the manufacturing and construction industries.

Therefore, lean applied to the design phase creates the potential for high value in the whole process with well-defined systems, structures and materials to meet customer needs (Emmitt et al. 2004). As a result, the application of lean thinking concept in structural designs can be achieved through lean principles, techniques, processes, practices and tools to deliver value for customers (Fig. 2).

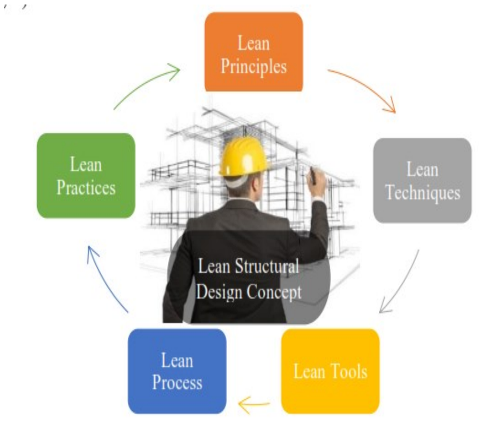

Figure 2: Summary of Lean Structural Design Concept

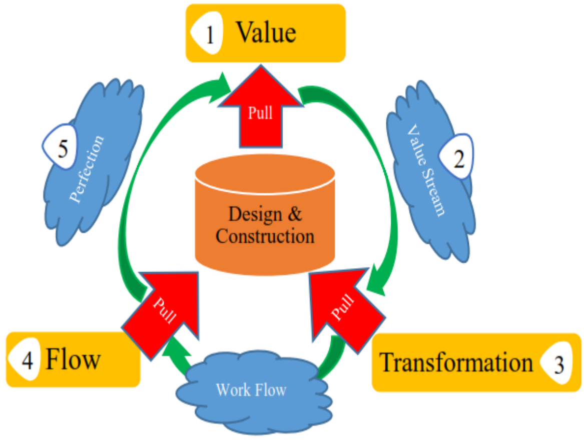

Figure 3: Fundamental Lean Principles Framework (After Womack and Jones 1996, Koskela 2000)

LEAN PRINCIPLES APPLICABLE TO LSD

Womack and Jones (1996) proposed five lean thinking principles to implement lean in manufacturing, which are value, value stream, flow, pull and perfection. Koskela (2000) further proposed theory of production founded on Transformation-Flow-Value principles acknowledged as TFV model where (T)ransformational view of work done is combined with work (F)low and (V)alue delivery. The five principles of lean thinking and TFV theory of production have become the fundamental framework for lean application in all phases of construction projects (Figure 3).

THE VALUE PRINCIPLE

Value is the first principle of lean thinking as underscored by Womack and Jones (1996) and emphasised to be the single most important factor (Welo and Ringen, 2016). Various researches have defined value for client related to the outcome of a productivity focusing on performance, cost, risks, quality, schedule, appropriateness, availability, profitability, and sustainability, which imply value can be fully realised when these are fulfilled. Further research on value identified two key perspectives as customers value and designers value (Vieira, 2013; Emmitt et al. 2004). Even though several studies have emphasised on meeting the customer value needs, it is essential that designer values are not side-lined as they have significant and direct influence on customer value generation (Salvatierra-Garrido et al. 2009). Designers' values are dynamic and very much dependent on client value, which makes customer value paramount and must be given maximum attention in the design process (Vieira, 2013). SE must have ultimate focus on value for customers (design chain next customer and end-product customer) and design accordingly. Citing an example, SE should be in the position to provide an additional floor framing and miscellaneous metal items to make it easier for the HVAC and plumbing engineers leading to overall cost and schedule savings even though the structural cost increases.

VALUE STREAM PRINCIPLE

Value stream refers to the series of information and tasks required for a specific product creation, capable of revealing value added activities, indispensable non-value added activities and unnecessary non-value added activities (Womack and Jones, 1996; Marvel and Standridge, 2009; Ko and Chung, 2014). In design, the identified value activities are enhanced and utilised together with the necessary non-value added activities (e.g. administration work, mandatory testing) whilst unnecessary non-value added activities such as waiting, moving and inspection are removed by appropriating flow, pull and perfection (Huovila et al. 1994; Formoso et al. 1998; Marzouk et al. 2011).

Applying lean to the value stream requires a comprehensive overview of value generation and waste reduction (Ballard 2000). There has been a general propagative and conclusive emphasis on designers primarily focusing on value generation as it eventually result in waste elimination in the design process (Mossman 2009; Haque and James-Moore 2004). This can be achieved by creating the right process to generate the right product for the right customer at the right time and in the right amount known as Just-in Time.

TRANSFORMATION PRINCIPLE

Transformation has been the dominant view in design management that simply enables identification of design tasks broken down hierarchically to optimise and control design task attributes (Pikas et al. 2015). However, a number of researches claimed that the design process traditionally is conceptualised as a conversion of inputs to outputs. Excessive emphasis on design as only conversion whilst flow and value components are ignored result in large incidence of non-value-added activities in the design process (Huovila et al. 1994; Tzortzopoulos and Formoso, 1999; Koskela, 2000; Jorgensen and Emmitt, 2009). This is because the single-minded transformational view is incapable of revealing appropriate usage of resources to satisfy customer requirements (Koskela, 1992; Freire and Alarcon, 2002). The conversional process itself is not in order as designers are left to figure out the order of design tasks making it chaotic and characterised with wastes.

FLOW PRINCIPLE

Flow in design process reduces waste by minimisation of waiting time for information to be used, time spent for information to be inspected for conformance to requirements and time spent in moving information from one designer to the next. Principally, flow ensures coordination of interdependent flows as well as integration of design phase with procurement and construction phases (Ballard and Koskela, 1998; Koskela, 2000; Freire and Alarcon, 2002). Typically, flow in design relates to data and information identified to be multiple, dynamic, iterative, and concurrent making it more complex to manage as against physical materials that flow in manufacturing (Cai and Freiheit, 2011; Lostuvali et al. 2012). Several researchers have proposed ways to ensure process flow such as focusing on what the next customer needs/end product (Womack and Jones, 1996; Bogus et al. 2000), removal of data and information barriers (Hicks, 2007), standardisation of design elements and modularisation (Bjornfot, 2008) and use of integrated information system for automatic exchange of data in real-time (Marzouk et al. 2011). It is evident that flow in design is intrinsic to human actions as emphasised by Cai and Freiheit (2011) that management and designers are the key regulators for efficient flow to generate value. By application of flow principle, SE can be effective in service delivery when the design processes currently disjointed are linked to ensure teamwork, rapid feedback on earlier quality problems, control over the process and direct pressure for designers to solve problems (Liker, 2004).

PULL PRINCIPLE

Applying pull in the design process ensures that no activity produces goods or services until the next customer requests. This can be achieved by scheduling the entire process backwards such that the required delivery date becomes the end date (Womack and Jones, 1996; Marzouk et al. 2011; Cai and Freiheit, 2011). This approach defines process sequence and order, eliminates intermediate inventories, reduce lead time, and prevent overproduction for the desired products (Morgan and Liker, 2006; Cai and Freiheit, 2011; Vieira, 2013). Pulling is the strategy to allow customers pull the value stream to deliver product from designers as opposed the traditional method of designers pushing the product towards the clients (Marvel and Standridge, 2009; Cai and Freiheit, 2011). Cai and Freiheit (2011) articulated that unlike the manufacturing sector which has fixed, linear and sequential process that facilitate the pull system, the dynamic and iterative nature of information flow does not favour only pull concept and therefore should be combined with push system. In similar view, Ballard (2008) and Kim and Lee (2009) suggested push technology to be applied in the early design stages especially during the project definition and later switch to pull system as a major source of value flow. The challenge therefore has to do with clear distinction between when to apply push and pull but Cai and Freiheit (2011) after careful study recommended the boundary to be moved earlier in the process to allow for more customer pull leading to cutting-edge customer value generation.

PERFECTION PRINCIPLE

The concluding principle in lean is to create a continuous learning process built on transparency through solving problems targeted at perfecting the system and defining value (Marzouk et al. 2011; Cai and Freiheit, 2011). Research has identified the process to be endless as there is continuous interaction among the principles, which consequently influences perfection. In order to work towards perfection, structural design systems should be continuously evaluated and refined, seeking for new suitable and innovative structural systems. Deshpande et al. (2012) stated the need to audit the implemented lean techniques, identify the success stories, roadblocks and lessons learned, which should be fed back into the system to ensure continuous improvement of the process towards perfection. Typically, the process can be mapped, implemented, feedback obtained from participants and necessary actions taken to effect changes branded as Plan-Do-Check-Act (Lostuvali et al. 2012).

LEAN TECHNIQUES AND METHODS APPLIED TO LSD

TARGET VALUE DESIGN

Target Value Design (TVD) is a management method for designing and delivering customer value aligned with defined target (Ballard, 2008; Lee et al. 2010). Target setting in TVD enables customers to get exactly what they need with no waste. By the principle rule in TVD, target set cannot be exceeded and only the customer can alter the target scope, cost, schedule or quality and applicable only when the budget for the desired outcome was jointly validated and justified by customer and all the other design participants (Tommelein and Ballard, 2016). Recent research therefore suggests that cost in TVD can be established from three perspectives: client (Macomber et al. 2007; Ballard, 2008), designers (Mossman et al. 2010) and bidders (Lee et al. 2010). Effective target costing can only be defined with collaborative efforts to ensure design process and product are shaped to deliver customer values whilst designs are developed to match cost. Based on the following principles of TVD postulated by Macomber et al. (2007) and benchmarks by Tommelein and Ballard (2016) SE can collaboratively work with other team members to implement TVD:

- Detailed engagement with customers (end-user, suppliers, internal customers and permitting agencies) to evaluate and validate business case and establish target value – budget/cost, schedule, quality, etc.
- Collaboratively plan the project with customers
- Design to meet the defined targets
- Design and detail in sequence of the customer who will use it (pull system)
- Collaboratively implementing learning and innovation in design
- Review and reflect throughout the design process

SET-BASED DESIGN

Set-Based Design (SBD) emerged from set-based concurrent engineering introduced by Ward et al. (1995) to manage Toyota's product development process objectively aimed at applying all relevant criteria from the outset of design to produce, evaluate and choose from design alternatives (Sobek et al. 1999; Ballard, 2000a and 2008; Arroyo et al. 2012). Based on SBD, designers concurrently carry forward, explore a set of many feasible solutions, and eventually narrow down the design options by eliminating inferior alternatives until convergence on the best suit solution (Sobek et al. 1999; Lee et al. 2010; Mossman et al. 2010). This therefore identifies SBD to be a typical funnelling design process. SBD are achieved under these principles: (1) mapping the design space by identification of alternatives to carry forward; (2) integrating and determining solutions from intersections of intervals; and (3) establishing feasibility by maintaining consistency with pre-existing design before committing to a design solution (Sobek et al. 1999; Ballard, 2008). A critical overview of SBD reveals its incapacity to provide detailed guidance on how to select options and so are jointly applied with Choosing by Advantage (CBA) technique (Haque and James-Moore, 2004; Lee et al. 2010).

CHOOSING BY ADVANTAGE

According to Suhr (1999) CBA is a technique for consistent good decision making on design options by focusing on the valued advantages, which is followed by actions and subsequently generate an outcome. Lee et al. (2010) further stated that CBA system allows all participants to collaboratively share their expertise and make inputs in the selection of best suits option from design alternatives and this system also provides an outlined steps on the decision making process to prevent common mistakes such as double counting (Mossman et al. 2010). CBA system emphasises that decision-making must be anchored on project value as decisions are subjective (Lee et al. 2010; Tommelein and Ballard, 2016) and based on factors that reveal significant differences among alternatives but not just important factors in decision (Arroyo et al. 2012). Furthermore, Tommelein and Ballard (2016) emphasised on evaluation of money related to external and market conditions Consequently, SE together with other designers can apply CBA using the guiding principles and steps as proposed by Suhr (1999) (Fig 4).

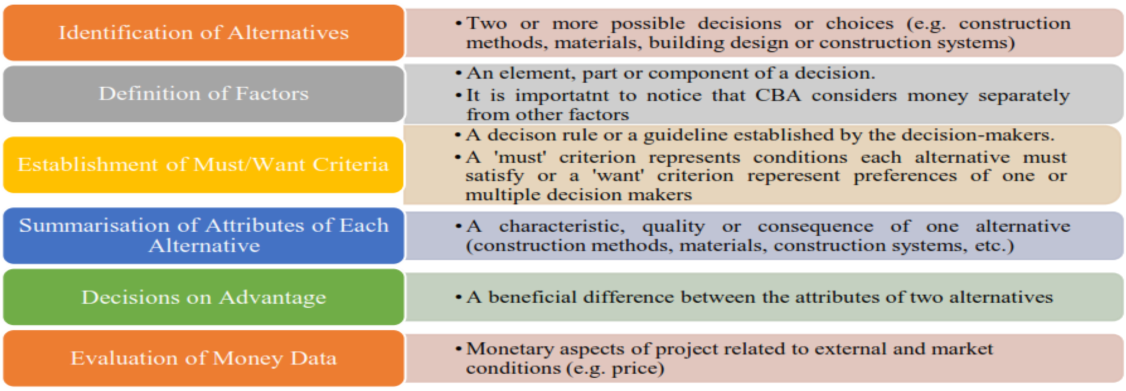

Figure 4: Principal Steps for Implementing CBA

LEAN TOOLS FOR LSD

VALUE STREAM MAPPING

Research has identified Value Stream Mapping (VSM) is a core lean tool used to capture the present state of value stream with regards to information and material flows, identify opportunities to improve flow whilst ensuring waste reduction and proposing future state showing plans of development (Lostuvali et al. 2012; Sisson, 2014). VSM outlines both value adding and non-value adding activities, lead-time of activities, distance travelled and details of inventory in a process and thereby identifying areas to remove waste, improve and shorten the lead time (Sisson, 2014). In a study by Lostuvali et al. (2012) application of VSM to Cathedral Hill Hospital Project resulted in improved designs with effective pull planning sections, effective collection and dissemination of right information to the right people at the right time, proper management of interdisciplinary relationships and proper control of the design process regarding solving problems. VSM application in rigorous iterative design process is very challenging and therefore best appropriated by designers with detailed knowledge of the product's value stream flow.

QUALITY FUNCTION DEPLOYMENT

Quality Function Deployment (QFD) is one of the lean tools that facilitates identification of customer needs and requirements at the design phase (Gargione, 1999; Morris, 1999; Ballard and Zabelle, 2000b; Jensen et al. 2009). QFD is usually applied in a matrix form outlining customer-desired metrics from general to the detailed level and the results are subsequently translated into product characteristics to serve as guide in the production (Gargione, 1999; Jensen et al. 2009). Ballard and Zabelle (2000b) emphasised that QFD is used to comparatively assess design concepts against desired features of a product and thereby creating more opportunities to the customers than they possibly projected.

DESIGN STRUCTURE MATRIX

The Design Structure Matrix (DSM) is a systematic tool for finding the optimal order originally developed by Steward (1981) and applied to represent design information flows such that design tasks are outlined and their interdependencies are assessed to show tasks to be completed both in series and parallel (Koskela et al. 1997; Morris, 1999). DSM generally facilitates planning of the design phases, which was demonstrated by Koskela et al. (1997). The design tasks are first organised in their projected sequential order as matrix rows and columns such as activities ‘A’ to ‘J’ in Figure 5. Sequential activities such as ‘A’, ‘B’ and ‘C’ are executed in sequence for one to follow the next whilst parallel activities (e.g. D and E) can be implemented in arbitrary order in reference to each other. Iterative activities (e.g. G, H, I) often with marks above the diagonal and called blocks should be concurrently executed. DSM helps to manage domain related information flow problems leading to reduced wastes and improved quality in design (Mota et al. 2019). Nonetheless, DSM lacks production control mechanisms and therefore have been combined with other lean tools such as Last Planner System (Koskela et al. 1997).

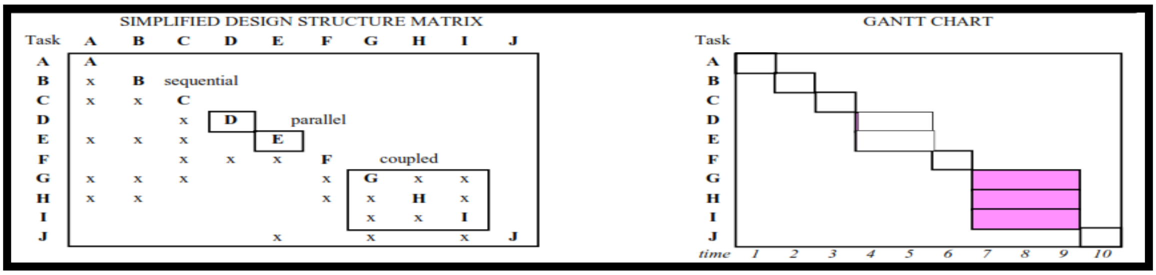

Figure 5: Simplified DSM (from Koskela et al. 1997)

LAST PLANNER SYSTEM

The Last Planner System (LPS) is a lean tool originally designed to facilitate stabilisation of production work flow where decisions and commitment to tasks are made by the last responsible person known as the ‘last planner’ (Morris, 1999; Ballard and Howell, 2003; Jorgensen and Emmitt, 2009). The last planner is responsible for allocating the work or doing the work. The LPS in its present state is illustrated in Figure 6.

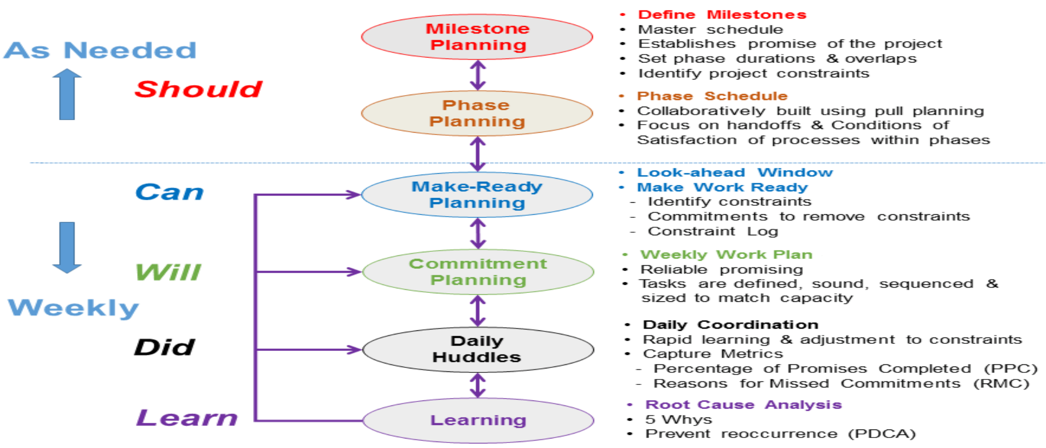

Figure 6: Representation of LPS (from LCI, 2017)

Taking cues from LPS application by various researchers and practitioners such as office building project (Koskela et al. 1997), small high tech project (Miles, 1998) and hospital projects (Hamzeh et al. 2009; Lostuvali et al. 2012), SE can participate in LPS implementation to design as follows:

- Apply “Should Do” technique to establish milestones for the design process and product development
- Key designers being the last planners should be involved and collaboratively work with other design participants to plan and phase the design using pull planning.

- Implement look-ahead window approach to define the "Can Do" design tasks by identifying and removing constraints.
- Make reliable promises and commit to executing design tasks on weekly basis.
- Review and assess daily tasks using PPC and incorporate lessons learned into the system for immediate actions.

5S

The 5S is a systematic process tool used in organising a workplace such that it contains only the materials needed and appropriately designated resulting in work efficiency, reduced waste, optimum value and productivity (Sisson, 2014; Kumar and Ramasamy, 2016). For example, the design workspace should be re-organised for the design team to be close to one another, placing printers near the design team and ensuring materials and documents that aid design are placed at ergonomic positions to reduce stretching and straining. 5S (Fig 7) were coined from Japanese terms as Seiri (Sort), Seiton (Straighten or Set to order), Seiso (Shine), Seiketsu (Standardise) and Shitsuke (Sustain).

Figure 7: Summary of 5S for Workplace Organisation

CONCLUSIONS

This paper focused on the first part of the study where an understanding of lean was gained with respect to structural designs. The research revealed that LSD involved the application of lean thinking concept in structural designs through lean principles, techniques, processes, practices and tools to deliver value for customers.

This research was mainly based on literature and the practical applicability of the findings to assess the understanding and implementation of lean from SE point of views form part of the second phase of the study. Therefore, further research will be carried out focusing on the relationship between structural engineers and lean using case studies. Further studies will also be done to discuss possible hindrances to LSD and corresponding solutions.

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